

THE TRAVEL TIME RELIABILITY OF A PARK-AND-RIDE TRANSPORT NETWORK

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M.Sc. (Mathematics, Electronics, and Information Engineering)

Thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

August 2019

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November 2018

ACKNOWLEDGEMENTS

This journey of undertaking a doctorate through research and thesis would not have been possible without the support of a number of people. Firstly, I would like to express my sincere gratitude to my supervisors, Professor Geoff Rose and Professor Graham Currie, both for their excellent guidance and advice and their immense patience throughout this journey. I treasure their excellent directions and support at all phases of my journey. I cannot express sufficiently my gratitude for how fortunate I have been to have had the opportunity to be supervised by such talented and cooperative individuals. Professor Terry Liu and Professor Majid Sarvi are also acknowledged as my former supervisors, who first provided me with the opportunity to commence research on park-and-ride. I would also like to thank the PhD students in the transport group for making this time joyful. In particular, I would like to express my thanks to the most helpful and humble people I have ever met Chris De Gruyter, Richard Amoh-Gyimah and Brendan Pender, for their encouraging words and for providing me with information quickly whenever I needed it. I am also grateful to Jenny Manson and Min Major, our Research and Postgraduate Manager respectively, who have always amazed me by their caring and supportive assistance, and to Jane Moodie, the Graduate Research Student Academic Support Lecturer, for being available to assist with any enquiries. Dr. Alex McKnight assisted by proofreading the final draft for grammatical and stylistic errors. Civil engineering students are also acknowledged for their efforts in supporting the data collection. Most importantly, I would like to thank my husband Aziz, who has been beside me with all his ceaseless support to deal with my oscillating emotions of doing a PhD. I am grateful to Aziz for encouraging me in every possible way and to Ayham who has been our adorable supportive little child towards the accomplishment of my journey. I would like to thank my amazing parents (I am their only hope and aspiration) for being my continual support along my life journey and for the confidence they have instilled in me. Both my parents-in-law are also thanked for offering their help in different ways.

EXECUTIVE SUMMARY

Park-and-Ride (P&R) is an important initiative designed to increase public transport usage. P&R facilities enable commuters to drive to parking facilities located at public transport stations, park their vehicles and use public transport to reach their ultimate destinations.

P&R relieves the negative impacts caused by excessive automobile usage. Therefore, increasing P&R is considered extremely important by transport engineers, transit operators and urban planners. High public transport ridership, little transfer time and a reasonable fare structure have always been the most common measures to increase the coverage of P&R system. Although the research literature identifies many P&R successes, these schemes sometimes struggle to achieve their objectives, which may include reduced vehicle kilometres travelled (VKT), increased transit mode share and reduced traffic congestion. The performance of a P&R network, and therefore the number of people who use it, depends on the overall quality of service it provides to its users.

Travel time reliability, which has become an emerging theme in transport research in recent years, can be defined as the probability of a trip being completed successfully within a specified time. Travel time reliability associated with a P&R network is a major concern for P&R users who seek a reliable estimate of the travel time in order to plan their journeys. Therefore, variations in travel time affect travel time reliability, making the transport network unreliable for its users. Unexpected delays caused by variations in travel time in the transport network cause commuters' inconvenience and may also have financial and other impacts. Hence, reliability analysis is an important consideration in offering a smooth and efficient transportation service to network users. However, very few studies analyse travel time reliability in the context of a P&R network and for that reason this represents an innovative area in transport research.

The broad aim of this thesis is to develop a framework for the design of P&R networks which will enable decisions to be made about the location and capacity of P&R facilities, in order to maximise the performance of the network in terms of travel time reliability. To achieve this

broad research aim, a research approach was developed which involved three key components as described below.

The first component of this research developed an in-depth understanding of the factors affecting P&R users' travel choices as driving, public transport only and P&R mode. The study has explored the mode change behaviour of P&R users. Based on survey data on P&R users at different station car parks and bus terminals in Melbourne, the choice of mode change of P&R users was investigated. This research has identified that the travel time is the most influential factor in P&R users' choice of travel mode. Travel time reliability is related to the probability distribution of travel time and is relevant at the level of individual links as well as the whole network. Since the distribution of travel time describes the nature and pattern of travel time variability, enhanced understanding of the distribution of travel time is a prerequisite for improved reliability analysis. That issue is addressed in the second component of the research, which was undertaken to quantify a travel time reliability measurement index for a P&R network. The third and final research component focuses on the optimisation of a P&R network in terms of travel time reliability.

This research complements research on the reliability analysis of road networks. This area of research is generally confined to either examining different assumptions about the underlying distributions of travel time or curve fitting travel time distributions to existing travel time data sets. In contrast to previous work, this research has developed and applied an exact distribution of overall travel time in a P&R network. In summary, this thesis provides three original contributions to knowledge in line with the research components. It has contributed by the development of an exact expression for the distribution of travel time in a P&R network, followed by the derivation of a measurement index of network reliability for a P&R network. This research has also developed an approach to the determination of the optimal location and corresponding parking capacity of P&R facilities by optimising the travel time reliability of a P&R network.

LIST OF PUBLICATIONS

The following publications have arisen from the research reported in this thesis:

Conference Presentation

- Islam, S., Rose, G. & Currie, G. (2017) ‘Quantifying Park-and-Ride Network Reliability based on Probabilistic Link Volumes’, poster presentation at TRB Workshop on Doctoral Research in Transportation Modeling and Travel Behavior, Transportation Research Board 96th Annual Meeting, Washington D.C. (one of 16 posters selected for presentation)

Peer-reviewed Conference Papers

- Islam, S., Rose, G. & Currie, G. (2016) ‘Quantifying Transport Network Reliability based on Probabilistic Link Volumes’, 14th World Conference on Transport Research, Shanghai, China
- Islam, S.T., Liu, Z. and Sarvi, M., (2015). ‘Park-and-ride network design in a bi-modal transport network optimising network reliability’, Australasian Transport Research Forum (ATRF), 37th, 2015, Sydney, New South Wales, Australia

Peer-reviewed Journal Paper (Published)

- Islam, S., Liu, Z-Y & Sarvi, M. (2015) ‘Exploring the mode change behaviour of park-and-ride users. Mathematical Problems in Engineering, Volume 2015, Article ID 282750, 8 pages

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CHAPTER ONE:
INTRODUCTION

1.1 Introduction

Park-and-Ride (P&R) is defined as an operation in which commuters travelling in private vehicles either as drivers or as passengers, gather at a common site where they transfer to higher-occupancy vehicles to complete their journeys to work (Noel, 1988). The rapid expansion of private vehicle ownership and comparatively limited road space has caused serious traffic congestion and environmental pollution in most developing countries (Dijk et al, 2013). Traffic congestion is a major issue in the transport infrastructure of cities all over the world and affects the daily life of citizens. Due to the limited capacity of transportation infrastructure, traffic-related congestion and the associated environmental pollution as a result of emissions have resulted in the deterioration of the quality of life and safety in urban areas of many cities. Consequently, tackling congestion and thus improving traffic management systems have been dominant themes in transport research (Manns, 2010).

Public transport use has been promoted in many cities around the world to facilitate people's travel (Qin et al., 2013) and is an effective way to mitigate growing traffic congestion (Liu and Meng, 2012). Therefore, the promotion of public transportation is viewed as a strategy by transport engineers, transit operators and urban planners in order to reduce the use of private cars in urban areas and thus decrease the adverse impacts of transportation, especially on the environment (Rosli et al., 2012). The consideration of various forms of public transportation, increased coverage of public transport systems, high passenger ridership and affordable fare structures are regarded as measures to increase public transportation usage (Rosli et al., 2012). Of these strategies, P&R is a transportation infrastructure initiative which encourages commuters to drive to public transport stations, park their cars and access public transport to reach their destination. P&R has been used as a means of travel demand management in many western countries since the 1930s (Noel, 1988) and is becoming a key initiative to promote public transit ridership. P&R is an essential element in the expansion of the catchment areas of stations and by increasing the usage of public transport, P&R contributes to the sustainable development of transportation systems.

This thesis provides a framework for the analysis of the travel time reliability of a P&R network. This research provides insights that will assist the strategic design of P&R facilities and improve the performance in terms of travel time and reliability of the entire transport system.

The performance of a transportation system depends on the overall quality of service it provides to its users. The reliability of the service of a transportation network is a key measurement indicator for the assessment of the performance of a transportation system. The reliability of travel time associated with a transportation system is a major concern to network users. Hence, reliability analysis is an important consideration in offering a smooth and efficient transportation service to network users. P&R exhibits a major contribution as an effective element of planning the public transport, which has been well considered as the most important strategy in achieving sustainable environment. The key objectives of P&R schemes include: (1) to increase the availability of alternatives to driving alone; (2) to increase the public transit mode share; (3) to expand the reach of transit into low density areas; (4) to offer safe and secure parking locations for commuters; (5) to reduce city parking demand and thus reduce inner city street congestion; (6) to reduce vehicle kilometres travelled (VKT) and Relieving neighborhoods of uncontrolled and informal on-street parking (Evans Iv and Pratt, 2003). However, P&R needs to be well planned and optimally designed to be successful in achieving its goals and being retained as a sustainable infrastructure.

As the literature review highlights, additional research is needed on the travel behaviour of commuters as well as P&R network design to maximise the contribution to the sustainability of the entire transport network. However, little is known about factors affecting the travel behaviour of people using P&R. Furthermore, modelling of P&R network design that optimizes the reliability of the transportation system as a whole is yet to be explored.

Three key research gaps emerge from the literature review which are identified and detailed in Chapter 2 of this thesis. This thesis aims to address these key research gaps.

1.2 Research Aim and Objectives

The broad aim of this research is:

To develop a framework for the design of P&R networks which will enable decisions to be made about the location and capacity of P&R facilities, in order to enhance the performance of the network in terms of travel time reliability.

This thesis explores the travel behaviour aspect and operational aspect of P&R to achieve the above aim.

The objectives are devised in response to the wider research gaps identified from the literature review (presented in Chapter 2). The key objectives are as follows:

- To develop an in-depth understanding of the factors affecting P&R users' travel choices
- To quantify a reliability measurement index to assess travel time reliability of a P&R network
- To develop a model to optimise the travel time reliability of a P&R network

1.3 Thesis structure

This thesis is structured around seven chapters including this introduction. The structure of the thesis along with the original contributions to knowledge flowing from the research is presented in Figure 1.1.

Chapter 2 Literature review. This chapter provides a synthesis of the literature on various aspects of P&R practices worldwide. The chapter includes an investigation of factors that affect the use of P&R. Modeling studies related to P&R design and reliability analysis are also described. This chapter concludes by outlining the key knowledge gaps in this domain.

Chapter 3 Research methodology. This chapter articulates the overall research approach to address the gaps in research and the proposed methodology to justify the approach.

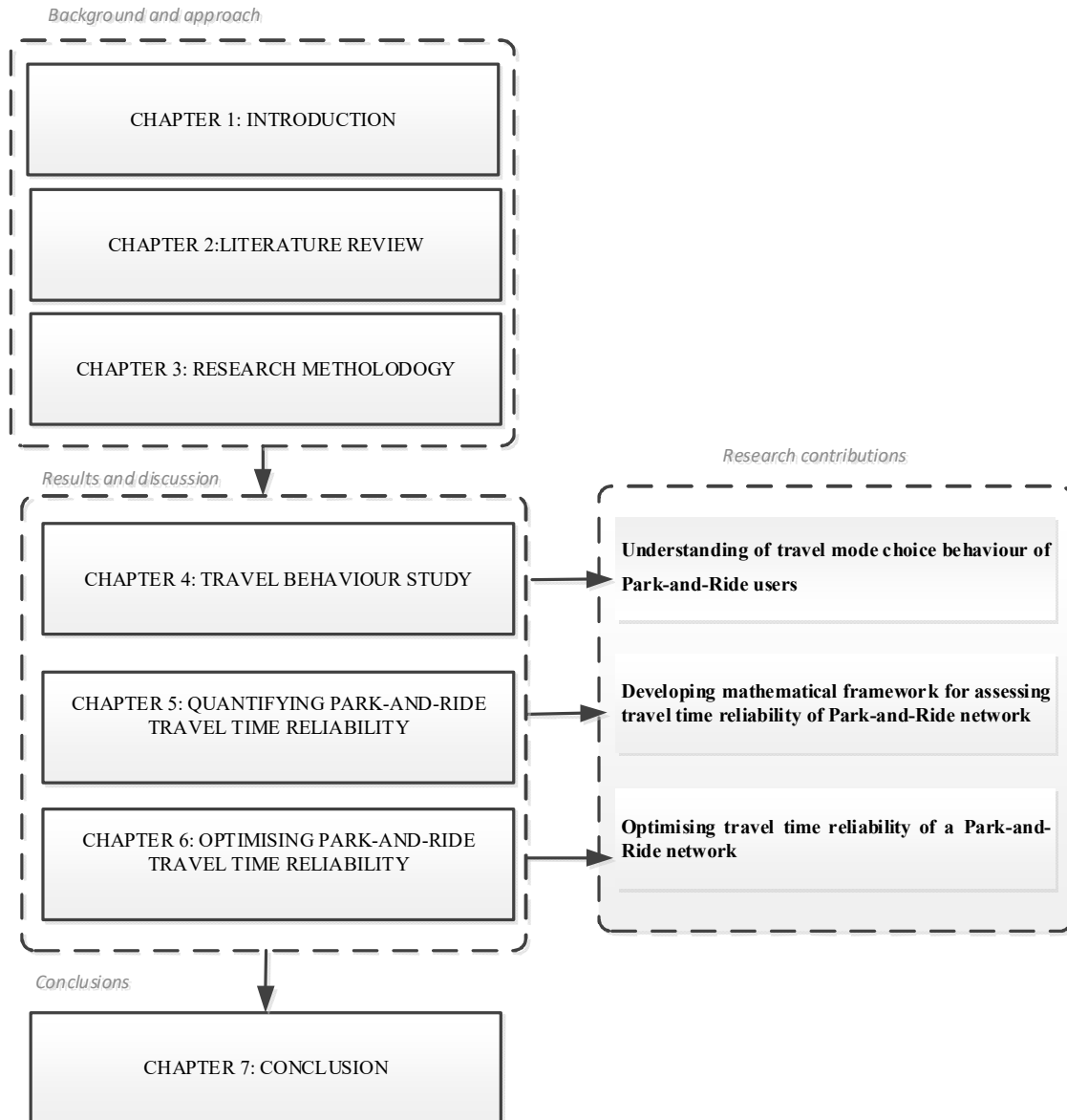


Figure 1.1: Thesis structure

Chapter 4 Travel behaviour study. This chapter reports the findings of an intercept interview survey conducted at Melbourne P&R stations to explore the sensitivity to mode change of P&R users.

Chapter 5 Quantifying P&R travel time reliability. This chapter proposes an exact expression for the probability density function (PDF) of travel time in the P&R network.

Chapter 6 Optimising P&R travel time reliability. This chapter presents an optimisation model designed to assist in making decisions about location and capacity in order to help to optimise the transport network travel time reliability of the P&R scheme.

Chapter 7 Conclusions. This chapter provides a summary of the major contributions of this research, followed by a discussion and directions for future research.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The continuous traffic growth in mega-cities has created challenges to the achievement of sustainable urban development (Banister, 2000). The increasing cars are growing the noise and exhaust emissions. Other effects of these developments are physical interruption, hindrance and jamming (Hamid et al., 2008). However, network capacity expansion through new road construction has never been a sustainable solution to traffic congestion, because of the limited land space especially in urban areas, and because new or widened roads attract more traffic demand, thus causing unwanted congestion in the unchanged connecting roads. Encouraging public transport use by the implementation of congestion pricing regimes to increase the cost of the use of private cars in CBD areas (Liu and Meng, 2012) is one way to mitigate growing traffic congestion. Therefore, promotion of the use of public transport is regarded as a universal solution, because the spatial efficiency of public transport is much higher, and its average fuel consumption rate and emission rate is less than one tenth those of road traffic (Meng & Liu, 2012).

Public transport systems are not very attractive to commuters living in the suburbs and travelling to the city because of the inconvenience of taking public transport at the very beginning of their journey. The key reasons for this inconvenience are longer trip times, lack of door-to-door service, inconvenient public transport itineraries and low bus frequencies. In suburban areas of a developed country like Australia, the residential density is too low to support adequate feeder services for commuters, and this makes P&R an important part of the solution (Qin et al., 2013; Liu and Meng, 2012). As a result, P&R services have become an integral part of demand management and congestion mitigation schemes.

P&R is becoming one of the most essential components of congestion management schemes, with the objective of increasing the mode share of public transport, which results in a more sustainable metropolitan transport system. P&R aims to influence travellers' attitudes and behaviour to shift from private vehicle use to mixed modes of transport, i.e. private vehicles and public transport. However, the role of P&R schemes in increasing public transport use and reducing private vehicle use is unclear. Despite the critical impact of P&R schemes on commuter behaviour, no studies to date have systematically analyzed the effect of P&R sites on changing users' travel mode. Therefore, this chapter provides a review of the literature on P&R, including the elucidation of the reasons for P&R schemes being sustainable. Next, it draws on the results of transport research using behavioural case studies and some references on logistic regression used in choice and

behaviour studies in the research literature. A review of P&R approaches around the world and research related to P&R behaviour modelling are discussed. The network assessment and design of P&R are evaluated and modelling approaches and research on reliability analysis are also highlighted. Finally, key research gaps are established and summarised.

Method followed to review literature

Procedure

The review of literature investigated published studies in “Scopus” database. The keywords entered were park and ride in combination with travel time reliability. Literature was searched between July 2013 and September 2014, without specifying temporal boundaries for the search.

The search terms and operators were the following:

“Park and Ride” OR “Park-and-Ride” OR “P&R”) AND (“Travel time reliability” OR “Transit reliability” OR “Travel Mode Choice” OR “Travel behaviour” OR “Optimisation” OR “Optimal location” OR “Public transport”)

Inclusion and Exclusion Criteria

Published research on park and ride scheme, survey results, analysing travel time reliability, public transport use, optimal location were searched. Inclusion criteria were: 1) peer reviewed empirical studies; 2) written in English language, and 5) using numerical models, statistical models etc. All other studies were excluded.

Results

Figure 2.1 shows the results from the search and identification of studies. After $n = 398$ identified studies, $n = 198$ were used for abstract screening. Based on abstract reading, articles were included when the research objectives of the paper were responding to the criteria and excluded when not. $N = 118$ studies were retained for full-text reading, of which 8 studies were excluded because they did again fail to fulfil the inclusion criteria. 110 studies were selected to be included in the list of references. The years of publication range from 1976-2014, and the number of published studies has been increasing since 2010.

