IMPROVING METHODS TO ESTIMATE THE TRAFFIC CONGESTION IMPACTS OF URBAN PUBLIC TRANSPORT

Duy Quy Nguyen-Phuoc

BSc (Civil Eng.), MSc (Civil Eng.)

A thesis submitted for the degree of Doctor of Philosophy at
Monash University in 2018

Institute of Transport Studies
Department of Civil Engineering
Monash University

Copyright notice

Abstract

Traffic congestion has been a major issue in many cities worldwide. It causes delay, energy waste and environmental pollution. Public transport is considered to be an efficient solution that can deal with traffic congestion. It provides an alternative transport mode for riders and reduces the number of car trips on the road network. Transport researchers have developed a number of approaches which aim to assess the benefits of public transport such as cost saving or pollution reduction. However, from a literature review the traffic congestion effects associated with public transport have been explored by only limited studies which adopted unrealistic assumptions and presented simplistic constructs. No systematic methods have been proposed to estimate these impacts. Given this deficiency in the literature, this thesis proposes that further research should be undertaken with the aim of developing a more precise approach for assessing the traffic congestion impacts of public transport.

To achieve the overall research aim, seven stages of work have been identified. The first stage involves the review of relevant literature on the traffic congestion effect of public transport. The second stage is to gain an in-depth understanding of mode shift from public transport when public transport is unavailable and to explore factors influencing mode shift. In the third stage, a transport network modelling is used to assess the network-wide congestion relief effect of urban public transport. The net congestion impacts of individual public transport modes (bus, tram and train) are explored in the fourth stage, fifth stage and sixth stage. In the final stage, the net traffic congestion effect of the entire public transport system is assessed by integrating both positive and negative effects of public transport.

The main methodology using to assess the congestion impacts associated with public transport is to contrast the level of congestion on the road network in two scenarios ‘with public transport’ and ‘without public transport’. The Victorian Integrated Transport Model (VITM), a strategic transport modelling platform, provides the general assessment of congestion level of the road network in the scenario ‘with public transport’ but it cannot model correctly the negative impacts that public transport itself can have on vehicle traffic. In addition, VITM does not give detailed information about the level of congestion in the scenario ‘without public transport’. In my research, this model is significantly improved to estimate the level of congestion in two scenarios ‘with public transport’ and ‘without public transport’. The difference between these two levels of congestion is considered to be the traffic congestion effect of public transport. Hence, using this extended model, it is now possible to estimate the effects of public transport on traffic congestion.

The findings show that in the morning peak hours, Melbourne's public transport system contributes to reduce vehicle time travelled and total delay on the road network by around 48%. The public transport system also reduces the number of severely congested links by more than 60%. The congestion impact of public transport varied spatially across regions. The highest effect in relieving traffic congestion is in inner areas, traditionally the most congested part of the city.

The major contribution of this research is the development of a more comprehensive methodology that can be used to measure the traffic congestion effects associated with public transport. With the new method, traffic authorities can identify the effectiveness of public transport in relieving traffic congestion on a particular corridor or an area. Based on the results, they can decide whether a public transport system needs to be improved. In addition, understanding the congestion relief impact of public transport can provide guidance both from an operational and a strategic point of view. From the operational perspective, routes and corridors facing congestion can be targeted for attention to seek a desired level of congestion relief. From a strategic perspective, appropriate public transport policies can be developed to encourage desired development in designated locations and again seek desired levels of congestion relief.

In summary, the traffic congestion effects associated with urban public transport have been examined through a qualitative, quantitative, microsimulation and macrosimulation modelling approach detailed in this thesis. Results from the analyses indicate that the net effect of the entire Melbourne's public transport system on traffic congestion is significant and positive.

Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Publications during enrolment

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

Refereed Journal Papers

1. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2017, 'Local and system-wide traffic effects of urban road-rail level crossings: A new estimation technique', *Journal of Transport Geography*. Vol. 60, pp. 89-97.
   SSCI, Q1, IF=2.68
2. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2017, 'Net Impacts of Streetcar Operations on Traffic Congestion in Melbourne, Australia', *Transportation Research Record: Journal of the Transportation Research Board*. Vol. 2648, pp. 1-9.
   SCI, Q2, IF=0.60
3. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2018, 'Understanding public transport user behaviour adjustment if public transport ceases - A qualitative study', *Transport Research Part F*.
   SSCI, Q2, IF=1.83
4. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2018, 'Transit user reactions to major service withdrawal – A behavioural study'. *Transport Policy*.
   SSCI, Q2, IF=2.27
5. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2018, 'The impact of public transport strike on travel behaviour and traffic congestion', *International Journal of Sustainable Transportation*. DOI: 10.1080/15568318.2017.1419322.
   SSCI, Q2, IF=1.96