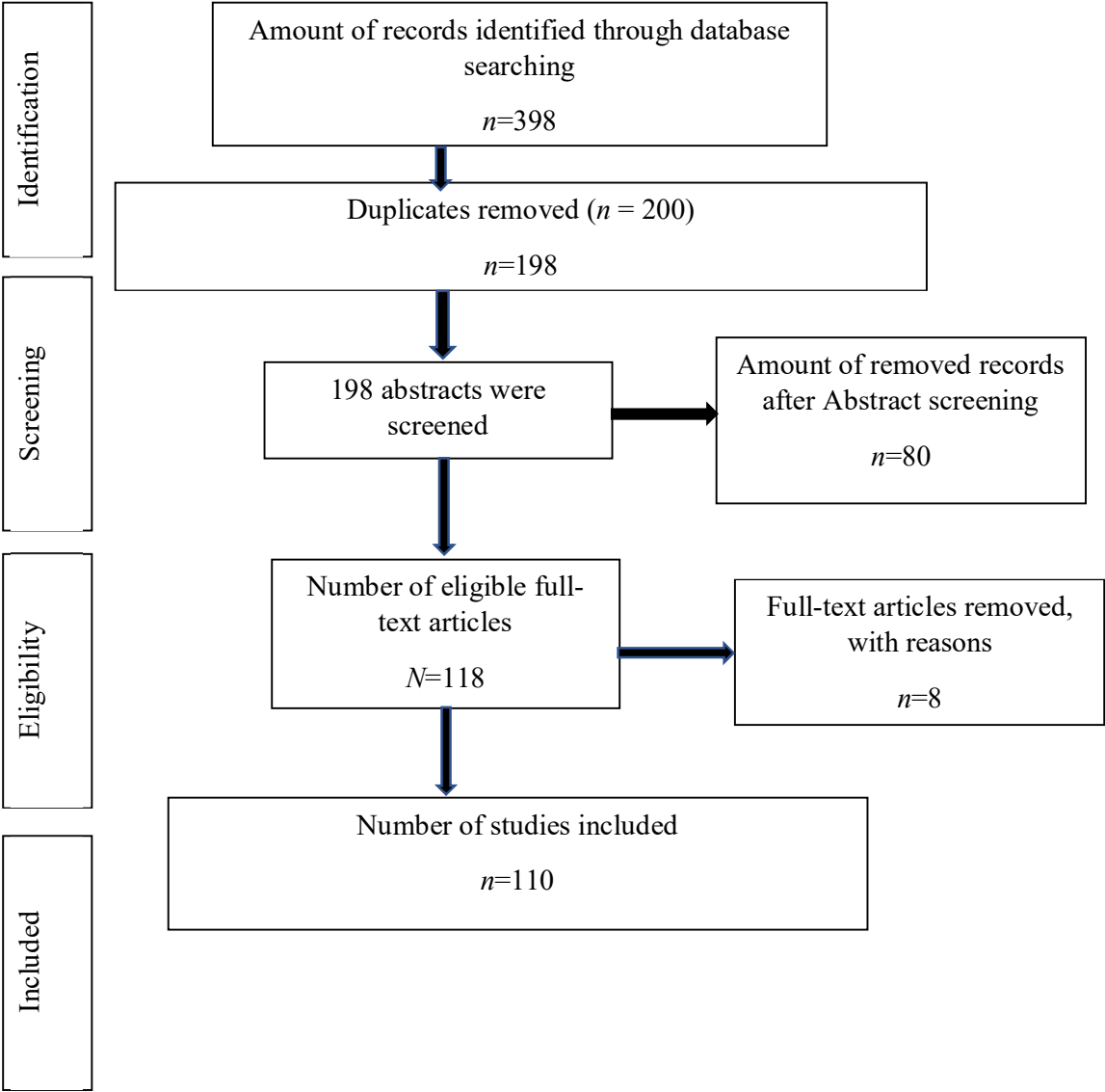


Figure 2.1. Included studied

2.2 P&R as a sustainable strategy

Modern transportation systems have become increasingly dependent on cars, and this is one of the major causes of increasing traffic congestion and related environmental pollution (Sperling et al., 2010). This continuous traffic growth has imposed challenges in achieving sustainable urban development according to Banister, who found that the levels of mobility and car ownership have risen substantially over the recent past and the increases seem likely to continue (Banister, 2000). For example, in European Union member countries, there was a greater than 34% increase from 1985-95 and it is likely that the number will increase by a further 50% by 2020 (Banister, 2000). However, the capacity of the road network is not increasing in a similar way, and this motor vehicle-based transportation system has therefore become one of the major constraints to the achievement of sustainable transportation systems. Several different definitions of sustainable transport systems are reported in the literature. According to the definition given by The Centre of Sustainable Transportation, a sustainable transportation system is one which is able to meet the basic needs of individuals; is affordable and operates efficiently; limits emissions and waste; and minimizes consumption of non-renewable resources (Gilbert, 2003). The Brundtland Commission defined sustainable development as “development which meets present needs without compromising the ability of future generations to achieve their own needs and aspirations (Rosli et al., 2012).

Traffic congestion is one of the major reasons for the worsening quality of our lives. The propagation of huge numbers of vehicles on the road network affects modern cities and has therefore become a great concern in studies related to transportation. Most countries are keen to implement traffic management systems to address traffic congestion, and traffic congestion management has been largely dependent on supply and demand. The construction of new roads is not sustainable in the long term due to the limited resources available. On the other hand, if new roads are built or existing roads are widened, new traffic demand is generated, which in turn causes congestion on other non-modified roads and the entire network is affected. Therefore, the promotion of the use of public transport is regarded as a well-established solution by transportation planners, engineers and urban developers. One of the reasons for considering public transport use as a universal solution is the greater spatial efficiency and much lower fuel consumption and the associated emissions (less than one tenth of those of road traffic) (Meng and Liu, 2012).

In low population-density cities such as those in Australia, the public transport system is less attractive compared to those of dense cities in Europe and Asia. The passenger demand in low-density suburban areas is lower due to low bus frequency, infrequent and inconvenient bus schedules, longer trip times and lack of door-to-door services. These factors in turn may result in inconvenience to commuters and travellers living away from train lines in taking public transport compared to driving. Thus, a P&R service becomes an important and viable scheme to achieve increased use of public transport. Therefore, of the various strategies, P&R is becoming an integral part of transportation planning and management. In essence, P&R is transportation demand management (TDM) strategy for the achievement of sustainable transportation goals and objectives. The purpose of TDM is to remove single-occupant vehicles from roads while keeping a variety of mobility options and increasing passenger-carrying capacity without the expense of adding new roads or links (Rosli et al., 2012). P&R parking facilities can be served as one of the most effective measures of traffic management during the periods of major events as proposed by Chen (2013) in their work taking an example of P&R traffic management during the period of World Expo Shanghai 2011 (Chen et al., 2013).

There has been variety of issues related to P&R facility establishment. Whether to provide P&R facility, where to provide, how it should be designed and implemented are some major concerns for P&R provider, transit operator, transportation agency or urban/transportation planners/engineers. In previous literatures, discussions have been made regarding the potential benefits, dis-benefits encompassing P&R scheme. Feasible policy making decisions for P&R depend on the analysis of influencing factors for P&R choice and P&R demand analysis. P&R needs to be a part of a policy package which gradually reforms the regime of auto mobility towards one of an effective mobility mix, with each mode contributing according to, but not beyond, its particular advantages in sustainable mobility terms (Parkhurst and meek, 2014).

Consequently, P&R schemes can help promote sustainable travel patterns at local and strategic levels (DoE, 2000). The main objective of P&R schemes is to reduce congestion on the road network by taking cars off the road and encouraging public transit mode sharing. Research shows the benefits in terms of the reduction of traffic and overall vehicle-kilometres following the incorporation of P&R schemes in transport networks (Whitfield and Cooper, 1998). However, P&R must be well designed and optimally located to be successful in attracting users

to make optimum use of the facility and then use public transport for the remainder of their journey.

2.3 Role of P&R around the world

As a result of the recognition of city and federal transportation officials of the need to plan for coordinated, continuous and comprehensive urban transportation modes, P&R schemes have gained enormous popularity since they were introduced in the 1930s in the USA (Noel, 1988). The light rail system in Charlotte, North Carolina in US has been taken as a case study using several P&R removal scenarios to examine the potential impact of P&R removal on VKT (Duncan and Cook, 2014). This study found that the P&R removal would lead the average P&R passenger to increase their driving by 8-15 VKT per round trip.

Bus-based P&R schemes were initiated during the 1960s and 1970s in the UK as a solution to infrastructural capacity constraints (Meek et al., 2009). In spite of the UK government's withdrawal of political support for P&R schemes as there was conflict in understanding its role in reducing car usage, local authorities continued to adopt P&R schemes as they considered them a positive option for them (Meek et al., 2009). A study in the UK and the Netherlands explores the impact of the introduction of P& R on urban car mobility, especially its potential transformative impact. The overall car restraining effect of P&R hoped for was mostly not achieved due to transfer from public transport-only trips and from cycling and because overall parking supply across city centres increased (Dijk and Parkhurst, 2014). The linear regression analysis of the results of a survey conducted in some of the major cities in Europe by Dijk and Montalvo (2011) that economic implications of P&R, perceived demand for P & R, and organisational learning capabilities are the most important drivers for city governments whether or not to engage in P&R development, explaining 40% of the variance in their actual engagement in P&R deployment (Dijk and Montalvo, 2011).

Since the success of the first trial P&R facility on the Kowloon-Canton Railway Corporation (KCRC) rail network and Sheung Shui in Hong Kong in 1997, the scheme has been in operation (Lam et al., 2001). The Transport Department and the KCRC collaboratively provided financial incentives for the use of this P&R facility which benefitted them by the resulting modal shift

from private vehicles to rail mode, thus reducing the number of private vehicles on the roads and traffic congestion levels and increasing patronage for the KCRC. China is in the beginning phase in terms of P&R schemes, and Beijing and Shanghai recently conducted pilot studies on the feasibility of P&R facilities (Qin et al., 2013). A parking utilization survey conducted at some selected park and ride facilities along the Kelana Jaya LRT Line and Putrajaya Public transportation terminal showed that overall parking utilization pattern was generally high with the occupancy rate of more than 85% at the Terminal Putra station and more than 92% at the Kelana Jaya station (Kadar et al., 2014) .

Comprehensive researches and analysis of Vilnius City (in Lithuania) transport system had been undertaken in order to eliminate those negative impacts of growing rates of vehicles use to commute to the city on the local inhabitants and the study showed that it is advisable to implement nine park and ride lots at the main suburban entrance roads to Vilnius City (Burinskienė et al., 2014). Economical welfare maximisation approach have been used to assess the survey responses of P&R users of two sites in Sapporo , Japan and the results have suggested that that P&R choice is not only influenced by parking fees, but also by the fares and other attributes of alternative transportation modes (Kono et al., 2014).

P&R has played an important role in Australian transportation systems for over 40 years (Barter, 2010). The low-density residential urban sprawl of Australian major urban cities has generated greater dependency on private vehicles, which in turn is responsible for traffic congestion. Urban traffic congestion causes environmental air pollution. To alleviate traffic congestion on the road network and the associated traffic-related pollution, governments have adopted more sustainable methods of transportation. To enhance this, P&R was introduced several decades ago as a transportation demand management tool with the motto of increasing public transport ride sharing. It has become an important scheme to promote public transport usage in Australian cities. Rail-based P&R systems are commonly established in Australian cities, and this approach is suitable for the mitigation of traffic congestion in cities, as most congestion occurs only in town centres, where the usage of public transport should be encouraged. Some demand-related and behaviour surveys were found in the literature review which had been conducted in Canberra, Adelaide and Melbourne. The P&R strategies in these cities derived from the literature review are described in the following section.

2.4 P&R in the Australian context

P&R strategies evolved in the Australian Capital Territory (ACT) in 2004 when the ACT government recognized the need to develop a sustainable transport plan (SMEC, 2007). This plan chiefly focused on transport demand management and the objective was to attain a sustainable future transport system to maintain the values of living and working in Canberra. The ACT P&R facilities are mostly allocated to surface car parks close to the bus interchanges in the town centre which have approximately 200 spaces in total or surface car parks at a number of centres. Snowy Mountains Engineering Corporation (SMEC) Australia conducted a travel demand survey in Canberra to gather insights into the travel patterns of P&R users in Canberra (SMEC, 2007). The results of the survey indicated that 98% of the respondents parked their cars and then caught a bus for a large part of their journey and 73% of the respondents switched from cars. Issues such as lack of sufficient bus services, lack of safety of vehicles and people, crowded buses and misuse of the P&R system were identified by the demand survey.

A study in Adelaide captured the changes in the travel behaviour changes of users facilitated by the then newly established P&R facility at the Adelaide Entertainment Centre (AEC) on the fringe of Adelaide (Wiseman et al., 2012). The results showed that 48 out of 161 respondents reported that they previously drove to the city but now used a combination of cars and mass transit after the opening of a P&R facility (i.e. 29.8% of car users shifted to the P&R scheme). Prior to the presence of the P&R facility, 101 out of 161 respondents used public transport for their entire journey to CBD. However, with the opening of the P&R, there has also been a concern where the survey showed that the remaining 96 (since 5 of previous users still continued to use bus/train to go to P&R facility) ex-bus and train patrons have shifted to using a car to access the P&R which consist of 82.3% i.e. 79 out of 96 users. In essence, the P&R facility at the AEC centre facilitated the increase of vehicles on the road network and there was a rise in vehicle kilometers travelled (VKT) for both cars and the overall transport network. Studies conducted in south-east Queensland (SEQ) found several factors underlying the probability of a parking space within a P&R lot being occupied for a certain time interval (Sharma et.al, 2018).

In Melbourne, public transport accounts for only 10% of all travel in the metropolitan area, which is significantly lower than the figure for comparable cities such as Sydney, Toronto and Montreal (Public Transport Users Association, 2010). Since the 1970s the Victorian

Government has invested heavily in P&R facilities across the metropolitan rail network. Since 2014, two different types of P&R systems have been in operation in Melbourne:

- Free parking provision at Melbourne metropolitan, urban and suburban train stations.
- Doncaster P&R shuttle bus service.

Although there was a tram-based P&R system in Melbourne it has been phased out. Yarra Trams launched “Melbourne’s first dedicated P&R program”, which began operation on September 11th, 2001 (Yarratrams, 2000). During this program, three car parks were available for use on the Melbourne CBD fringe. These included Etihad Stadium (formerly known as Colonial Stadium) located to the city’s west, Melbourne Museum at the CBD’s east and Olympic Park situated towards the south-east (Yarra Trams, 2000).

The Victorian Government introduced a levy on public and private car parking spaces in the city of Melbourne and the adjacent inner city in January 2006 to encourage public transport use and discourage the use of private and public vehicles (Hamer et al., 2009). In 2006, a total of 36,500 parking spaces were available for travelers at both regional and metropolitan railway stations in Victoria (Hamer, 2010). However, the demand exceeded the supply by 40%. In response to the excess demand, the Victorian Government committed to the provision of an additional 5000 car parking spaces in 2006 at railway stations in the regional and metropolitan rail network. As a step towards fulfilling the commitment, there were up-grades at seven stations which delivered an additional 580 car parking spaces for commuters. A survey conducted at the seven up-graded stations showed that 36% of car drivers shifted to public transport and 29% of new users were added who did not make similar trips prior to the up-grade.

Another survey conducted in 2003 at the Surrey Hills railway station (Palmer and Donnison, 2003) revealed that, if the P&R facility is full upon arrival, only 4% of drivers drive to their destination while 48% prefer to park in a nearby street, and only 5% drive to their destination if the parking facility is closed, while 46% park in a nearby street. These survey results indicate the great demand for P&R in Melbourne. Despite the positive effects of P&R, studies focusing directly on travelers’ acceptance of P&R are rare (Duncan et al., 2013).

The present research included a survey case study at P&R facilities at Metropolitan railway stations and the Doncaster bus terminal in Melbourne to explore the travel mode change behaviour of P&R

users. It is hoped that this study will assist planners to make effective decisions to plan for future P&R facilities and improve the sustainability of the entire transport infrastructure system.

2.5 Behavioural modelling

Research attention has been directed at modelling the behaviour of P&R commuters. Some models have been proposed for single-mode transportation networks while others have been proposed for multimodal transportation networks.

The decision behaviour of P&R users is another important concern for transportation planners, policy makers and engineers to enable them to develop better plans for P&R facilities. Decision-making behaviour in relation to P&R was analyzed in a recent study which utilized decision field theory (DFT) to establish a decision model of P&R (Qin et al., 2013). Their model analyzes the decision-making process from a psychological point of view, and three decision characteristics of individual travelers are considered: simple decision, indecision and preference decision. This proposed model demonstrated reliable performance based on the error difference obtained from the simulated results generated by the proposed model and real-life experimental data. A study exists of the lot choice behaviour of P&R users where two multinomial models are used: random utilization (RUM) and random regret minimization (RRM) (Sharma et al. 2017). The authors concluded that the RRM concept may be useful to model P&R lot choices in strategic transport models (Sharma et al 2017). In previous studies, discrete-choice models have been developed to investigate factors influencing travel behaviour (Ying et al., 2009). Several researches in literature have used the model in their studies (Hamid et al., 2008; Zheng et al., 2010; Duncan et al., 2013). Literature exist on the modelling of the public-transport users' behaviour (Ceder et al., 2013) which shows that Out-of-vehicle times with lower variability were preferred by transit users when making transfers.

2.6 Modelling for Network Assessment and Design of P&R

The performance of P&R depends on the location of the parking facility and its capacity i.e. the size of the parking lot. Choice behaviour analysis and decision behaviour analysis are

important factors in the development of a successful P&R scheme. Qin and Guan (2012) studied P&R behaviour in Beijing by conducting a P&R behaviour survey at 11 representative parking lots. The influential factors for the P&R behaviour were discussed with a binary logit model and the results showed that travel time and cost were the most important influential factors in P&R choice. The travellers' income level, occupation type and the destination of the trip could also affect one's P&R behaviour to a certain extent.

The network equilibrium problem was formulated with the incorporation of P&R assuming the symmetric travel cost function (Fernández et al., 1994) and the asymmetric travel cost function (García and Marín, 2005). A variational inequality (VI) formulation has been proposed for the modelling of P&R services on multimodal transport networks incorporating the parking behaviour of car commuters and elastic travel demand (Li et al., 2007). This study was extended by Liu and Meng, who considered a bus-based P&R system in conjunction with a congestion-pricing scheme (Liu and Meng, 2012). In their work, the network equilibrium flow problem was formulated according to which users' travel behaviours were assumed to follow probit-based stochastic user equilibrium (SUE). A combined-modal traffic assignment model has been constructed which considered the stochastic factors of network and analyzed the effect of P&R policy on reducing traffic congestion (Lin et al., 2011). Du and Wang (2014) considered continuum modeling of P&R services for a linear travel corridor. In their work, an equilibrium travel pattern is formulated as a linear complimentary system. Another study by these researchers used a linear-complimentary system modeling approach for P&R services (Wang and Du, 2013). Previous studies which focussed on modelling for the location design of P&R are discussed below.

Location design modelling

Modelling approaches reported in the literature regarding the P&R location design problem can be distinguished as those using traditional optimization models and those using computational techniques/software programs.

Various objectives have been taken into consideration in determining the optimal location of P&R facilities. For example, linear programming has been utilized to optimize vehicle travel energy (Schoon, 1980), while some researchers have minimized the total system cost in order

to determine the optimal location of P&R facilities (Sargious and Janarthanan, 1983). In the cost minimization approach, Sargious and Janarthanan suggested locating stations such that the total system cost is minimized for commuters and the community as a whole (Sargious and Janarthanan, 1983).

Geographic Information System (GIS) has been used in some previous studies to determine the optimal location of P&R facilities. A hybrid knowledge-based expert system and geographic information system tool has been developed, which aids the human decision-making process in the planning of P&R facilities and in determining the optimal location for P&R services (Faghri et al., 2002). The model has been employed on hypothetical roadways as well as actual roadways in the US and has proven to be successful in finding optimal locations that match actual proposals by expert planners and engineers. Another approach of GIS has been in the delineation of market areas for P&R facilities, taking both travel cost and travel direction into consideration (Farhan and Murray, 2005). Horner and Grubestic (2001) evaluated potential sites for P&R on urban rail lines by the use of flexible GIS system-based methodology and Horner and Groves (2007) proposed the use of traditional travel demand modelling to create a site-specific suitability index to rank and compare potential P&R sites

The deterministic mode choice approach has been reported in some studies considering the linear monocentric city. This approach has been utilized in analysing the optimal location and pricing of a P&R facility with the two different objectives of profit maximization and social cost minimization (Wang et al., 2004). The numerical validation of Wang et al.'s proposed model showed the influence of the operator's objective function on the choice of location of P&R facilities was of great importance. An extension of the work of Wang et al. was carried out by Liu and colleagues (Liu et al., 2009), who conducted a general multi-modal analysis in a competitive railway/highway system with infinite P&R services along a linear monocentric city travel corridor incorporating the in-carriage crowding cost function, multiple P&R facilities and the use/non-use intensity of each P&R facility in order to characterize commuters' modal choices and P&R transfer behaviours. In addition to a linear city, a two-dimensional city scenario was taken into consideration in a study by Yushimito et al., (2012). In their work they developed analytical formulations to find optimal P&R locations which maximize the potential market demand and estimate the potential catchment area of the P&R facilities. This work approximated the P&R catchment area parabolically, which fairly estimates the P&R catchment area and overcomes the limitations of alternative approaches and "rules of thumb"

used by practitioners and researchers (Yushimito et al., 2012). An analytical technique to determine the market demand for P&R facility location has been considered in a previous study with the incorporation of measures of effectiveness (MOE) for different indices such as congestion, emissions, potential demand, connectivity and accessibility (Isa et al., 2010).

Other approaches have been adopted to find the best locations for P&R facilities, including the demand analysis approach (Keck and Liou, 1976; Hendricks and Outwater, 1998). Some recent studies on the optimal location of P&R facilities have focused on the shortest travel time path with the objective of capturing maximum traffic flow from the network, thus minimizing network traffic (Khakbaz et al., 2013). This study was the first to consider several CBDs in solving the P&R facility location problem, and the successful solution of their genetic algorithm-based problem proved efficient in solving large-sized problems and was implemented in a case study in a city in Iran. Research exists on a spatial optimization model for the location of P&R facilities based on P-Hub formulation (Aros-Vera et al., 2013). This proposed model takes into account both origin and destination traffic rather than close to origin traffic only. The logit discrete choice model was utilized to determine the proportion of users patronizing particular facilities (Aros-Vera et al., 2013), with the purpose of finding the best locations for P&R facilities to maximize patronage. In their proposed model, these researchers used linearization of the demand model by transforming the binary non-linear to a linear mixed-integer programming problem. There is another research work found in the literature to promote transit patronage where a bi-level programming model has been developed to optimize the locations and capacity for rail-based park-and-ride sites (Chen et al., 2014).

Cui et al focused on cost-efficient solutions to facility location problems employing a mixed integer program (MIP) formulation and a continuous approximation (CA) model to study the reliable incapacitated fixed-charge location problem with the objective of minimizing the initial set-up cost and expected transportation costs in both normal and failure scenarios (Cui et al., 2010). A custom-designed Lagrangian relaxation (LR) algorithm was used to solve the problem, which is efficient for computing global optimal solutions in the case of small- or medium-sized problems. A location-based service application has been developed in a recent work to ease the P&R users to choose the best train station using a multicriteria decision making model (Chen et al., 2014). The author has claimed the tool developed is economical which can save travel cost and time of P&R users. Bi-level model has been developed in one of the previous studies in China adopting SW maximization as the optimization objective which leads

to a win-win outcome for both P&R service providers and users (Fan et al., 2014). P&R locating model has been developed orienting transportation demand management to minimise their construction and the total transportation cost (Cai et al., 2014). Bi-level model exists to solve multi-objective Park and ride network design problem based on goal programming approach considering several user-defined goals (Chen et al., 2014). In previous studies, Garcia and Marin presented a bi-level model to find optimal parking investment and pricing decisions, and a simulated annealing algorithm was adopted to solve the model (Garcia and Marin, 2002).

2.7 Reliability analysis

Travel time is one of the major aspects of transportation systems, and variability in travel time is due to various unsteady characteristics of key conditions which are the direct source of traffic congestion (Hojati et al., 2009). There are two types of congestion in networks: recurrent and non-recurrent. Recurrent congestion is due to everyday excess travel demand during peak traffic flow, while non-recurrent congestion is due to unpredictable and unsteady situations (Hojati et al., 2009). Traffic congestion which is the result of the limited capacity of transportation infrastructure is linked to the deterioration in quality of life indicators and safety in the modern world. This makes the traffic conditions on the network unreliable. The establishment of network reliability has become a significant concern for transport authorities in the design of transportation infrastructure and networks. In any transit service travel time must be reliable to attract more choice riders (Watkins et al., 2011). Travel time reliability, a measure of network reliability, is defined as the probability of a trip being completed successfully within the specified time (Bell and Iida, 1999). Therefore, variations in travel time affect travel time reliability, making the transport network unreliable for its users. Unexpected delays caused by variations in travel time in the transport network cause inconvenience to commuters and may also have financial and other impacts. Therefore, travel time reliability is one of the key assessment indicators for the evaluation of transportation network performance. Travel time reliability is an emerging topic of interest in transport research. Literature exist on the modelling, assessment, analysis and measurement of travel time reliability on various aspects of transportation.

Different kinds of measurement, methods of analysis and definitions of the reliability of networks are presented in the research literature. Transit network optimisation model has been formulated considering travel time reliability on road (Yao et al., 2014). Their model showed to be improving the reliability of a transit network by reducing the travel time passengers in general. A traffic flow simulator has been utilised to investigate transportation network reliability, in which variations of perceived travel time error and fluctuations of origin-destination (OD) demand are explicitly considered (Lam and Xu, 1999). Another measurement of travel time reliability was carried out using travel time variance derived from a path flow estimator (Bell and Iida, 1997). Utility to users as a measure of network performance reliability has been considered (Bell, 1999), while Yin and Ieda used different risk-taking behaviours of commuters when challenged by uncertain traffic conditions on the network as a result of non-recurrent congestion. The different decision-making behaviours of commuters were examined using a disutility approach and commuters were assumed to choose paths with the minimal expected disutility between origins and destinations (Yin and Ieda, 2001). Studies exist on transit reliability where Watkins et al (2011) have used real-time transit information by observing the riders arriving at Seattle-area bus stops to measure their wait time while asking about their perceived time of waiting (Watkins et al., 2011). Benefits of real-time transit information has also been identified in one study by Gooze et al (2013) where they provide a perspective of the margin of error the transit riders come to expect and the negative effects resulting from inaccuracies with the real-time data (Gooze et al., 2013).

Literature exist on the modeling, assessment, analysis and measurement of travel time reliability on various aspects of transportation. Nicholson (2003) highlighted that a range of techniques have been employed in reliability analysis including (1) Graph theory methods; (2) Game theory approaches; (3) Absorbing Markov chains; (4) Monte Carlo simulation and (5) Micro simulation. He identified Micro simulation modeling techniques as the best modeling approach for assessing the reliability of the network (Nicholson, 2003). Travel time variations in bus services have been studied in the literature to evaluate the travel time distributions (Ma et al., 2015). In Ma et al's evaluation, Gaussian mixture model (GMM) distributions were found to be superior to other forms of distributions.

Travel time variation in the network is the result of several uncertainties caused from the supply side, demand side and other external factors on the road network (Chalumuri and Yasuo, 2014). A Stochastic Response Surface Method (SRSM) has been used to model the travel time

variations under uncertainties (Chalumuri and Yasuo, 2014). In their work, SRSM model and regression models have been compared to evaluate the relationship between travel time variability and different kinds of uncertain variables such as: traffic volume; traffic accidents and amount of rain fall. These analyses was conducted on the Kobe Route on the Hanshin expressway in Japan.

Traffic volume i.e. the number of vehicles in the network has been identified as an important factor in modeling travel time reliability (Hojati et al., 2009). A pilot case study conducted based on the data obtained from the urban freeway of Brisbane has been used to analyse the relationship between travel time reliability measures and vehicle flows (Hojati et al., 2009). In their work, three different measures of travel time reliability namely: Percent variation (PV); Buffer Time Index (BTI) and Misery Index (MI) were evaluated and all indices have shown the similar trend of distributions pattern with the increasing traffic volumes.

Concisely, there are two major methods of travel time reliability analysis as probabilistic method and simulation based method (Li et al., 2016). Clark and Watling (2005) proposed a technique to estimate the probability density function (PDF) of travel time in the whole network by computing the moments of the distribution of total travel time in the network. In this work, the multivariate moments of the link flow vector have been derived first and then the computed moments have been fitted into existing density function curves. One key assumption was to consider drivers facing unpredictable variation in travel time which is not possible to re-equilibrate. Numerical results were used to explore the impacts of changes in link capacity on the network reliability.

The effect of P&R policy in improving the link travel time reliability has been analysed in a research study done by Lin where he showed the relationship among the rate of travel demand of multi-modes, reliability preference factor and travel demand utility factor (lin et al., 2011). Literature is confined to mainly road network reliability analysis and a very limited work on P&R network reliability. Some recent studies have focused on analysing travel time reliability for P&R network which are based on the assumptions of underlying travel time distributions for the P&R network or data fitting (Li et al., 2016); (Fan, 2012). There are a number of examples of fitting continuous distributions to observed travel time data. The distributions used to represent travel time variability include the skewed distribution (Wardrop, 1950); Gamma or lognormal distributions (Herman and Lam, 1974), Weibull distributions (Al-Deek and

Emam, 2006). Travel time distributions have been fitted to data from ten corridors in the Adelaide Metropolitan road network (Susilawati et al., 2010). The results from their analysis showed that none of the corridors' travel time distributions follow a normal distribution although a log normal distribution was appropriate in some cases. Subsequent research modeled travel time variability on those Adelaide roads with Burr Type XII distribution and concluded it was an appropriate model for both links and routes (Susilawati et al., 2013). Burr distribution has also been used by Taylor to model travel time reliability (Taylor, 2012). However, the effect of the location and parking capacity of particular P&R schemes on the reliability of transportation networks as a whole has not been considered in research to date.

2.8 Summary

Key research gaps are summarised as follows:

- Although the research literature identifies many P&R successes, these schemes sometimes struggle to achieve their objectives of increasing public transport use thus reducing vehicle use on road. Despite the critical impact of P&R scheme on commuters' behaviour, no comprehensive study is available on the travel mode change behaviour of P&R users.
- Literature is confined to mainly road network reliability analysis and a very limited work on P&R network reliability. Some recent studies have focused on analysing travel time reliability for P&R network which are based on the assumptions of underlying travel time distributions for the P&R network or data fitting rather than the development and use of the exact expression of travel time variations in the network. No study yet has explored the reliability analysis of P&R networks based on exact distribution of travel time variability.
- The effect of the location and parking capacity of particular P&R schemes on the network reliability of transportation networks as a whole has not been researched. No study to date has attempted to optimise network reliability for P&R network design. Consequently, P&R network design in a bi-modal transportation system considering travel time reliability is a novel area in transport research.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter discusses the methodology adopted in this thesis to achieve the research objectives. The aim of the research is to address the gaps in knowledge identified in the literature review. The research objectives are presented in Section 3.2 and Section 3.3 summarises each of the objectives. The final section provides concluding remarks.

3.2 Research Objectives

Following the research aim established in Chapter 1, three specific objectives were established as follows :

1. Explore the factors that influence the travel mode choices of P&R users.
2. Develop a mathematical framework to assess the travel time reliability of a P&R network.
3. Assist in improving decisions about P&R facilities (location and capacity) by developing an approach to optimisation that addresses travel time reliability.

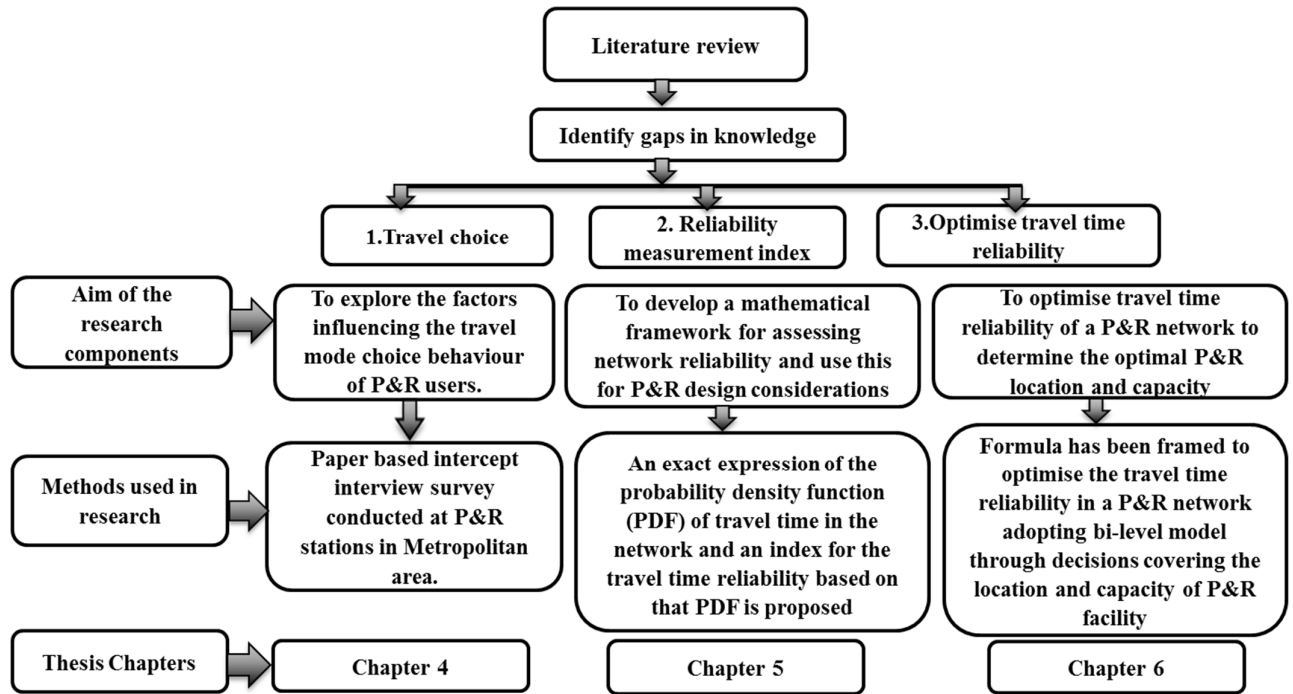


Figure 3.1 : Research Approach

3.3 Overall research approach

The research gaps were identified in Chapter 2 and each research objective is summarised in Section 3.2. In order to achieve the research objectives, three key research components were identified, as shown in Figure 3.1. Key findings from each research component are reported in Chapters 4-6. A brief description of each research component is provided in the following sections.

Research Component 1 : Travel demand analysis for P&R mode choices

Factors affecting the choice of P&R and the extent of its effectiveness on how they affect the travel mode change behaviour of commuters most were explored through a survey of P&R users at different metropolitan railway stations. The main objective of this study was to investigate the key factors in the mode change behaviour of P&R users. Based on a survey of

P&R users at different stations in Melbourne, this research component has aimed to gain a better understanding of the functioning of P&R and mode change behaviour of P&R users. An intercept interview survey was conducted since this type of survey approach is designed to be conducted outside the home while the respondent is in the process of using a mode transport. In this study three specific railway stations and a designated bus P&R facility in Melbourne are chosen. Survey stations locations are selected for the purpose of this survey due to the practicality of the locations to be accessed by the survey teams. A field survey was conducted based on a questionnaire consisting of revealed preference (RP) and stated preference (SP) questions as well as demographic questions. The RP survey was conducted to understand the existing choices and experiences of commuters using the P&R service. The SP Survey was used to examine travellers' preference of P&R under nine hypothetical scenarios. The empirical model reveals that the travel time taken by transit vehicles and the transfer times at P&R stations are the primary factors affecting individuals' decisions to choose public transport over driving.

Research Component 2 : Quantifying reliability measurement index for P&R networks

Travel time has been found to be the most influential factor in P&R users' travel choices. Therefore, a network with reliable travel time is an important issue to be considered, which leads to this second part of research component that involves quantifying a travel time reliability measurement index for a P&R network. The aim of this component is to develop a mathematical framework for the assessment of network reliability and use this for design considerations. This task led to the development of an exact expression of the probability density function (PDF) of travel time in the network. Based on the PDF of travel time, an index for travel time reliability is then proposed. Setting a threshold value for the total network travel time as, $T = \theta$; where θ be the maximum allowable network travel time without degrading network performance beyond an acceptable level, the network reliability index can be derived as $R(\theta) = \int_0^\theta f_T(t)dt$. Here, the reliability index $R(\theta)$ is a real number within (1.0, 0.0) where 1.0 and 0.0 respectively represents that that network reliability is at its highest and lowest. Detail derivation is presented in the relevant chapter.

Research Component 3 : Optimising travel time reliability of P&R network

The third part of the research component develops an optimisation approach to assist in improving decisions about P&R facilities (location and capacity) to address the travel time reliability of the network. This task determines the optimal P&R scheme in terms of optimal P&R location and the corresponding parking capacity. This research component developed a bi-level programming model to determine the optimal parking location and the corresponding capacity. The objective of the upper level is to minimize the total expected travel disutility in the entire network. The lower level is the commuters' route choice problem and travellers are assumed to choose the path/route with minimal expected travel disutility. This disutility-related multi-class user equilibrium is formulated as a non-linear complimentary problem which is a non-additive path-cost problem. Genetic algorithm (GA) is a well-known heuristic for solving optimization problems. GA begins with a feasible set of possible candidate solutions called a population mimicking the natural selection process. In this study, GA is implemented to solve the bi-level model by adopting a new approach to the solution and the GA verified by a numerical example considering a P&R network to demonstrate the feasibility of the solution. Details of the solution algorithm has been provided in the relevant chapter.

3.4 Summary

This chapter has described the approach to addressing the research gaps identified in the previous chapter. The research methodology proposed to achieve the research objectives encompassed three key research components.

The first research component includes an intercept interview which was used at different P&R facilities in metropolitan Melbourne. The empirical models using multinomial logistic regression revealed that the travel times taken by transit vehicles and the transfer times at P&R stations are the primary factors affecting individuals' decisions to choose public transport, whereas parking fees are an additional factor affecting commuters' choice of driving. Travel time has been found to be the most influential factor in P&R users' travel choice. Therefore, a network with reliable travel time is an important issue to be considered, which leads to the next research task to quantify the travel time reliability measurement index for a P&R network. A mathematical framework was then developed for the assessment of network reliability and this

was used for design considerations. The optimisation of the theoretically developed model is not tractable, and the network has not been optimised in terms of travel time reliability. Therefore, this led to the third research component, which was to optimise the travel time reliability in a P&R network. This then determined the optimal P&R scheme, i.e. the optimal P&R location and capacity. Efforts have been made to overcome the existing gaps in the literature on the mode choice analysis of P&R users, exact expressions for travel time reliability and optimising the travel time reliability of P&R networks. However, opportunities exist to address outstanding limitations in the future. This topic is covered in Chapter 7 in a discussion of future research directions.

CHAPTER FOUR: TRAVEL BEHAVIOUR STUDY

4.1 Introduction

The role of P&R schemes in increasing public transport use and reducing private vehicle use is unclear, and despite the critical impact of P&R schemes on commuter behaviour, no studies to date have systematically analyzed the effect of P&R sites on changing users' choice of travel mode. The aim of this chapter is to address this research gap by exploring factors which determine the choice to use P&R and comparing them with factors determining the selection of other modes of transport. It documents the mode change behaviour of travelers using P&R services. In order to achieve this aim, an intercept interview survey was conducted at different P&R station car parks in Melbourne. Multinomial logistic regression was used to investigate the factors affecting the mode change behaviour of commuters, and it is hoped that aspects of the findings may enable the government to take steps to reduce the obstacles that prevent commuters from using this sustainable transport mode. The survey methodology and approaches are described, including the categories of questions asked. This is followed by a presentation of the results and their implications. Finally, a conclusion and a discussion of future directions of research in this field are offered.

4.2 Research method

Factors affecting the choice of P&R and the extent of its effectiveness in how they most affect the travel mode change behaviour of commuters were explored through a survey of P&R users at different metropolitan railway stations. The main objective of this study was to investigate the key factors in the mode change behaviour of P&R users. Based on a survey of P&R users at different stations in Melbourne, we hoped to gain a better understanding of the functioning of P&R and the mode change behaviour of P&R users. Details of the survey methodology are explained in the following sections.