Journal Papers in Under Review

1. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2017, 'Traffic congestion relief consequent on public transport: The state of the art', *Transport Review*. (Pass 1st round, submitted the revision)
   SSCI, Q1, IF=3.33
2. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C., Kim, I. & Young, W., 2017, 'Net impact of bus operations on traffic congestion in Melbourne', *Transport Research Part A*. (Pass 1st round with minor revision, submitted the revision)
   SCI, Q1, IF=2.67
3. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2017, 'Congestion relief and public transport: An enhanced method using disaggregate mode shift evidence', *Case Studies on Transport Policy. (Under Review)*
4. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2017, 'Quantifying the net traffic congestion effect of urban public transport – Including both negative and positive effects', *Public Transport. (Under Review)*

Peer-Reviewed Conference Papers

1. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2018, ‘ Quantifying the net traffic congestion effect of urban public transport – Including both negative and positive effects’, Transportation Research Board (TRB) 97th Annual Meeting, Washington, D.C., United States.
   ERA Ranking – A, ERA Conference ID – 44128
2. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2017, ‘ Estimating the net traffic congestion impact associated with urban public transport – A Melbourne, Australia Case Study’, 39th Australasian Transport Research Forum (ATRF), Auckland, New Zealand.
   ERA Ranking – A, ERA Conference ID – 42260
3. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2017, ‘Transit user reactions to major service withdrawal - A behavioural study’, Transportation Research Board (TRB) 96th Annual Meeting, Washington, D.C., United States.
   ERA Ranking – A, ERA Conference ID – 44128
4. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2017, ‘Exploring the impacts of public transport strikes on travel behaviour and traffic congestion’, Transportation Research Board (TRB) 96th Annual Meeting, Washington, D.C., United States.
   ERA Ranking – A, ERA Conference ID – 44128
5. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2017, ‘Net impacts of street car operations on traffic congestion in Melbourne’, Transportation Research Board (TRB) 96th Annual Meeting, Washington, D.C., United States.
   ERA Ranking – A, ERA Conference ID – 44128
6. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2016, ‘Modelling the direct impact of tram operations on traffic’, 23rd World Congress on Intelligent Transport System (ITS), Melbourne, Australia.
7. **Nguyen-Phuoc, D.Q.**, Currie, C. & Young, W., 2016, ‘Estimating net traffic congestion relief associated with public transport - preliminary results’, 14th World Conference on Transport Research (WCTR), Shanghai, China.
   ERA Ranking – A, ERA Conference ID – 44255
8. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2016, ‘Understanding public transport user behavior adjustment if public transport ceases - A qualitative study’, 38th Australasian Transport Research Forum (ATRF), Melbourne, Australia.
   ERA Ranking – A, ERA Conference ID – 42260
9. **Nguyen-Phuoc, D.Q.**, Currie, G., De Gruyter, C. & Young, W., 2016, ‘Modelling the Net Traffic Congestion Relief Impact of Street Car Networks – A Melbourne, Australia Case Study’, 38th Australasian Transport Research Forum (ATRF), Melbourne, Australia.
   ERA Ranking – A, ERA Conference ID – 42260
10. **Nguyen-Phuoc, D.Q.**, Currie, C. & Young, W., 2015, ‘New method for evaluating public transport congestion relief’, Conference of Australian Institutes of Transport Research (CAITR), 33rd. Year 2015.
    ERA Ranking – C, ERA Conference ID – 42633
11. **Nguyen-Phuoc, D.Q.**, Currie, C. & Young, W., 2015, ‘Public transport congestion relief measurement–a new framework and its impacts’, 37th Australasian Transport Research Forum (ATRF), Sydney, New South Wales, Australia.
    ERA Ranking – A, ERA Conference ID – 42260

Thesis including published works General Declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes four original papers published in peer reviewed journals and four original papers submitted to peer reviewed journals. The core theme of the thesis is to develop enhanced methods for assessing the net short-term traffic congestion impact associated with the urban public transport system in Melbourne, Australia. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the candidate, working within the Department of Civil Engineering under the supervision of Professor Graham Currie, Professor William Young and Dr Chris De Gruyter. The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research.

In the case of Chapter 2 to Chapter 9 my contribution to the work involved the following:

Thesis chapter	Paper	Publication title	Publication status*	Nature and extent (%) of student's contribution
2	1	Traffic congestion relief consequent on public transport: The state of the art	*Returned for revision*	70%
4	2	Understanding public transport user behavior adjustment if public transport ceases - A qualitative study	*Published*	70%
4	3	Transit user reactions to major service withdrawal – A behavioural study	*Published*	70%
5	4	Congestion relief and public transport: An enhanced method using disaggregate mode shift evidence	*Under review*	70%
6	5	Net impact of bus operations on traffic congestion in Melbourne	*Returned for revision*	70%
7	6	Net traffic congestion impacts of street car operations in Melbourne, Australia	*Published*	70%
8	7	Local and system-wide traffic effects of urban road-rail level crossings: A new estimation technique	*Published*	70%
9	8	Quantifying the net traffic congestion effect of urban public transport – Including both negative and positive effects	*Under review*	70%

** e.g. 'published'/ 'in press'/ 'accepted'/ 'returned for revision'*

I have not renumbered sections of submitted or published papers in order to generate a consistent presentation within the thesis.