4.3 Survey Procedure

An intercept interview approach was used at three different railway stations and a designated bus P&R facility in Melbourne, as indicated in Table 4.1. Survey locations were chosen to enable many P&R users to be approached. One key consideration in the selection of the stations

for the survey was the practicality of the locations to be accessed by the survey teams and their level of use as P&R stations, as opposed to stations where the main access was by walking. Participants were selected as they alighted from the train and they were invited to be interviewed. One hundred and forty-three participants were surveyed, and they completed the entire questionnaire.

Three criteria were chosen to select unbiased sample responses. These were that the respondent was (1) using the P&R site on the day of the survey, (2) not a tourist and (3) 18 years old and over. Criteria 1 and 2 ensured that the respondents actually used the P&R service and were aware of the scheme.

Table 4.1. Survey Locations

Survey locations in Melbourne	Distance from city (km)	Parking capacity
Doncaster	18	400
Glen Waverley (1930)	24	340
East Malvern (1929)	14	676
Blackburn (1882)	22	112

4.4 Questionnaire

The questionnaire comprised two major components: (a) Revealed Preference (RP) questions and (b) Stated Preference (SP) questions. The RP part contained trip-based questions which revealed information about the respondents' current travel behaviour, previous mode of travel, and perspectives on current transport-related issues. The SP survey helped in analysing the travellers' travel mode acceptance behaviour. The difference between these two types of surveys is that the former reveals what respondents do in the real world whereas the latter predicts what respondents would do under different circumstances. SP is able to create sufficient variation for researchers to evaluate various kinds of underlying combinations. Another advantage of SP is that it can simulate things that have not happened in reality. In this way, researchers can forecast trends in the future (Hensher et al., 2005; Train, 2009).

An orthogonal fractional factorial design was generated using SPSS, consisting of nine SP scenarios in total. Each SP scenario contained three choices of transport mode (i.e. car, public transport only and P&R) and three variables each assigned three different attribute levels were selected as factors influencing commuters' decisions in relation to travel mode choice: (a) the price of parking in the city (\$10, \$20, \$40); (b) public transport only travel time (PTTT): 40min, 60 min, 90min; (c) Transfer time at P&R stations (TT): 5 min, 10 min, 20min. It is to be noted that the "transfer time" here equals "parking time + walking time to the platform + waiting time for the train".

In addition, the questionnaire included questions relating to socio-demographic characteristics (e.g., age, gender, annual income, education, employment status, car ownership). The surveys were conducted on weekdays from 4.30pm to 6.30pm. The afternoon period was chosen for the conduct of the survey in order to avoid the morning rush hour when commuters are often in a hurry not to miss their train or bus. Each questionnaire took approximately 10 minutes to complete. An incentive gift voucher was included to increase the response rate given that the questionnaire was longer than usually employed in an intercept survey where respondents would usually be asked three or four questions. Each eligible participant was provided with an AUS\$10 gift voucher as the incentive. A copy of the questionnaire is provided in Appendix.

4.5 Survey Data

Participants were first asked some questions about their trip origin and destination, which revealed information about the purpose of their travel, how far they travelled to their destination from the P&R facility, and their frequency of use of P&R each week. Each of the questions related to their trip included five alternative options for respondents to choose from.

A number of questions about past and current travel habits were also asked. For example, participants were asked which modes they used to travel to their destination prior to starting to use P&R mode (they could choose various travel mode options including the answer 'did not make a similar trip before') and the reasons for choosing P&R compared to other possible options (they could select a number of reasons for their choice of P&R). The responses to this question suggested that a high proportion of people have shifted to P&R mode from driving

mode (44%) and the reason for choosing P&R was mostly the ease and convenience of using P&R (68%), including no traffic congestion, no parking at work, infrequent buses from home/trip origin, and the convenience of reading books or official documents in the transit vehicle. The users who used public transport all the way to their destination have now shifted part of their travel from the car to P&R (19%). The results of the survey are depicted in Figure 4.1, which shows the previous travel mode of users. Figure 4.2 shows the reasons for road users shifting from driving mode to P&R mode.

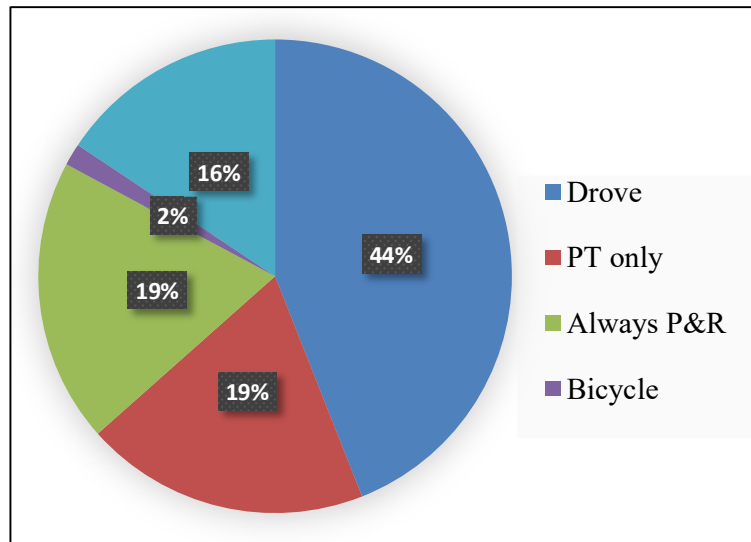


Figure 4.1: Previous travel mode

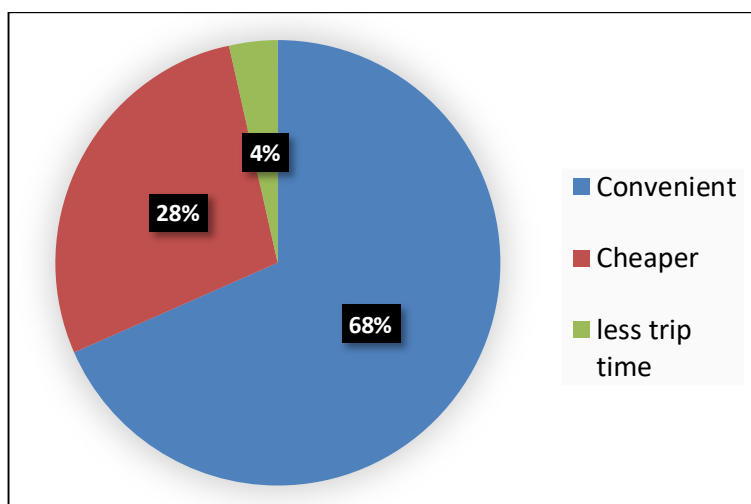


Figure 4.2: Reasons for shifting to P&R from previous driving mode

In addition, participants were asked what they would do if, upon arrival at the P&R site, they found no parking space was available. Most commuters were inclined to park on the streets nearby, as is clear from Figure 4.3.

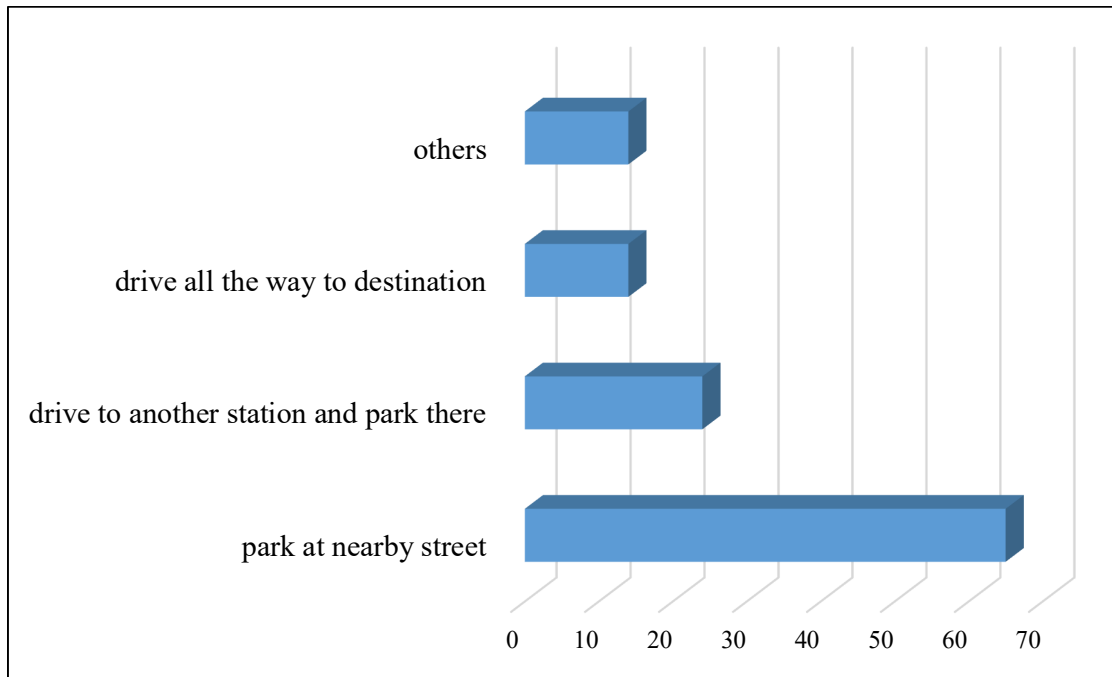


Figure 4.3: Commuters' decision when no parking space is available at P&R site

Respondents' general experience of the public transport service, the P&R facility and the traffic conditions in Melbourne were explored using a five-point Likert scale, in which low numbers indicated negative experiences. Participants were then asked nine SP questions with different parking costs in the CBD, travel times taken by transit vehicles and transfer times at P&R stations in order to explore choices among three travel modes: driving, public transport only and P&R mode. The nine SP scenarios are outlined in Table 4.2.

Finally, respondents were asked a series of questions requesting demographic information, which included the respondent's gender, age, occupation, origin post-code, number of cars they had access to and annual income range. Demographically the survey included a little bit of higher number of males (54%) than females (46%). Age-wise the sample was largely

comprised of respondents of age ranging between 36 -49 years (36%) and 50 years and over (28%). Income ranges of the P&R users is chiefly ranging between 60k-80k and over (33%).

Table 4.2. Nine Stated-Preference Choice Scenarios

Scenarios	Parking price (\$)	Travel time by public transport alone (min)	Transfer time at P&R station (min)
1	40	90	5
2	10	60	20
3	40	40	20
4	10	90	10
5	20	90	20
6	40	60	10
7	20	60	5
8	20	40	10
9	10	40	5

4.6 Results and analysis

The survey results were analysed to explore the respondents' current behaviour, frequency of travel, reasons for choosing P&R over other modes, and their opinions about a range of transport-related and P&R facility-related issues. Commuters' personal attitude response ratings were analyzed, and the results suggest that the convenience of the P&R site, satisfaction with the public transport service and transfer time at the P&R facility were the most common positive answers with a Likert scale of 4, as shown in **Figure 4.4**.

Multinomial logistic regression analysis was used for the nine SP scenarios. In the research literature, logistic regression is used to describe and test hypotheses about relationships between a categorical outcome variable and one or more categorical or continuous predictor variables (Peng et al., 2002). Logistic regression has been used in research on different types of behavioral and decision analysis (Johnson et al., 1995). Multinomial logistic regression was

used to derive the P&R access station choice model. It should be noted that in order to derive the probability function for the travel mode choice, a distributional function of the random error component needs to be assumed. We assumed that the error term follows the Independent and Identical Gumbel Distribution (IID Gumbel).

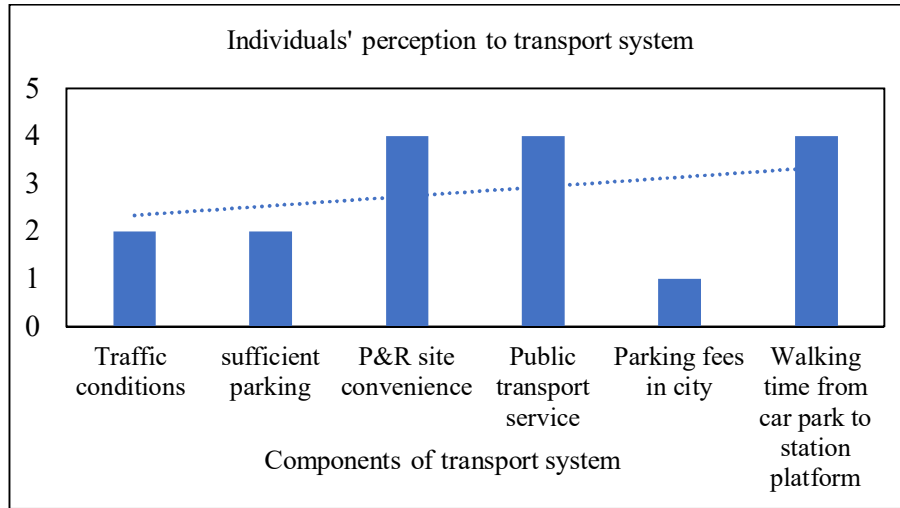


Figure 4.4: Satisfaction with components of transport system

In this study, our response variable is “Choice”, which is of three outcomes of choice of travel mode: Drive, Public transport only and P&R mode. Multinomial logistic regression is a suitable technique to use, because it was developed to model nominal outcome variables, in which the log odds of the outcomes are modeled as a linear combination of the predictor variables. In this model, the logit is the natural logarithm of the odds or the likelihood ratio that the dependent variable is 1 (choosing a particular mode) as opposed to 0 (not choosing a particular mode). The probability P of a particular choice of travel mode is given by:

$$y = \text{logit}(P) = \ln\left(\frac{P}{1-P}\right) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \quad (4.1)$$

Where, α is the intercept, X_j are the independent variables $j=1, 2, 3$, and β_i are the corresponding coefficients $i=1, 2, 3$.

Factors affecting P&R users' choice

A statistical analysis was carried out to investigate the factors affecting P&R users' choice of travel mode. The factors analyzed to investigate the effects on choice of P&R were Transfer time at P&R site, Travel time by public transport, Parking price, and Traffic conditions.

Parking price and Traffic congestion in city

RP data were utilized to analyze the effects of parking price and traffic congestion on individuals' travel mode choice, and the results are shown in **Table 4.3**.

Similar to congestion pricing schemes (Liu and Meng, 2013) high parking prices in the city affect travelers' choice of travel mode. In the case of extremely high parking fees in the city commuters choose P&R (61.6%) over driving alone (4.7%). On the other hand, with lower parking prices in the city commuters are more inclined to use P&R (100%). This may be because they perceive that traffic congestion will get worse because the lower parking prices will encourage others to drive to the city while higher CBD parking prices currently moderate that demand. When there is concern about road traffic congestion in and around the CBD, travelers can choose to drive all the way or use P&R. In the case of extremely high traffic congestion, 95.7% of respondents stated that they would choose P&R while in congestion-free situations, individuals would prefer to drive (100%).

Table 4.3. Effects of parking price and traffic congestion on choice of mode

Parking price vs. Choice			
	Public transport only	Driving	P&R
Extremely high	33.7%	4.7%	61.6%*
Low	0.0%	0.0%	100%*
Traffic congestion vs. Choice			
Extremely congested	4.3%	0.0%	95.7%**
Not congested at all	0.0%	100%**	0.0%

Note: * $p < 0.05$ and ** $p < 0.0001$

Determinants of mode change behaviour

SP data were analyzed to determine the factors influencing the mode change behaviour of commuters. Their choice of travel modes was compared on the basis of pre-defined values for: parking price in the CBD, total public transport only travel time (PTTT) and total transfer time at P&R stations (TT). These variables were determined by focusing on the local context that is considered to influence the choice of commuters' daily travel mode. Relationships among variables were tested empirically using multinomial logistic regression in SPSS. The definitions of variables are provided in **Table 4.4**. The models for public transport only mode and driving alone mode were estimated relative to the P&R mode baseline. Variables that were statistically significant are reported.

Table 4.4. Definitions of Variables

Variable Name	Description
Choice (drive)	1, if individual chose driving; 0, otherwise
Choice (public transport alone)	1, if individual chose public transport alone; 0, otherwise
Choice (P&R)	1, if individual chose P&R; 0, otherwise
Parking price in city	\$10; \$20; \$40
Travel time taken by public transport alone (when public transport is used for the whole trip)	40min; 60min; 90min
Transfer time at P&R station (parking time + walking time to the platform + waiting time for the train)	5min; 10min; 20min

The reasons for individuals choosing public transport over P&R mode and driving over P&R mode were investigated. The price of parking in the city does not have a significant influence on individual commuters choosing public transport, whereas travel time taken by public transport only mode and transfer time at P&R station make individuals more likely to choose public transport alone for their whole journey. On the other hand, public transport travel time influences commuters to take P&R mode over driving if the transit travel time becomes less. Transfer time at the parking station is another sensitive factor affecting peoples' choice of transport mode. The results of the comparison between public transport alone mode and P&R mode and between driving alone mode and P&R mode are presented in **Table 4.5**.

Table 4.5. Results (relative to P&R mode)

Public Transport only			
Variables	B	Exp(B)	Sig.
(1) Public transport travel time (PTTT)			
40 min.	1.724	5.605	.000
60 min.	.994	2.702	.000
90 min.	base		
(2) P&R transfer time (TT)			
5 min.	-1.710	.117	.000
10 min.	-1.008	.247	.000
20 min.	base		
Intercept	-1.736	.247	.000
Driving only			
Variables	B	Exp(B)	Sig.
(1) Parking price			
\$10	2.459	11.696	.000
\$20	1.165	3.206	.000
(2) Public transport travel time (PTTT)			
40 min.	-.583	.558	.023
90 min.	base		
(3) P&R transfer time (TT)			
5 min.	-.996	.3369	.000
10 min.	-.437	.646	.057
20 min.	base		
Intercept	-2.415	.646	.000
Cox & Snell R2	.216		

Probability of choosing Public Transport Only mode over P&R mode

Based on the p-values of the t-tests, four attribute levels for two factors were found to be significant ($p < 0.0001$). It should be noted that for the independent variables, 90-minute public transport travel time, and 20-minute transfer time at P&R stations were taken as base variables. From the results we can see that PTTT and TT at the P&R station are the only significant factors impacting the choice of public transport mode only over P&R mode. As parking price was insignificant it was omitted from the model of probability of choice of public transport alone mode over probability of choosing P&R mode.

The odds ratio for 60-minute (relative to 90-minute) travel time is greater than one ($OR = 2.702$), indicating that the likelihood of choosing public transport only mode is greater than choosing P&R mode. For 40 min. PTTT relative to 90 min. PTTT, the relative chance of preferring public transport only to P&R would be expected to increase by a factor of 5.605 if the other variables in the model are held constant. In other words, commuters with 40 min. PTTT are more likely than commuters with 60 min. PTTT to prefer public transport only to P&R.

On the other hand, the TT at the P&R station negatively influences travelers' decision to choose public transport only mode compared with P&R mode. The coefficients for 5 minute (-1.710) and 10 minutes (-1.008) indicate that the decision of travelers to choose public transport declines negatively over the decision to choose P&R mode. Therefore, in the cases of 5 minutes and 10 minutes TT at P&R stations, respondents are 88.3% ($OR = .117$) and 75.3% ($OR = .247$) respectively less likely to choose public transport only than P&R mode.

Probability of choosing Driving alone over P&R mode

Based on the p-values of the t-tests, five attribute levels of three factors were found to be significant ($p < 0.05$). It should be noted that for the independent variables, \$40 parking price, 90 minutes PTTT and 20 minutes P&R station TT were taken as base variables. According to the results, the parking price in the city, PTTT and TT at the P&R station are significant factors impacting the choice of driving alone over P&R mode.

In the case when the parking price in the city becomes \$10 per day, travelers are more inclined to drive to the city rather than choose P&R mode ($OR = 11.696$). If the parking price in the city

is higher (\$20 per day) but relatively lower than the base price (\$40 per day), there is still the likelihood of commuters choosing driving (OR=3.206) to the city over P&R mode.

On the other hand, the likelihood of choosing driving only over P&R mode decreases in the case of less PTTT (40 minutes relative to 90 minutes), as the results show negatively declining interest in travelers' choosing driving (coefficient -.583). This is also clear from OR=.558, for 40min PTTT relative to 90min PTTT, indicating that the relative chance for preferring driving only to P&R would be expected to decrease by a factor of .558 if the other variables in the model are held constant. In other words, commuters with 40 min. PTTT are less likely than commuters with 90 min. PTTT to prefer driving only to P&R.

The transfer time at the P&R station is another negative factor influencing the decision to choose driving rather than P&R mode. The multinomial logit for 5 min. TT relative to 20 min. TT is .996 units lower for driving only relative to P&R if all other predictor variables in the model are held constant. In other words, commuters with 5 min. TT are less likely than commuters with 10 min. TT (coefficient -.437) to prefer driving only to P&R mode. Therefore, the network context of the P&R should be further extended by considering some practical issues, e.g., those related to survey methods (Qu et al., 2015), traffic flow dispersion (Bie et al., 2012; Bie et al., 2013) and travel time perception errors (Liu et al., 2013; Meng et al., 2014; Yan et al., 2013).

4.7 Conclusions

This chapter has explored the mode change behaviour of P&R users. Based on survey data on P&R users at different station car parks and bus terminals in Melbourne, the choice of mode change of P&R users was investigated. Multinomial logistic regression in SPSS was used in this study to estimate models for public transport only mode and driving mode with a reference P&R mode.

This study has identified that PTTT and TT at P&R stations are factors when choosing public transport only mode over P&R mode. Lower PTTT increases the probability of choosing public transport only mode for the entire journey, while lower TT is a very convincing factor for travelers to choose P&R mode over Public transport only mode. Therefore, travel time is the most influential factor in P&R users' choice of travel mode.

The results showed that lower parking prices in the city positively influence commuters to opt for driving all the way rather than choosing P&R mode, while lower PTTT and TT at P&R stations lead to a greater likelihood of commuters choosing P&R mode over driving.

As the population growth in Melbourne has recently shown a higher trend, it will become the largest city in Australia within the next 50 years. Therefore, the mode change behaviours of commuters will have a significant influence on deciding the city's transportation system. Therefore, governments need to think holistically when planning transportation infrastructure. The models and the results reported in this study could be used in future for P&R schemes and the design of P&R infrastructure.

CHAPTER FIVE:
QUANTIFYING PARK-AND-RIDE TRAVEL TIME RELIABILITY

5.1 Introduction

The reliability of the transportation network service is a key measurement indicator in the assessment of the performance of a transportation system. The reliability of travel time associated with a particular transportation system is a major concern to network users. In order to plan their journeys from an origin to a destination, users need a reliable estimate of travel time. Travel time reliability is relevant at the level of the individual link and the network as a whole. Travel time reliability has become an emerging theme in transport research in recent years and is defined as the probability of a trip being completed successfully within the specified time (Bell and Iida, 1999). Therefore, variations in travel time affect travel time reliability, making the transport network unreliable for its users. Unexpected delays caused by variations in travel time in the transport network cause commuters' inconvenience and may also have financial and other impacts. Hence, reliability analysis is an important consideration in offering a smooth and efficient transportation service to network users.

Travel time reliability is related to the probability distribution of travel time. Since travel time distribution describes the nature and pattern of travel time variability, the development of enhanced understanding of the distribution of travel time is a prerequisite for reliability analysis (Ma et al., 2015). Recent analysis of the travel time reliability of networks has been chiefly confined to either different assumptions about the underlying distributions of travel time or curve fitting of existing travel time data sets, rather than the development and use of the exact expression of travel time variations in the network. Moreover, no study yet has developed the exact distribution of overall travel time in a P&R network. P&R network has been considered to be composed of five links components. The derivations of travel time for five different links of the P&R network has been utilized to derive the probability density function (PDF) of the total travel time in a P&R network. Therefore, the contribution of this research work is two-fold: firstly, to develop an exact expression for the distribution of travel time in P&R network and secondly, to derive a measurement index of network reliability for a P&R network. The insights from this study are applicable for any distribution of traffic network link flow. The PDF of P&R network link flow have been represented by Normal and exponential distributions. A novel travel time PDF and a measure of network reliability for P&R transportation network are derived from those distributions in this research.

The chapter begins by describing the methodology and the proposed derivation, followed by a numerical example and concludes with suggestions for future research.

5.2 Methodology and derivations

The methodology adopted in this study commences by deriving the PDF of average link travel time considering any arbitrary PDF of link flow. This is followed by deriving the PDF of total link travel time. The PDF of total network travel time is then derived using the characteristic function (CF) method. Finally, this research derives transport network travel time reliability considering maximum allowable travel time as the threshold.

P&R trip is considered to be comprised of five components as (1) Auto link; (2) Rail link; (3) Dummy link for parking search time; (4) Walking dummy link and (5) Waiting time dummy link. Separate Probability Density Function (PDF) are derived for each of the five components of P&R mode. Previous works in literature have considered only specific network configuration. But the derived PDF from this paper can be applied for any general network structure and any general PDF of the link flow. Considering a maximum allowable travel time as the threshold, the analysis which follows seeks to derive an expression for the travel time reliability of a P&R network. The PDFs for each of component of the P&R network are described in the following sections. Figure 1 presents the overall P&R network including its components in the transportation system.

Auto link travel time on roads

Auto link travel time represents the time taken by commuters to drive from their trip origin (usually home) to a P&R facility. Recent studies only considered different assumptions of travel time distributions or curve fitting of the existing travel time data sets by auto mode (Susilawati et al., 2013). But different types of situation on the road may affect the road network reliability which requires to the need to know exact probability distribution of travel time on the road network.

The Bureau of Public Roads (BPR) function represents link travel time in terms of link flow and capacity. The average link travel time for link a is represented by

$$t_a(v_a) = t_f \left(1 + \alpha \left[\frac{v_a}{C_a} \right]^\beta \right) \quad (5.1)$$

where, t_f is the free flow travel time, α, β are constants, v_a is link a traffic flow and C_a is link a capacity. Using a fundamental PDF derivation theorem and the expression above, the PDF of the link travel time is derived as a function of the PDF of link flows. Then the PDF of total auto link travel time is derived using the relationship as expressed in equation (5.2)

$$T_a(v_a) = v_a t_a(v_a) \quad (5.2)$$

Where T_a is the total link travel time, expressed as a function of link flow.

The PDF of total travel time in the network is then derived using a characteristic function method.

PDF of average auto link travel time $t_a(v_a)$

Considering $f_{v_a}(v_a)$ is the arbitrary PDF of v_a which is known, the PDF of $t_a(v_a)$ is derived as (Papoulis and Pillai, 2002):

$$f_{t_a}(t_a) = \sum_{i=1}^{\beta} \frac{f_{v_a}(V_{ai})}{|t'_a(V_{ai})|} \quad (5.3)$$

where, V_{ai} is the i -th real root of the polynomial $P_a(v_a) = 0$ obtained from (5.1) as

$$P_a(v_a) = v_a^\beta + \frac{c_a^\beta (t_f - t_a)}{\alpha t_f} \quad (5.4)$$

and $t'_a(.)$ is the first derivative of $t_a(.)$.

As defined by BPR, $\beta = 4$ is commonly used (Wang et al., 2012; Clark and Watling, 2005) and hence Equation (5.4) becomes a quartic polynomial. The solution of a quartic polynomial is quite well-known and the four roots of Equation (5.4) can be shown as

$$V_{a1,a2,a3,a4} = \pm S \pm \frac{1}{2} \sqrt{-4S^2} \quad (5.5)$$

where,

$$S = \frac{1}{2} \sqrt{\frac{Qc_a^\beta}{3t_f\alpha} + \frac{4(t_f - t_a)}{Q}} \quad (5.56)$$

$$Q = \left(\frac{-12t_f\alpha(t_f - t_a)}{c_a^\beta} \right)^{\frac{1}{2}} \quad (5.7)$$

PDF of total auto link travel time, $T_a(v_a)$

By following a similar approach as described in deriving the PDF of average auto link travel time, the PDF of $T_a(v_a)$ can be shown to be :

$$f_{T_a}(T_a) = \sum_{i=1}^{\beta+1} \frac{f_{v_a}(V_{ai})}{|T'_a(V_{ai})|} \quad (5.8)$$

(Papoulis and Pillai, 2002)

where, V_{ai} is the i-th real root of the polynomial $P_a(v_a) = 0$ obtained from (5.1) and (5.8) as:

$$P_a(v_a) = v_a^{\beta+1} + \frac{c_a^\beta}{\alpha} v_a - \frac{c_a^\beta T_a}{\alpha t_f} \quad (5.9)$$

and $T'_a(.)$ is the first derivative of $T_a(.)$. Now for $\beta = 4$, the polynomial in (5.10) is a fifth degree or quintic polynomial, especially in Bring Jerrard quintic form (Birkeland, 1858). The solution to such polynomials may be less well-known, but does exist (Birkeland, 1858). Based on Birkeland (1858), the five roots of (5.9) can be presented in terms of hyper geometric functions. Common mathematical software such as MATLAB and Mathematica can be used for the root derivation.

Parking search time link

Parking search time is the time commuters, on arrival at the car park within the P&R facility spend to search for parking spot to park their car. This search time is influenced by the parking capacity and the volume of vehicular flow at parking site i.e. the parking demand (Li et al., 2007b). Parking search time, t_p is represented by BPR function as shown in Equation (5.10).

PDF of parking search time, $t_p(v_p)$

Literature shows that parking search time is usually considered as normally distributed (Li et al., 2007a). The parking search time has been found to be represented by Bureau of Public Roads (BPR) function (Lam et al., 2006). Based on previous works, it is assumed that parking search time follows normal distribution with mean t_p as shown in Equation (5.10). The PDF of parking search time is represented as $f_{t_p}(t_p)$.

$$t_p(v_p) = t_p^0 + 0.31 \left(\frac{v_p}{c_p} \right)^4 ; \quad (5.10)$$

where t_p^0 , v_p , and c_p are the free-flow parking search time, the volume of parking flow, and the capacity of the parking facility p , respectively.

The volume of vehicular flow at parking site i.e. the parking demand is expressed as shown in equation (5.11)

$$v_p = \frac{1}{\gamma} \sum_{r \in R} \sum_{s \in S} q_{rs,p}^a; \quad (5.11)$$

Where, $q_{rs,p}^a$ is the travel demand by auto mode via parking site, p , between OD pair (r,s) . The parameter, γ is the convertor to convert the parking volume from passenger units to vehicular units.

Walking link

Walking time is the time commuters spend in the P&R facility to transfer from car park to public transport platform. Walking time depends on the distance between parking location and train platform as well as the walking speed of commuters (Li et al., 2007a). Here this time is represented as t_w and the PDF of walking time is expressed as $f_{t_w}(t_w)$.

PDF of walking link time, t_w

Walking time is considered as normally distributed and can be represented as Equation (5.12).

$$f_{t_w}(t_w) = N(\mu_w, \sigma_w^2) \quad (5.12)$$

Where, μ_w is the mean and σ_w^2 is the variance of walking time distribution.

Waiting time link for train station

Waiting time is the time P&R users spend on waiting for train to arrive at the platform connected at P&R facility. This waiting time at the train station platform is represented as t_{wt} , follows uniform distribution adopted from the work by Wenbo in 2012 as shown in Equation (13) (Fan, 2012).

PDF of waiting time, t_{wt}

The PDF of waiting time is expressed as $f_{t_{wt}}(t_{wt})$, where,

$$\text{Waiting time, } t_{wt} \sim (0, 1/F^b) \quad (5.13)$$

In Equation (5.13), F^b represents the dispatching frequency of the train from the platform.

Rail link travel time

Since the time taken by train can be considered as a deterministic variable for a definite route, the travel time on rail link is considered to be taking up a constant value, C . If the length of the rail link is L_x , the link flow on the rail link is, v_{lx} and the maximum capacity is \hat{C} . The travel time of the rail link, t_{lx} is expressed as

$$\delta_{t_{lx}} = \begin{cases} 1, & \text{if } t_{lx} = C \\ 0, & \text{otherwise} \end{cases} \quad (5.14)$$

PDF of total network travel time

The total network travel time is presented as

$$T(v_L) = \sum_{i \in (a,p,w,wt,lx)=1}^{L_i} \{T_a(v_a) + t_p(v_p) + t_w + t_{wt} + t_{lx}\} \quad (5.15)$$

Now, the PDF of the total network travel time, $T(v_L)$ can be obtained by convoluting all the PDFs of the five components of P&R link for $i \in (a, p, w, wt, lx) = 1$ to L (Papoulis and Pillai, 2002) as shown in Equation (5.17).

$$f_T(T) = f_{T_1}(T_1) * f_{T_2}(T_1) * \dots * f_{T_L}(T_L) \quad (5.16)$$

Where T represents total network travel time and $*$ represents a convolution function. However, this is a numerically intensive operation. Also, it's intractable to derive a closed form expression for the PDF of total network travel time by following this method. Hence, we propose a characteristic function (CF) based method (Papoulis and Pillai, 2002) for deriving the PDF of total network travel time, $T(v_L)$. The CF of a random variable is defined as, $\varphi_x(\omega) = \int_{-\infty}^{\infty} f(x) e^{j\omega x} dx$; where $f(x)$ is the PDF of random variable x . The PDF and the CF of the random variable $T(v_L)$ are related by the Equation (5.18).

$$f_T(T) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \Phi_T(\omega) e^{-j\omega v_L} dv_L \quad (5.17)$$

Where $\Phi_T(\omega)$ is the CF of $T(v_L)$ that is defined as $\Phi_T(\omega) = E[e^{j\omega T(v_L)}]$ where $E[.]$ represents mean value. As a special case, if the link travel times are independent of each other, the CF can be further simplified as

$$\Phi_T(\omega) = \prod_{a=1}^{L_a} \Phi_{T_a}(\omega) \prod_{p=1}^{L_p} \Phi_{t_p}(\omega) \prod_{w=1}^{L_w} \Phi_{t_w}(\omega) \prod_{wt=1}^{L_{wt}} \Phi_{t_{wt}}(\omega);$$

Where, $\Phi_{T_a}(\omega) = E[e^{j\omega v_a T_a}]$; $\Phi_{t_p}(\omega) = E[e^{j\omega t_p}]$; $\Phi_{t_w}(\omega) = E[e^{j\omega t_w}]$; $\Phi_{t_{wt}}(\omega) = E[e^{j\omega t_{wt}}]$.

Reliability

Setting a threshold value for the total network travel time as, $T = \theta$; where θ be the maximum allowable network travel time without degrading network performance beyond an acceptable level, the network reliability index can be derived as

$$R(\theta) = \int_0^\theta f_T(t) dt \quad (5.18)$$

It should be noted that the reliability index $R(\theta)$ is a real number within (1.0, 0.0) where 1.0 and 0.0 respectively represents that that network reliability is at its highest and lowest.

5.3 Numerical example

Although the derivation presented in previous section is quite general and can be applied for any arbitrary network and arbitrary PDF of link flow, in this section numerical examples are presented by considering a simple transport network and Gaussian PDF of link flow. As previously mentioned, Gaussian approximation of link flow PDF is widely used in literature and is supported by central limit theorem (Clark and Watling, 2005). However, even though the link flow variation can be well-represented by a Gaussian PDF, the density of the network

total travel time is not actually Gaussian and exactly represented by (5.16) or (5.17). This aspect will be investigated in this section along with its impact on network reliability. An example network has been considered as shown in Figure 5.1 as well as the network configuration is shown in Table 5.1.

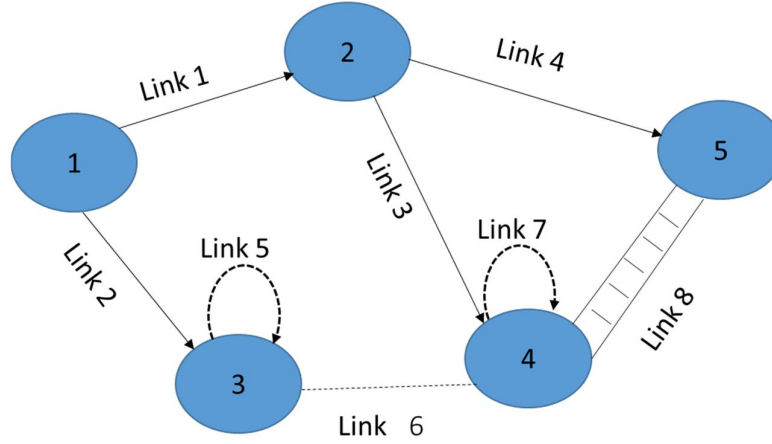


Figure 5.1: P&R network

Table 5.1: Network configuration

Auto Link	Parking search time link	Walking link	Waiting link	Rail link
Link 1; Link 2; Link 3 and Link 4	Link 5	Link 6	Link 7	Link 8

Table 5.2. Network parameters considered for Gaussian link flow PDF

Link, a	t_f	α	β	C_a	μ_a	σ_a
1	4	0.15	4	10 to 60	8	8
2	6				7	7
3	2				5	5
4	5				3	3
5	3				8	8

The Gaussian PDF of a link flow is represented by

$$f_{v_a}(v_a) = \frac{1}{\sigma_a \sqrt{2\pi}} \exp\left(-\frac{(v_a - \mu_a)^2}{2\sigma_a^2}\right) \quad (5.14)$$

where, μ_a is the mean and σ_a is the standard deviation of the link flow, v_a . Once we know the link flow PDF, the PDF of total link travel time and total network travel time can be obtained using (5.9) and (5.12), respectively. The data shown in Table 5.2 are considered for the numerical example. The impact of variations in link flow and capacity has been investigated, however, the numerical example presented here does not explicitly model origin-destination (OD) flow constraints. Figure 5.2 shows the PDF of total link travel time, T_a considering $C_1 = C_2 = C_4 = C_5 = 40$ and $C_3 = 60$. As the figure shows, link 3 and 4 total link travel time PDFs assume a petite shape whereas those for other links assume flatter shapes. The shape of the PDF is determined by the parameters, mean and variance of the link flow, the capacity of the link and link free flow time (and α and β , which are considered constant in this study). However, the shape can be seen to be dominated by the link flow variance. Since link travel time, T_a , can only assume a positive value equal to or greater than zero, its PDF exists only for $T_a \geq 0$.

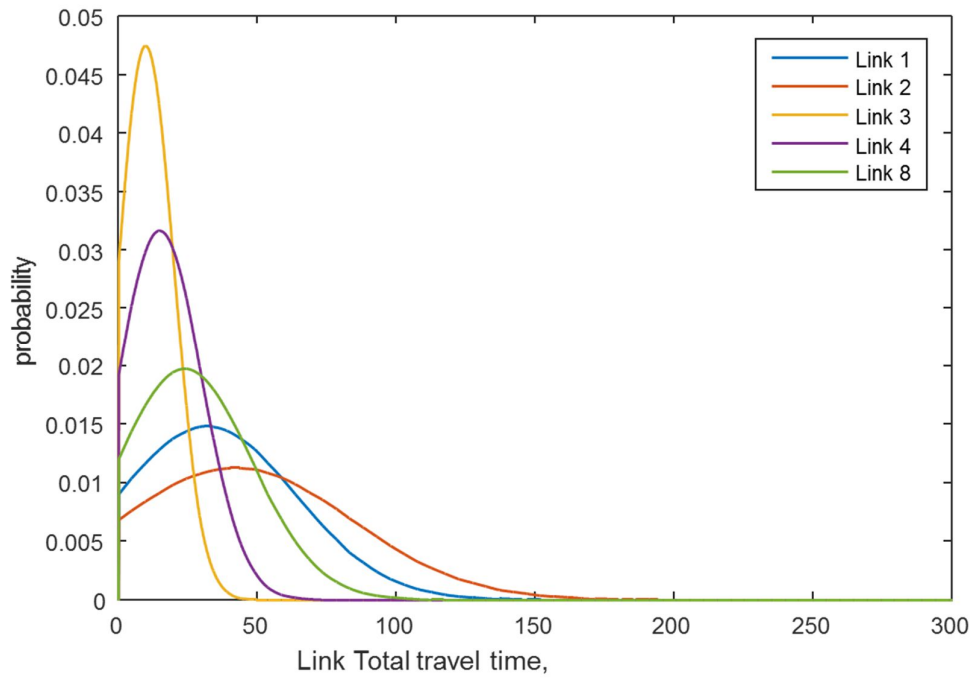


Figure 5.2 Probability distribution function of travel time for P&R components.

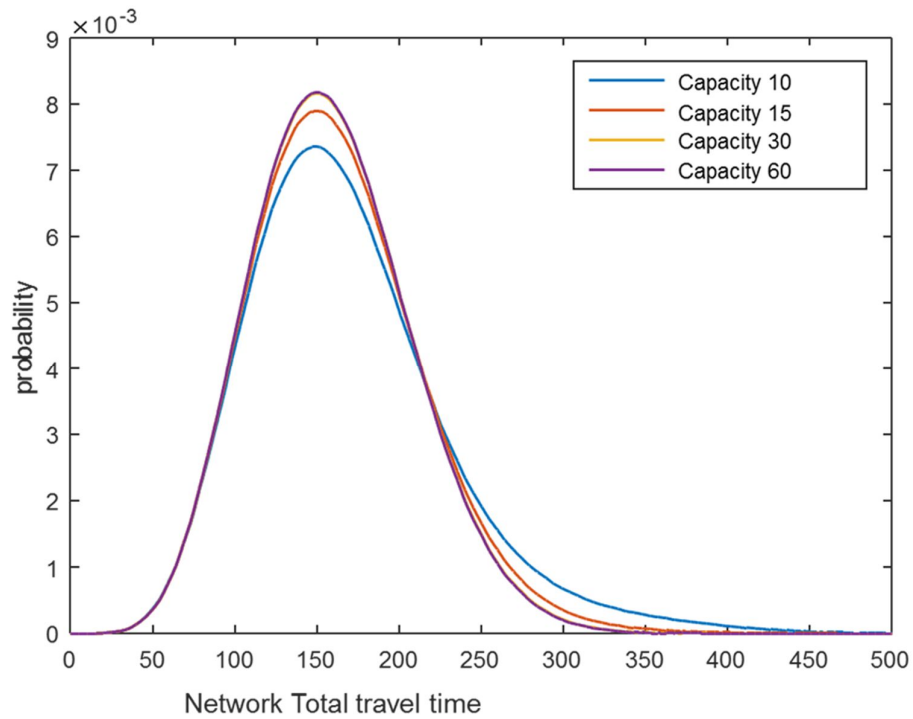


Figure 5.3 Probability distribution function of total P&R network travel time

Figure 5.3 presents the PDF of total network travel time considering $C_2 = C_4 = C_5 = 40$ and $C_3 = 60$ and varying C_1 from 10 to 60. The flatness of the PDF is seen to be inversely proportional to the capacity of link 1. Especially if the capacity becomes too small, the PDF seems to have a much wider tail. It should be noted here, that if the designer's objective is to improve network reliability, he or she should be more concerned if a PDF with a wide tail appears for total network travel time. The straightforward interpretation of this is that for a PDF with a wide tail, given a target maximum travel time to be maintained, there still remains some probability of longer network travel time (i.e. degraded performance or unreliable network). It is clear from Figure 5.4 that the shape of the total network travel time PDF is very different from a Gaussian PDF, especially if the network has any bottleneck, such as lower than needed capacity in any link.

Figure 5.4 presents total network reliability vs. varied link capacity independently for each of the five links, while the capacity of all other links is fixed at 10. The reliability threshold is considered to be 250 units. It is worth noting that, specifically at capacity 10 point, all the links have capacity 10. Hence, we can understand the variation of which link capacity impacts network reliability most. As the figure indicates, while all the links have a capacity of 10, the network reliability is around 0.817. If we now increase only link 1 capacity while keeping all other link capacities at 10, we can see that network reliability rises to close to 0.867 for link 1 or link 5 capacity of 30. However, if we choose any other link to increase the capacity instead of link 1 or link 5, much lower reliability gains can be achieved, even at a much higher capacity such as 60. By increasing the capacity of link 4, almost no gain in reliability can be achieved. Link 1 and link 5 appear to be the two most influential links, an observation consistent with that of Clark and Watling (2005).

Figure. 5.5 shows the total network reliability vs. the varied mean link flow multiplication factor, where we multiply the mean link flow of a single link by the multiplying factor shown on the x-axis of Figure 5.5. While the mean flow of a specific link is varied, flows through all other links are kept constant at mean value. Standard deviations of link flows are the same as in Table 5.2 and the following capacities are considered: $C_2 = C_4 = C_5 = 40$ and $C_3 = 60$. A reliability threshold of 250 units has been used as in Figure 5.5. As the figure shows, an increment of link flow in link 2 leads to the highest degradation of network reliability, whereas

an increment of link flow in link 3 has the least impact on network reliability. Note that these conclusions are highly dependent on the specific parameters used for the network configuration.

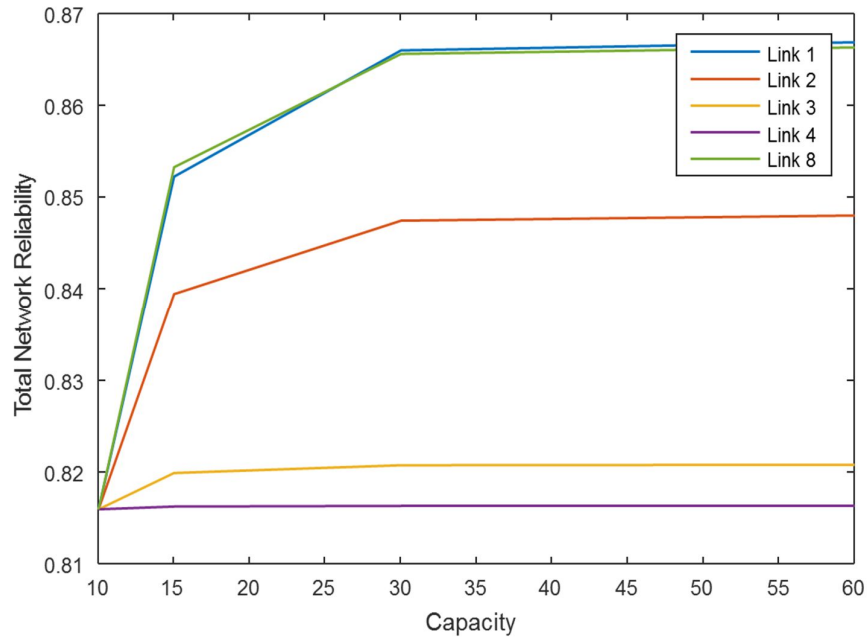


Figure 5.4 Impact of link capacity variation on network reliability

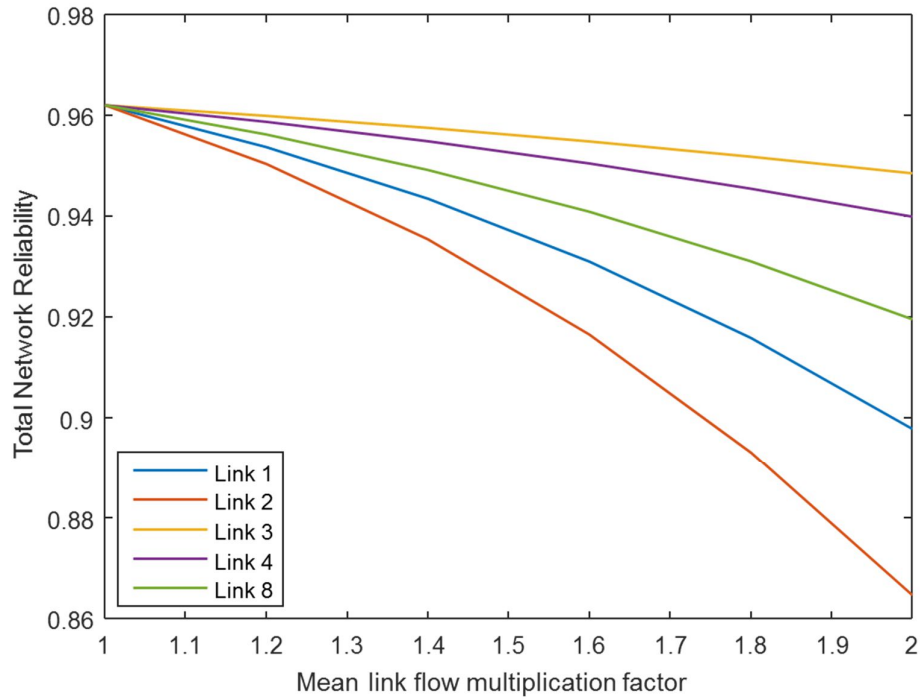


Figure 5.5 Impact of link flow variation on network reliability

5.4 Conclusions

This chapter presented a mathematical framework for deriving the exact PDFs of the P&R network total travel time in terms of an arbitrary link flow PDF which is then used for calculating the travel time reliability of a P&R network. The methodology outlined in this research work is generic and can be applied for any network configuration and link flow PDF. Techniques as 1) derivation of a PDF of a function of a random variable 2) solution of quintic polynomial 3) characteristic function method of deriving PDF of a sum of random variables have been applied to reach the final form of the PDF of P&R network total travel time. Considering a maximum allowable travel time as the threshold, an expression for P&R network travel time reliability is then derived. Numerical examples have been presented by considering a well-known network and Gaussian PDF of link flow. Future research will aim at checking for network equilibrium situation. Numerical example considering exponential/double-exponential link flow distribution will also be investigated.

CHAPTER SIX:
OPTIMISING PARK-AND-RIDE TRAVEL TIME RELIABILITY

6.1 Introduction

Travel time is one of the major performance parameters of transportation systems. Travel time varies dynamically and variability in travel time is due to various characteristics of key conditions which are the direct source of traffic congestion (Hojati et al., 2009). There are two types of congestion in the network: recurrent and non-recurrent. Recurrent congestion is due to everyday excess travel demand during peak traffic flow, while non-recurrent congestion is due to unpredictable and changing situations (Hojati et al., 2009). This traffic congestion adversely affects traffic conditions, making the entire transport network unreliable. Transport network reliability is defined as the probability that a transportation system accomplishes its expected objectives and functions according to a certain travel time constraint (Fan, 2012). Establishing network reliability has become a significant concern for transport authorities in the design of transportation infrastructure and networks. Therefore, as a measure of network reliability, travel time reliability is one of the key assessment indicators for the evaluation of transportation network performance.

Previous literature on P&R is chiefly confined to travel demand forecasting, planning or behavioural analysis of P&R (Farhan and Murray, 2008; Hendricks and Outwater, 1998). Few references have been found on the reliability modeling of P&R mode. It has been revealed by some empirical studies that travel time reliability is one of the major concerns for commuters (Li et al., 2016). Different kinds of measurement analysis of network reliability are presented in the research literature. For example, Lam and Xu. (1999) utilized a traffic flow simulator to investigate transportation network reliability, in which the variation of perceived travel time error and the fluctuations of origin-destination (OD) demand are explicitly considered. Another measurement of travel time reliability was carried out using travel time variance derived from a path-flow estimator (Bell and Iida, 1997). The utility of users as the measure for network performance reliability has been utilized in previous work by Bell (1999), and Yin and Ieda (2001) used different risk-taking behaviours of commuters when challenged with uncertain traffic conditions on the network as a result of non-recurrent congestion. The different decision-making behaviours of commuters have been examined using a disutility approach and commuters were assumed to choose paths with the minimal expected disutility between their origins and destinations (Yin and Ieda, 2001). Travel disutility as defined in their work refers

to the dislike associated with the level of travel time variations perceived by commuters and is considered to be a measurement index for network reliability in network design.

The research literature to date has focused on analysing the role of P&R facilities in promoting public transport mode share and has concluded that the location and capacity of P&R facilities and parking prices have impacts on the performance of P&R schemes. Modeling studies related to P&R systems include the work by Du and Wang (2014), who considered a continuum modeling approach for P&R services in a linear travel corridor. In their study, an equilibrium travel pattern is formulated as a linear complementary system. The linear complementary system modeling approach has also been employed in P&R services by Wang and Du (2013). A deterministic mode choice approach has been employed considering the linear monocentric city in some previous studies. For example, this approach has been utilized in analysing the optimal location and pricing of a P&R facility with the two different objectives of profit maximization and social cost minimization (Wang et al., 2004). The numerical validation of their proposed model showed the influence of the operator's objective function on the choice of location of P&R facilities as being of great importance. However, the effect of the location and parking capacity of particular P&R schemes on the network reliability of transportation networks as a whole has not been researched. The optimisation of travel time reliability of P&R networks has also not been studied in previous research. Consequently, P&R network design in a bi-modal transportation system considering travel time reliability is a novel area in transport research. This research adopts the travel disutility measurement method of Yin and Ieda (2001) to optimize the network travel time reliability of a bi-modal transport network consisting of auto and P&R sub-networks. Therefore, this research study contributes firstly by providing an optimal P&R scheme which determines the optimal location of the P&R facility and the corresponding capacity of the parking facility, and secondly by optimizing transport network reliability as a whole for a particular P&R scheme.

This chapter is structured as follows. The first section overviews previous research associated with travel time reliability and P&R modelling. This is followed by a section containing the model formulation and the solution algorithm. A numerical example is then presented, followed by conclusions and suggestions for future research directions.

6.2 Model Formulation

Bi-level model structure

The P&R network design problem is a generalized network design problem (NDP). In this context, the NDP reflects a hierarchical system comprising two levels of decision makers (Migdalas, 1995), whose decisions impact the performance of a P&R scheme. The upper level is the transport authority responsible for the provision of the P&R scheme. On the basis of the P&R scheme, which is provided, transport network users, who represent the lower level in the two-level hierarchy, make their travel decisions in order to maximize their own benefit. Formulating this as a NDP allows the optimal P&R scheme design to be identified, reflecting equilibrium conditions in the network. This bi-level problem is modelled as a Stackelberg duopoly game problem (Wang et al., 2004). The interaction between the leader and follower is known as a Stackelberg duopoly game. In a Stackelberg duopoly game, the first player, the leader, first makes a decision with the objective of maximizing its benefits, while the second player, the follower, reacts after the leader makes a decision to minimize his/her loss. The follower has full knowledge of the leader's decision and makes a decision depending on the leader's decision. The leader has full knowledge of this. Consequently, the follower's decision cannot be dictated, but can be influenced (Migdalas, 1995).

The transport authority makes decisions about the location and capacity of P&R facilities. While the transport authority is concerned about improving the efficiency of the whole transport system, it has to act within budget constraints. The perspective of the transport authority is captured in the upper level formulation of the model. Several practical constraints which impact on the P&R scheme design are formulated as upper level constraints. In this study, the objective of the upper level is to minimize the total travel disutility for both car commuters and P&R users. Reflecting the growing recognition of the importance of network reliability (Lam and Small, 2001), the upper level model formulation also seeks to maximise reliability in the network. The upper level model formulation is described in the following section.

Commuters (represented in the lower level of the model) are considered to exhibit different levels of risk aversion when faced with unreliable (i.e. variable) travel conditions in a transportation network. By adopting an expected disutility approach (Yin and Ieda, 2001), different network users' behaviours, ranging from risk-aversion, and risk-neutral to risk-seeking, can be incorporated in the model. Commuters are assumed to choose a route in a

multimodal transport network offering options to either commute by car or use P&R, which helps to minimise their expected travel disutility. Therefore, at the lower level, a disutility-related multi-class user equilibrium model formulation is used to solve the traffic assignment problem.

The P&R NDP formulated using a bi-modal transportation network is denoted by $G = (N, A)$, where N is the set of nodes and A is the set of links connecting nodes. The bi-modal transportation network G consists of a car-commuters sub-network and a P&R sub-network. The car and rail links are connected with corresponding P&R sites to make up the P&R links in the network. The detailed formulations of the upper level and lower level are described in the following sections.

Upper level model formulation

An optimal P&R scheme is determined using a reliability measurement approach in the upper level of the model. The reliability of the transport network can be measured by the total disutility associated with the dislike or dissatisfaction of commuters caused by the level of travel time variations in the network (Yin and Ieda, 2001). The aim of the transport authority is to optimise network reliability in the whole transportation system. Therefore, the concept of measuring the reliability in the whole transport network in terms of the total travel disutility has been formulated as an upper level objective function. Therefore, in this study, the total travel disutility in the bi-modal transportation system is the sum of the travel disutility of car commuters and P&R users.

There are two decision variables associated with the upper level:

- the location of the P&R facilities ($x \in X$), defined as a vector of binary (0-1) variables, and
- the capacity of the P&R parking lot ($y \in Y$), defined as an integer variable with a range $Y_{min} \leq Y \leq Y_{max}$, where Y_{min} is the minimum number of parking spaces and Y_{max} is the maximum number of parking spaces available in the P&R facility

The upper level model, which focuses on minimising the total disutility of travel in the network subject to a series of constraints, is formulated as follows:

$$\min Z = \sum_{i \in I} \sum_{od} \pi_{a,p\&r,i}^{od} (X, Y) q_i^{od} \quad (6.1)$$

subject to:

$$Y_{min} \leq Y \leq Y_{max} \quad (6.2)$$

$$R \geq R_{th} \quad (6.3)$$

$$Y < MX \quad (6.4)$$

$$0.7 \overline{C_{la}} \leq f_{a,i}^{od} \leq 1.0 \overline{C_{la}} \quad (6.5)$$

where:

a represents car commuting routes (paths)

$P\&R$ represents park-and-ride routes (paths)

OD: set of O-D pairs for the whole network

P^{od} : set of all paths between OD pair

I : 1, 2 and 3 corresponding to three types of commuters: risk-averse, risk-neutral and risk-prone, respectively

q_i^{od} : travel demand between OD pair (o, d)

$\pi_{a,p\&r,i}^{od}$: minimum expected path disutility for OD pair od and i th class of commuters, in other words, $\pi_{a,p\&r,i}^{od} = \min [\eta_{a,i}^{od}, \eta_{p\&r,i}^{od}]$ for all paths of the OD pair

$\eta_{a,i}^{od}$: expected path disutility for auto paths of OD pair $od = E [U_i(t_a^{od})] = \int U_i(t_a^{od}) dt_a^{od}$;

where, $t_a^{od} \sim N(\mu_a^{od}, \sigma_a^{od^2})$

$\eta_{p\&r,i}^{od}$: expected path disutility for P&R paths of OD pair od

$$=E[U_i(t_{p\&r}^{od})] = \int U_i(t_{p\&r}^{od}) dt_{p\&r}^{od}; \text{ where, } t_{p\&r}^{od} = N(\mu_{p\&r}^{od}, \sigma_{p\&r}^{od^2})$$

$E(.)$ represents the expected value

$N(\mu, \sigma^2)$ represents a normal distribution of path travel time with mean μ and variance σ^2

$U_i(.)$ is the disutility function, which is usually an upward convex function of path travel time for risk-averse commuters, a downward concave function of path travel time for risk-seeking commuters and a positive-sloped linear function for risk-neutral commuters.

The objective function minimises the total network travel disutility by considering both car commuting and P&R users. Constraint (2) is the size limitation for the parking sites. Constraint (3) is the reliability constraint of the network, where reliability is defined as:

$$R = \frac{\sum_i \sum_{od} \pi_{a,p\&r,i0}^{od} q_i^{od}}{\sum_i \sum_{od} \pi_{a,p\&r,i}^{od} q_i^{od}}; \pi_{a,p\&r,i0}^{od} = \text{the minimal expected disutility between OD pair } od \text{ for class } i$$

commuters considering that all link travel times are deterministic. This kind of reliability measurement formula is adopted from Yin and Ieda (2001). In this formulation, the designed network must have a reliability greater than or equal to a pre-defined threshold R_{th} . It should be noted that R has a maximum normalised value of 1.0. Constraint (4) determines the relationship between x_i and y_i , that y_i is determined by x_i . When $x_i = 0$, y_i should also be 0. When $x_i \neq 0$, y_i can be a random value between \underline{y} and \overline{y} . It should be noted that, in this study, the link travel time and path travel time are assumed to follow a normal distribution (Yin and Ieda, 2001).

The addition of more parking spaces at a P&R site would allow more commuters to choose P&R. If substantial space was dedicated to the provision of P&R facilities, it is possible that highway utilisation would drop as users switch to P&R, resulting in the parallel highway links operating well below capacity. The combination of 1) the very high capital costs associated with building substantial P&R parking facilities and 2) under-utilisation of the existing road network, is unlikely to be desirable from the perspective of the transport authority. Moderating, rather than eliminating, traffic congestion on the parallel highways is likely to be a more realistic objective for a P&R scheme and this is likely to result in a desire to alleviate traffic congestion by diverting any traffic in excess of the road capacity to the P&R link. This is reflected in constraint 5, where it is proposed that for any road link that has a parallel P&R

link, the establishment of P&R should not decrease flow on the road to less than 70% of its capacity. A more stringent road link usage criterion may be intended, but it may be difficult to obtain simultaneously for all OD pairs.

Lower level model formulation

On the basis of the location and capacity decisions regarding P&R facilities, which are the focus of the upper level of the model, users make their travel decisions, which in turn determine the utilization of the available P&R facilities. User equilibrium (UE) assignment is assumed to govern the behaviour of traffic in the network. The UE traffic assignment problem can be formulated as (i) a mathematical program (MP); (ii) a nonlinear complimentary problem (NCP); (iii) variational inequality or (iv) a fixed-point problem (FPP) (Lo and Chen, 2000).

This chapter considers commuters with a range of risk-taking behaviours i.e. multiple user classes, and the disutility-related multiclass user equilibrium problem is therefore formulated as a non-linear complimentary problem (NCP) (Yin and Ieda, 2001). According to the conditions of disutility-related multi-class user equilibrium, it is assumed that all commuters will try to minimize their own travel disutility when travelling from their origin to their destination (Yin and Ieda, 2001). As a result, network equilibrium will be reached when no commuters can change their expected travel disutility by unilaterally changing routes. The corresponding UE traffic assignment conditions are stated as follows:

$$\eta_{p,i}^{od} - \pi_{a,p\&r,i}^{od} \geq 0 \quad \forall od \in OD, \forall p \in P^{od}, \forall i \in I \quad (6.6)$$

$$(\eta_{p,i}^{od} - \pi_{a,p\&r,i}^{od})f_{p,i}^{od} = 0 \quad \forall od \in OD, \forall p \in P^{od}, \forall i \in I \quad (6.7)$$

$$\sum_{p \in P^{od}} f_{p,i}^{od} - q_i^{od} = 0 \quad \forall od \in OD, \forall i \in I \quad (6.8)$$

$$f \geq 0, \pi \geq 0 \quad (6.9)$$

The definitions of terms are as follows:

P^{od} = The set of all paths between OD pairs

$f_{p,i}^{od}$ = The flow of class i commuters on path p between O-D pair od

f = The vector of path flow, $f_{p,i}^{od}$ with dimension $n_1 = \sum_{od} |P^{od}| \times 3$ that equals three times the total number of paths in a network

$\eta_{p,i}^{od}$ = Expected disutility on path/route p between OD pair od for class i commuters

π = Vector of minimal expected disutility π_i^{od} with dimension $n_2 = |OD| \times 3$ that equals three times the total number of O-D pairs

Conditions (7) and (8) define the complementary slackness condition: $f_{p,i}^{od} = 0$, $(\eta_{p,i}^{od} - \pi_{a,p\&r,i}^{od}) > 0$ and $(\eta_{p,i}^{od} - \pi_{a,p\&r,i}^{od}) = 0$, $f_{p,i}^{od} \geq 0$; that is, when the expected disutility on path p is larger than the minimal disutility, the flow on that path is zero. When the expected disutility on path p is equal to the minimal disutility, the flow on that path is equal to or greater than zero. These complementary slackness conditions are equivalent to Wardrop's principle. Conditions (9) and (10) are the flow conservation and non-negativity constraints, respectively.

The equivalent NCP formulation of the UE conditions is (Lo and Chen 2000):

$$X \geq 0, F(X) \geq 0, X^T F(X) = 0 \quad (6.10)$$

with

$$X = \begin{pmatrix} f \\ \pi \end{pmatrix} \text{ and } F(X) = \begin{pmatrix} F^f(X) \\ F^\pi(X) \end{pmatrix} \quad (6.11)$$

where, $F^f(X)$ is the column vector of $(\eta_{p,i}^{od} - \pi_{a,p\&r,i}^{od}, \forall od \in OD, \forall p \in P^{od}, \forall i \in I)$, and $F^\pi(X)$ is the column vector of $(\sum_{p \in P^{od}} f_{p,i}^{od} - q_i^{od}, \forall od \in OD, \forall i \in I)$. For the original representation of the NCP shown in Equations (6.10) and (6.11), the existence and uniqueness of the solution have been established by Aashtiani (1979).

In general, to solve the original NCP problem associated with equilibrium is very difficult even for small-sized problems (Aashtiani 1979). However, some alternative approaches are mentioned in the literature. Equation (6.12) and (6.13) show one of these alternative approaches to solve NCP using the gap function, $G(x)$ (Lo and Chen 2000):

min, $G(X)$

subject to:

$$X \in [X \geq 0 \quad F(X) \geq 0] \quad (6.12)$$

$G(X)$ = The gap function to reformulate the NCP, based on Yin and Ieda's work (2001) is as follows:

where,

$$G(X) = \sum_i \sum_{od} \sum_p \sum 1/2 \left[\sqrt{(f_{p,i}^{od})^2 + (\eta_{p,i}^{od} - \pi_{a,p\&r,i}^{od})^2} - (f_{p,i}^{od} + \eta_{p,i}^{od} - \pi_{a,p\&r,i}^{od}) \right]^2 + \sum_i \sum_{od} 1/2 \left[\sqrt{(\pi_{a,p\&r,i}^{od})^2 + (\sum_{p \in P^{od}} f_{p,i}^{od} - q_i^{od})^2} - (\pi_{a,p\&r,i}^{od} + \sum_{p \in P^{od}} f_{p,i}^{od} - q_i^{od}) \right]^2 \quad (6.13)$$

In the present study, the disutility-related multi-class user equilibrium approach is adopted on a bi-modal network reflecting a combination of car and P&R modes. The car commuters transfer to rail mode through the corresponding parking facility. The time cost associated with car parking increases with the increase of P&R users. The travel time taken by the rail link is set to a constant value. Solving the NCP-related equilibrium problem in this case is extremely difficult, because it requires matrix inversion, which is intractable. The alternative gap function approach, $G(X)$, is difficult to adopt in the case of this multi-modal problem due to its mathematical complexity. Iterative approaches have been proposed to overcome the difficulties associated with solving NCP (Aashtiani, 1979), and the decomposition and linearization scheme described by Aashtiani can be used to deal with NCP-related problems. Hence, in this chapter a decomposition scheme is employed to solve the model. The relevant steps involved in the proposed decomposition procedure to solve our NCP-associated disutility-related multi-class user equilibrium problem are as follows:

- Choose a starting point at any origin between each OD pair and assign flow u_1 to link 1, where u_1 is a number between 0 to D and D = total travel demand for OD pairs
- Then assign the flow $u_2 = (D - u_1)$ to link 2 originating from the origin and continue recursively for all other links originating from the origin for the OD pair (i.e. for link 3 from origin assign the flow $u_3 = (D - u_1 - u_2)$).
- Apply similar decomposition to sub-branches (i.e. links) originating from a link that originated from the origin
- Then vary u_1 on path 1 from 0 to D in steps of Δ , where, Δ is a small number and update all other flows u_2, u_3 etc.
- Repeat the above for all OD pairs
- For each combination, test if the equilibrium criterion is reached while meeting all constraints.
- When the equilibrium criteria is reached, it is the equilibrium solution for the proposed NCP.

6.3 Solution Algorithm

The bi-level programming problem is NP-hard and relatively difficult to solve, even for a medium-sized network in terms of the number of links and nodes in the network among origins and destinations (Ben-Ayed et al., 1988). In this chapter, a genetic algorithm (GA) is employed to solve the proposed model. The GA is a well-known heuristic for solving optimization problems (Liu and Meng, 2013). GA begins with a feasible set of possible candidate solutions called a population mimicking the natural selection process. Each individual solution in the population is called a chromosome and assigned a survival probability, based on the value of the objective function (Mitchell, 1998). GA uses cross-over and mutation operators to breed the next generation, which replaces the predecessor generation. The algorithm is repeated with the new generation until a stopping condition is reached. Common stopping criteria include: a fixed number of generations is reached, the predetermined computation time is reached, the difference of the optimal solution between the two adjacent generations cannot be further reduced, the difference of the worst solution between the two adjacent generations cannot be further reduced, and the difference between the optimal solution and the worst solution cannot be further reduced. Several studies have utilized GA design networks (c.f. Fan and Machemehl, 2006; Guihaire and Hao, 2008).

In the present study, GA is used to determine the optimal P&R scheme. In the context of that problem, the chromosomes of the GA are designed as follows. All the railway stations in the network are numbered successively and each gene in one chromosome represents the decision on locating the P&R facility, which is a binary variable (0-1), and the corresponding size of the parking lot, which is an integer value between \underline{Y} and \bar{Y} . The chromosome, i.e. each P&R scheme, contains a feasible combination of P&R site location and corresponding size. The algorithm starts with an initial generation where all genes are randomly generated to produce an initial feasible solution. The detailed steps of the algorithm are given below:

Step 1: Initial population: let the population size be P_{size} . The maximum number of generations is set at i_{max} . Set the iteration counter, $i=1$. The initial population of the chromosomes consisting of location decision X_i and corresponding parking site capacity Y_i is generated randomly. The cross-over and mutation rate are set to P_{xover} and $P_{mutaiton}$ respectively.

Step 2: Evaluation: once the initial population is produced, now solve the bi-level problem for each newly-generated chromosome. The objective function for all the chromosomes is

determined using the value of the minimal expected disutility by solving the lower level traffic assignment problem. To ensure feasibility, each chromosome not subject to the budget and reliability constraints is multiplied by 100 to cause them to be eliminated in the next generation.

Step 3: Selection: From the existing chromosomes, select the one with lowest travel disutility i.e. the lower the value of the objective function of the chromosomes, the higher the probability of selection. In addition, the best chromosome of the previous population is kept in the next generation.

Step 4: Cross-over: Parents are chosen randomly from the chromosomes in the current generation and pairing is conducted between each parent to yield new chromosomes. Only the parking site capacity is to be cross-overed. If the parking size falls below the minimum range, \underline{Y} after crossover, then size is to be reset as \underline{Y} .

Step 5: Mutation: Genes from all the chromosomes in the current generations are chosen randomly and the values of chosen genes are modified by a pseudo-random number. The mutation contains two stages: mutation of location decision and mutation of capacity. First, the decision of location is modified by a 0-1 variable. If the previous decision is 1 and not modified, then modify the capacity by a random integer number between \underline{Y} and \bar{Y} . In this way, some new chromosomes are generated.

Sep 6: Termination: Terminate the algorithm if $i > i_{\max}$ or if the result does not improve after a considerable number of iterations, otherwise set $i=i+1$ and repeat from step 2.

6.4 Numerical Example

To numerically validate the proposed model, it is applied to a small example network. The network examined here is built on the basis of a road sub-road network and a P&R sub-network. The network consists of six nodes and ten links, as indicated in Figure 6.2. Of the ten links, seven are car links and three are rail links used as part of the P&R routes. Two O-D pairs are assumed: $1 \rightarrow 3$ and $2 \rightarrow 4$. The origins denote the suburbs while the destination nodes are locations in the city centre. Hence, the roads become increasingly narrow and therefore congested. The travel demands are assumed to be fixed at 300 for both OD pairs i.e. $D_{1-3}=D_{2-4}=300$. The link attributes for car links and for P&R links are presented in Table 6.1 and Table

6.2, respectively. The Bureau of Public Roads link travel time function is used as shown in Equations (6.14) and (6.15):

$$\mu_{la}(v_{la}) = t_{la}^0 [1 + 0.15 \cdot (\frac{v_{la}}{C_{la}})^4] \quad (6.14)$$

$$\mu_{lp\&r}(v_{lp\&r}) = t_{lp}^0 [1 + 0.15 \cdot (\frac{v_{lp}}{y_i})^4] + \mu_{lr} \quad (6.15)$$

where, t_{la}^0 is the car link free flow travel time, v_{la} is the car link flow and $\overline{C_{la}}$ is the average link capacity for the car link. t_{lp}^0 is the free flow time required for parking a car while transferring from the road link to the rail link for a P&R route, v_{lp} is the rail link flow i.e. equal to P&R flow and y_i is the parking size, and μ_{lr} is the subsequent rail link travel time.

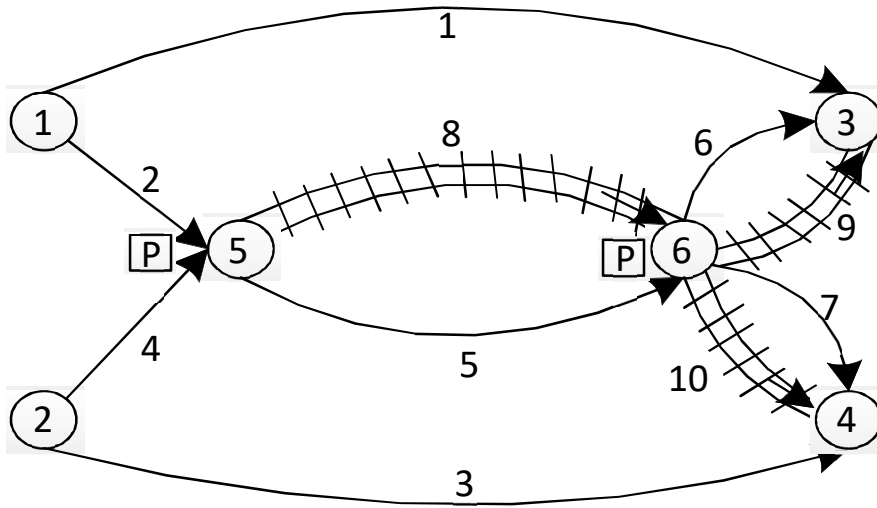


Figure 6.1 Example bi-modal traffic network

Table 6.1: Input data for auto links of example network

Parameter	Auto link						
	1	2	3	4	5	6	7
t_{la}^0	13.5	2	14.5	3	6.5	3.3	4
\bar{C}_{la}	150	150	150	150	300	80	100

Table 6.2: Input data for P&R links of example network

Parameter	P&R link		
	8	9	10
$t_{p\&r}^0$	0.2	0.2	0.2
$\mu_{p\&r}$	7	2.9	3.9

Each OD pair has three paths (two paths for auto mode and one path for P&R mode) as described in Table 6.3. Of all the six nodes, four nodes are considered to be railway stations. Of the four railway stations, two nodes (node 5 and node 6) are stations to be considered as P&R facilities. Only one site will be selected for a P&R facility, reflecting budget constraints. Therefore, in Table 6.3, path 3 for OD pair 1-3 is designated as 2-8-9 when the P&R facility is located at node 5 or 2-5-9 for the P&R facility located at node 6. This will also be the case for OD pair 1-4 where path 3 will be either 4-8-10 or 4-5-10.

Previous research suggests most travellers have a risk-averse attitude while some are risk-neutral and very few are risk-seeking (Yin and Ieda, 2001). In the present study, it is assumed that 70% of users are risk-averse, 20% are risk-neutral and 10% are risk-seekers. These proportions of users have also been utilized to assess the reliability of the road network in previous research (Yin and Ieda, 2001). The expected path travel disutilities for the three types of commuters are presented below, where Equations (6.16), (6.17) and (6.18) represent risk-averse, risk-neutral and risk-seeking commuters, respectively.

$$\eta_{p1}^{od} = \alpha_1 \cdot (\sum_{l \in L^{od}} \delta_{l,p}^{od} \beta_l^2 \mu_l^2) + \alpha_1 \cdot \sum_{l \in L^{od}} (\delta_{l,p}^{od} \mu_l)^2 + \gamma_1 \sum_{l \in L^{od}} \delta_{l,p}^{od} \mu_l + \omega_1 \quad (6.16)$$

$$\eta_{p2}^{od} = \gamma_2 \sum_{l \in L^{od}} \delta_{l,p}^{od} \mu_l + \omega_2 \quad (6.17)$$

$$\eta_{p3}^{od} = -\alpha_3 \cdot (\sum_{l \in L^{od}} \delta_{l,p}^{od} \beta_l^2 \mu_l^2) - \alpha_1 \cdot \sum_{l \in L^{od}} (\delta_{l,p}^{od} \mu_l)^2 + \gamma_3 \sum_{l \in L^{od}} \delta_{l,p}^{od} \mu_l + \omega_3 \quad (6.18)$$

The notation of the equations is as follows:

L^{od} : The set of all links between OD pairs od in the network;

β_l : A link-related constant which represents the link travel time variation

μ_l : The expected link travel time and standard deviation of the link travel time is $\sigma_l = \beta_l \mu_l$;

μ_p^{od} : Expected path travel time $= \sum_l \delta_{l,p}^{od} \mu_l$ and $\delta_{l,p}^{od} = 1$ if link l is a part of path p connecting OD pair od and $\delta_{l,p}^{od} = 0$ otherwise.

The travel time variations are assumed to be on link 5 (β_5) i.e. only link 5 is assumed in this chapter to have stochastic link travel time and all other remaining links are considered to be deterministic. The values of α, γ, ω for three different kinds of commuters are given below:

Risk-averse commuters, $\alpha = 1.0, \gamma = 1.0, \omega = 0$;

Risk-neutral commuters, $\alpha = 0, \gamma = 1.0, \omega = 0$;

Risk-seeking commuters, $\alpha = -0.01, \gamma = 1.0, \omega = 0$;

Table 6.3: OD pairs and corresponding paths for both auto and P&R mode

	OD Pair 1: Node 1 to Node 3	OD Pair 2: Node 2 to Node4
Path 1 (Road)	Link 1	Link 3
Path 2 (Road)	Links 2-5-6	Links 4-5-7
Path 3 (P&R)	Links 2-8-9 OR Links 2-5-9	Links 4-8-10 OR Links 4-5-10

The upper limit of the parking capacity \bar{Y} is set at 200 while the lower bound \underline{Y} is set at 10. The number of populations is set at 6. It is common to stop a genetic algorithm, either on reaching the maximum number of iterations or when a solution does not improve the value of the objective function within a certain number of iterations. In this study, the latter stopping criterion is applied if the value of the objective functions does not improve after 100 generations. The mutation (P_{mutaiton}) and cross-over (P_{xover}) rates are set at 0.25 and 0.45, respectively.

The evaluation procedure includes the traffic assignment problem based on the equivalent NCP formulation of the disutility-related multi-class user equilibrium and is solved by the decomposition technique. This lower level traffic assignment problem is solved for each newly-generated chromosome.

Figure 6.2 demonstrates the convergence of the GA and provides the minimal value of the objective function for each generation for the special case of $\beta_5 = 1$. The optimal P&R scheme and the corresponding value of the objective function are presented in Table 6.4. The results account for different considerations in the levels of travel time variations in link 5 (i.e. β_5). As the table shows, node 6 is the optimum choice of parking location when the network link travel times are deterministic. However, as soon as the link 5 travel time becomes stochastic, node 5 is the choice for the P&R facility. The parking capacity at each P&R facility also varies with the levels of variation in travel time on link 5, as can be seen in Table 6.4

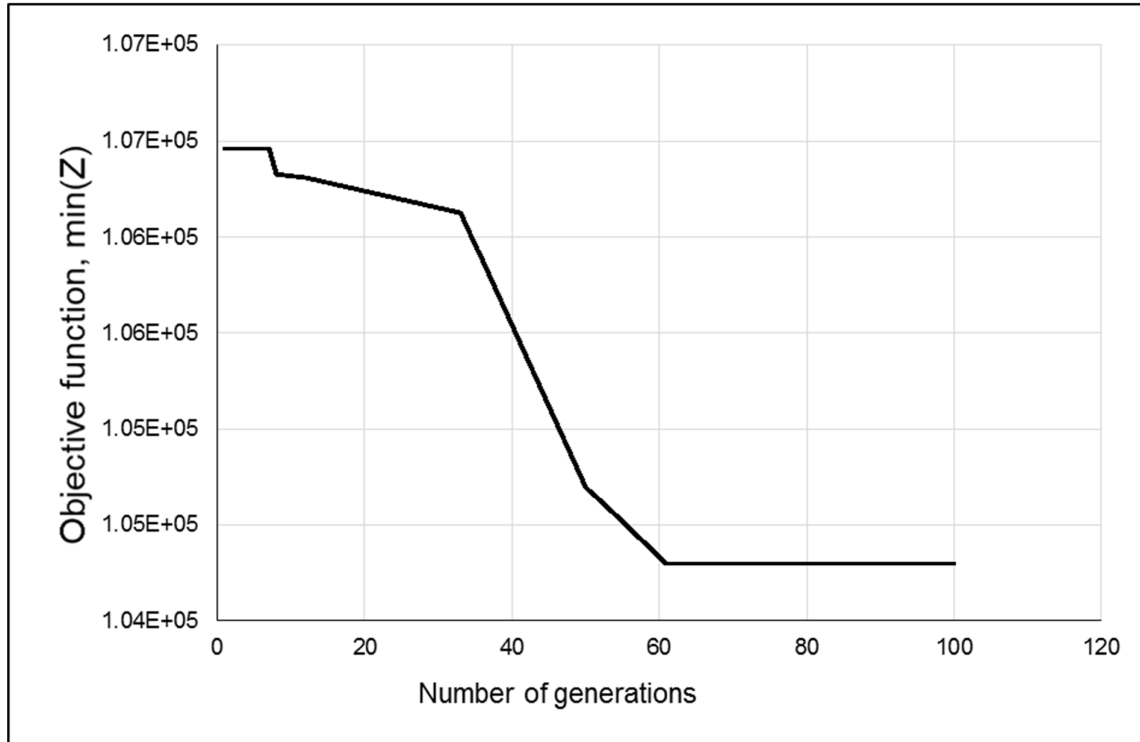


Figure 6.2 Convergence trend of GA for $\beta_5 = 1$

Table 6.5 presents a comparison between network reliabilities for the worst P&R decision (location and parking capacity) and the best P&R decision (location and parking capacity) for different travel time variations perceived on link 5 i.e. for different values of β_5 . It should be noted that the values of the network reliability obtained for the worst P&R decision are still larger than those for cases with no P&R considered (i.e. all auto links). Hence, the network reliability obtained for the worst P&R decision is used as the threshold value of reliability, R_{th} , for optimum P&R network design. Recall that under the constraint outlined in Equation (6.4), the reliability of the network must be larger than or equal to a threshold, R_{th} . The values of reliability presented in Table 6.5 are normalised for the best P&R decision at $\beta_5 = 0$, i.e. for the deterministic network. As can be seen from Table 6.5, the reliability of the network is greatly improved by the optimal decision of P&R facility location and the corresponding capacity. This improvement is evident for different degrees of travel time variation in the network, as indicated in Table 6.5.

Table 6.4: Optimal P&R decision (Combination of users)

Values of β_s	Optimal P&R scheme		Travel Disutility (Z)
	Parking Location	Parking Capacity	
0 (Deterministic case)	Node 6	62	96222
1	Node 5	38	104300
2 (High variability case)	Node 5	13	150760

Table 6.5: Reliability improvement by upper level network design

Values of β_s	Network reliability for no P&R (all auto links only)	Network reliability for worst P&R decision; also used as R_{th}	Improved network reliability by optimal P&R decision, R
0	0.76	0.85	1.0
1	0.72	0.80	0.92
2	0.58	0.61	0.64

6.4 Conclusions

This chapter has presented a heuristic approach to P&R network design in a bi-modal transport network designed to identify optimal location and capacity in order to optimise the reliability of the network in terms of the travel disutility within the whole network. A bi-level programming model has been developed to determine the optimal P&R scheme which minimises expected travel disutility. The upper level model minimises the total travel disutility for the whole network, while the lower level is a network users' route choice equilibrium problem. The network users, while making decisions on the choice of path in the network under non-recurrent congestion, are considered to exhibit different risk-taking behaviours, depending

on the level of variation of their perceived travel time, which is referred to as travel disutility. The disutility-related multi-class user equilibrium approach was employed in the lower level problem. An efficient solution algorithm based on the genetic algorithm has been proposed to solve the P&R network design problem.

The model was applied to a small network and the results revealed that the reliability of the network as a whole is improved with the incorporation of the optimal decision for the location and capacity of the P&R facility. It should be noted that solving particularly the lower level NCP traffic assignment problem becomes intractable as the network size increases in terms of the number of nodes and links in the network between origins and destinations. The numerical example presented here is based on the combination of commuters exhibiting three different types of behaviour.

CHAPTER SEVEN:
CONCLUSION

7.1 Introduction

The focus of this thesis has been on gaining a better understanding of the travel mode choice behaviour of P&R users, concentrating on the exploration of factors that affect P&R users' travel choices. The research has developed a framework for the design of P&R networks which will enable decisions to be made about the location and capacity of P&R facilities, in order to maximise the performance of the network in terms of travel time reliability. The research work undertaken has provided a number of original contributions to knowledge in this field, as presented in Chapters 4-6. This chapter concludes the thesis by providing a summary of the major contributions, followed by a discussion of the limitations and future directions of this research.

7.2 Summary of key contributions

This research has made contributions in three major areas relevant to the travel time reliability of P&R transport networks. These include exploring P&R users' travel choices (Chapter Four) ; quantifying the travel time reliability of P&R networks (Chapter Five) and optimising P&R network travel time reliability (Chapter Six). The major contributions in each of those areas are outlined as follows :

- This research has explored the mode change behaviour of P&R users. Based on survey data on P&R users at different station car parks and bus terminals in Melbourne, the choice of mode change of P&R users was investigated. This research has identified that Public Transport Travel Time (PTTT) and Transfer Time (TT) at P&R stations are factors when choosing public transport only mode over P&R mode. Lower PTTT increases the probability of choosing public transport only mode for the entire journey, while lower TT is a very convincing factor for travelers to choose P&R mode over Public transport only mode. Therefore, travel time is the most influential factor in P&R users' choice of travel mode. The results show that lower parking prices in the city positively influence commuters to opt for driving all the way rather than choosing P&R mode, while lower PTTT and TT at P&R stations lead to a greater likelihood of commuters choosing P&R mode over driving.

- This research has presented a mathematical framework for deriving the exact PDFs of average link travel time and network total travel time in terms of an arbitrary link flow PDF which is then used to calculate network reliability. Techniques such as 1) derivation of the PDF of a function of a random variable 2) solution of quintic polynomial 3) characteristic function method of deriving PDF of a sum of random variables, have been applied to reach the final form of the PDF of network total travel time. Considering maximum allowable travel time as the threshold, an expression for transport network travel time reliability is then derived. The methodology outlined in this research is generic and can be applied to any network configuration and link flow PDF.

- This research has presented a heuristic approach to P&R network design in a bi-modal transport network designed to identify optimal location and capacity in order to optimise the reliability of the network in terms of the travel disutility within the whole network. A bi-level programming model has been developed to determine the optimal P&R scheme which minimises expected travel disutility. The upper level model minimises the total travel disutility for the whole network, while the lower level is a network users' route choice equilibrium problem. The reliability of the P&R network is improved with the incorporation of the optimal decision for the location and capacity of the P&R facility. The numerical example presented in this research is based on the combination of commuters exhibiting three different types of behaviours in terms of their risk propensity. This research task extends our understanding of modelling approaches and potential solutions which can improve network reliability.

7.3 Limitations

While this thesis has provided a number of original contributions to knowledge, it is also subject to a number of limitations.

In considering the survey of P&R users in metropolitan stations reported in Chapter four, this was limited to the three stations. The key consideration in the selection of the stations for the survey was the practicality of the locations to be accessed by the survey teams and their level of use as park and ride stations. The respondents are regarded as representative of P&R users and it is acknowledged that they are not representative of non-users. The sample size was limited as the scale of the resources available for the meant that the scope had to be carefully managed.

This work presented in Chapter five is a mathematical framework for deriving the exact PDFs of the P&R network total travel time in terms of an arbitrary link flow PDF which is then used for calculating the travel time reliability of a P&R network. The methodology outlined in this study is theoretical being the start of a new work since no previous work has explored this before.

The study presented in Chapter six optimises the travel time reliability of P&R network. It should be noted that solving particularly the lower level NCP traffic assignment problem becomes intractable as the network size increases in terms of the number of nodes and links in the network between origins and destinations. Due to the complexity being a current constraint on the application to the large networks, the present study could only be applied to small networks.

7.4 Future research

This research has found travel time to be the most influential factor in the choice of travel mode of P&R users. Future research can explore other factors such as pricing schemes. Travel time reliability specific question could be included in future work. Policy makers can develop effective promotional strategies to increase public support for P&R schemes.

This research has developed and applied an exact distribution of overall travel time in a P&R network. However, future research can consider network equilibrium situations. Numerical examples considering exponential/double-exponential link flow distributions can also be investigated.

The research extends our understanding of modelling approaches and potential solutions which can improve P&R network travel time reliability. However, fixed travel demand is considered in this research. This could only be applied to small networks because of computational complexity. This provides a scope for future research to extend this work and enable larger networks to be analysed.

APPENDIX : SURVEY QUESTIONNAIRE

SECTION I

1. Are you using P&R for this trip?
 - ☐ Yes, I parked in a car park
 - ☐ Yes, I parked on the roadside
 - ☐ **No (survey terminated)**
2. Are you a Tourist from other city or country?
 - ☐ **Yes (survey terminated)**
 - ☐ No
3. What age group do you belong in?
 - ☐ **Below 18 (survey terminated)**
 - ☐ 18-25 years
 - ☐ 26-35 years
 - ☐ 36-49 years
 - ☐ 50 years and over years

PART ONE-TRIP BASED QUESTIONS

4. Where is the destination of your trip?
5. What is the main purpose of your trip?
 - ☐ Work
 - ☐ Study
 - ☐ Personal Business
 - ☐ Shopping /Leisure
 - ☐ Other
6. How long will it take you to reach your destination from this station?
 - ☐ Less than 10 minutes
 - ☐ 10-20 minutes
 - ☐ 20-30 minutes
 - ☐ 30-60 minutes
 - ☐ More than 60 minutes
7. How often do you travel through this station each week?
 - ☐ 6-7 days
 - ☐ 4-5days
 - ☐ 2-3 days

-
- ☐ Only 1 day
 - ☐ Less than once a week

PART TWO-MODE CHANGE QUESTIONS

8. How long have you been using this station?
- ☐ Less than 1 year
 - ☐ 1-2 years
 - ☐ 2-3 year
 - ☐ 3-4 years
 - ☐ More than 4 years
9. Previously, what mode did you use to travel to your destination?
- ☐ Driving for my entire journey
 - ☐ Public transport for entire journey
 - ☐ Always P&R
 - ☐ Bicycle
 - ☐ Walking
 - ☐ Others, please specify_____
10. Why do you choose to use Park and Ride today, rather than walk/cycle/bus, etc.? (Tick all that apply)
- ☐ Convenient
 - ☐ Cheaper
 - ☐ Less trip time
 - ☐ Easy to park at train stations
 - ☐ Better security at P&R site
 - ☐ Others, please specify_____
11. If you find no available parking space at the car park of the station, what would you do?
- ☐ Park at a nearby street
 - ☐ Drive to another train station, and park there
 - ☐ Drive all the way to the destination
 - ☐ Others, please specify _____

SECTION II

12. How would you describe the traffic conditions of your common trips in Melbourne in the past 6 months?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Extremely congested	Congested	Neutral	Not congested	Not congested at all

13. Do you think the parking space at this station is sufficient?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly disagree	Disagree	Neutral	Agree	Strongly agree

14. How would you rate the convenience of the location of this station?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Extremely inconvenient	Inconvenient	Neutral	Convenient	Very convenient

15. How satisfied are you with Melbourne's public transport services OVERALL?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Extremely dissatisfied	Dissatisfied	Neutral	Satisfied	Extremely satisfied

16. How do you think the Parking Fees in the CBD of Melbourne on a week day?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Extremely High	High	Neutral	Low	Extremely Low

17. How do you think the walking time from this station's parking area to the station platform?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Extremely long	Long	Neutral	Short	Extremely short

SECTION III

In this section, we will ask about your preferred travel modes, under some hypothetical scenarios. Suppose you are travelling from a suburb area to the CBD of Melbourne, and there are three available travel modes:

- You drive car for the whole trip and park in the CBD.
- You take public transport for the whole trip.
- You use P&R. Drive from the origin to a train station, park there and take train to the CBD.

Assume there are only three factors that may change your choice of travel mode:

- Total parking fare in the city (changes among \$10; \$20; \$40 /day)
- Total public transport travel time (when public transport is used for the whole trip; this value changes among 40min; 60min; 90min)
- Total transfer time spent at the P&R stations (changes among 5min; 10min; 20min)

Note that the “transfer time” above equals “parking time + walking time to the platform + waiting time for the train”.

Scenario 1

Factors	Values		
Total parking fare in the city	\$40/day		
Total public transport travel time	90min		
Total transfer time spent at the P&R stations	5min		
Your preferred mode of transport	Public Transport <input type="checkbox"/>	Car <input type="checkbox"/>	Park and Ride <input type="checkbox"/>

How likely would you choose P&R, compared with the other travel modes?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Very unlikely	Unlikely	Neutral	Likely	Very likely

Scenario 2

Factors	Values		
Total parking fare in the city	\$10/day		
Total public transport travel time	60min		
Total transfer time spent at the P&R stations	20min		
Your preferred mode of transport	Public Transport <input type="checkbox"/>	Car <input type="checkbox"/>	Park and Ride <input type="checkbox"/>

How likely would you choose P&R, compared with the other travel modes?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Very unlikely	Unlikely	Neutral	Likely	Very likely

Scenario 3

Factors	Values		
Total parking fare in the city	\$40/day		
Total public transport travel time	40min		
Total transfer time spent at the P&R stations	20min		
Your preferred mode of transport	Public Transport <input type="checkbox"/>	Car <input type="checkbox"/>	Park and Ride <input type="checkbox"/>

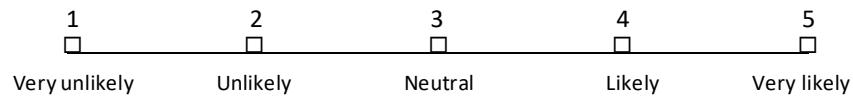
How likely would you choose P&R, compared with the other travel modes ?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Very unlikely	Unlikely	Neutral	Likely	Very likely

Scenario 4

Factors	Values		
Total parking fare in the city	\$10/day		
Total public transport travel time	90min		
Total transfer time spent at the P&R stations	10min		
Your preferred mode of transport	Public Transport <input type="checkbox"/>	Car <input type="checkbox"/>	Park and Ride <input type="checkbox"/>

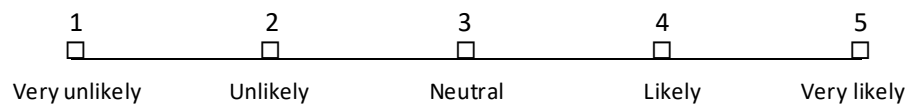
How likely would you choose P&R, compared with the other travel modes?



Scenario 5

Factors	Values		
Total parking fare in the city	\$20/day		
Total public transport travel time	90min		
Total transfer time spent at the P&R stations	20min		
Your preferred mode of transport	Public Transport <input type="checkbox"/>	Car <input type="checkbox"/>	Park and Ride <input type="checkbox"/>

How likely would you choose P&R, compared with the other travel modes?



Scenario 6

Factors	Values		
Total parking fare in the city	\$40/day		
Total public transport travel time	60min		
Total transfer time spent at the P&R stations	10min		
Your preferred mode of transport	Public Transport <input type="checkbox"/>	Car <input type="checkbox"/>	Park and Ride <input type="checkbox"/>

How likely would you choose P&R, compared with the other travel modes?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Very unlikely	Unlikely	Neutral	Likely	Very likely

Scenario 7

Factors	Values		
Total parking fare in the city	\$20/day		
Total public transport travel time	60min		
Total transfer time spent at the P&R stations	5min		
Your preferred mode of transport	Public Transport <input type="checkbox"/>	Car <input type="checkbox"/>	Park and Ride <input type="checkbox"/>

How likely would you choose P&R, compared with the other travel modes?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Very unlikely	Unlikely	Neutral	Likely	Very likely

Scenario 8

Factors	Values		
Total parking fare in the city	\$20/day		
Total public transport travel time	40min		
Total transfer time spent at the P&R stations	10min		
Your preferred mode of transport	Public Transport <input type="checkbox"/>	Car <input type="checkbox"/>	Park and Ride <input type="checkbox"/>

How likely would you choose P&R, compared with the other travel modes?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Very unlikely	Unlikely	Neutral	Likely	Very likely

Scenario 9

Factors	Values		
Total parking fare in the city	\$10/day		
Total public transport travel time	40min		
Total transfer time spent at the P&R stations	5min		
Your preferred mode of transport	Public Transport <input type="checkbox"/>	Car <input type="checkbox"/>	Park and Ride <input type="checkbox"/>

How likely would you choose P&R, compared with the other travel modes?

1	2	3	4	5
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Very unlikely	Unlikely	Neutral	Likely	Very likely

DEMOGRAPHIC QUESTIONS

1. Your Gender
 - ☐ Female
 - ☐ Male
2. What is your occupation?
 - ☐ Full-time / part-time
 - ☐ Self-employed
 - ☐ Retired
 - ☐ Unemployed
 - ☐ Student
 - ☐ Other
3. What is the post code of your home? (If not sure, please write down the name of your residential area)
 - ☐
4. How far is your trip origin from this station?
 - ☐ Within 100 m
 - ☐ 100 m-1 km
 - ☐ 1 km- 3 km
 - ☐ 3 km-10 km
 - ☐ More than 10 km
5. How many cars do you have access to?
 - ☐ One car
 - ☐ Two cars
 - ☐ Three cars
 - ☐ More than three cars
6. Your pre-tax personal annual income is in which category?
 - ☐ Less than \$20,000
 - ☐ \$20,001 - \$40,000
 - ☐ \$40,001 - \$60,000
 - ☐ \$60,001 - \$80,000
 - ☐ \$80,001 and above

In the end, do you have any other comments to the P&R services in Melbourne?

Thank you for completing this survey and enjoy the rest of your day.

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