Student signature: **Date:**

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the student and co-authors' contributions to this work. In instances where I am not the responsible author I have consulted with the responsible author to agree on the respective contributions of the authors

Main Supervisor signature: **Date:**

Acknowledgements

This thesis is the result of a long journey that would not be completed without the support from a number of people. Firstly, I would like to express my sincere gratitude to my supervisors, Professor Graham Currie, Professor William Young and Dr Chris De Gruyter for both their excellent guidance and valuable advice. Their motivation, patience, enthusiasm and immense knowledge made me feel more confident and motivated on my way. From a student who did not know much about research and publication, they have assisted me in developing my skills as an independent researcher. I feel so lucky to be a student supervised by such talented individuals. I would like to thank Dr Inhi Kim for his assistance in dealing with VISSIM. He has shown me many skills which save me a lot of time.

Thank you all PhD students in the transport group who always remind me to never take things too serious and made my journey more enjoyable. I would also like to express my thanks to Jenny Manson, our Research and Postdoc manager for her support for almost all administrative matters.

My sincere thanks to Craig Somerville and Neville Wood from VicRoads for their assistance in accessing a transport network model. Dr Henry Le from AECOM is also acknowledged for his brilliant assistance in dealing with my issues that I faced in the transport model.

Most importantly, I would like to thank my wife Diep Su who always beside me when I feel stressed with my research. She was also a patient audience who listened to every presentation I practiced. Although she has also been a PhD student in Swinburne University, she had spent much time for taking care our small family, preparing my lunch and my dinner every day during my PhD journey. Special thanks to Cherry, my lovely daughter, whose face made me happy especially when my feeling was going down. I would also like to thank my parents for their distance encouragement that helped me deal with challenges and enjoy my life in Australia.

Table of Contents

List of Figures

List of Tables

Chapter 1
INTRODUCTION

1.1 Introduction

This thesis explores the net traffic congestion impacts associated with urban public transport systems in the short-term. The contrast between the level of traffic congestion in two scenarios: 'with public transport' and 'without public transport' is considered the short-term public transport congestion impact. In the scenario of 'without public transport', mode shift from public transport to private car in the event of a whole-day removal of the entire public transport system with advanced notification is modelled. The focus of the research is on public transport systems in Melbourne, Australia. This chapter is the introduction of the thesis which explains the research context, the objectives for the thesis and outlines the full structure of the work.

1.2 Background

1.2.1 Traffic Congestion

Urban transport plays a pivotal role in almost all cities around the world because it provides access to employment, education, entertainment, health care and other services. However, with the rapid growth in private cars in recent years, traffic congestion has become a major issue in many large cities, particularly in metropolitan areas (Cervero, 1991, Downs, 1992, Dowling et al., 1998, Quiroga, 2000). The congestion in these areas is also increasing due to a rise in population, economy, urbanisation, housing, and jobs (ECMT, 2007). It not only has a direct impact on the daily lives of commuters through higher fuel consumption, delay and accidents, but also has an indirect effect on the environment through air pollution (Maitra et al., 1999). Thus, the growth of traffic congestion has become a concern to travellers and the community at large (Levinson and Lomax, 1996).

Traffic congestion is widely interpreted as one of the great productivity bottlenecks of developed economies (TTF, 2010). The actual economic effects of traffic congestion can differ by metropolitan area, based on its economic profile and business location pattern (Weisbrod et al., 2001). According to a report on traffic congestion published by the Texas Transportation Institute (TTI), in 2011 congestion cost Americans $US 121 billion in direct and indirect losses. By 2020 this number is expected to grow to $US 199 billion with travel delay totaling 8.4 billion hours (Schrank and Lomax, 2009). In Britain, the annual cost of congestion is around £10.9 billion and this figure is expected to rise to £22 billion per year by 2025 (Cabinet Office Strategy Unit, 2009). In Australia, analysis by the Bureau of Transport and Regional Economics (BTRE) shows that the total cost of congestion across the eight capital cities in 2005 was about $AU 11.1 billion (private vehicle delay contributed 52% while business vehicle delay contributed 48%). The three large cities including Sydney (at $AU 3.9 billion), Melbourne (at $AU 3.6 billion) and Brisbane (at $AU 1.44 billion) accounted for a major portion of this total (Cosgrove and Gargett, 2007). It is anticipated that the cost of congestion in Australia's cities could exceed $AU 20 billion by 2020 if recent trends in transport continue unabated (Garnaut, 2012).

There has been no widely accepted definition of traffic congestion because congestion is both a physical phenomenon and a relative phenomenon (ECMT, 2007). The physical phenomenon refers to the manner in which vehicles obstruct each other's progression when demand for road space exceeds supply. The relative phenomenon relates to user expectations with the performance of the transport system. A number of definitions have been provided by various researchers (Downs, 2005). As a result, measures for assessing the magnitude of traffic congestion on a roadway or a road network have been developed in many different directions. Economists and engineers differ in their approaches. Economic approaches to congestion include assessing the demand for travel interacting with the supply of transport services and are often based on the marginal cost arising from additional vehicles joining the traffic flow. In contrast, engineering approaches to congestion indicate how the capacity of a transport facility interacts with demand.

Traffic congestion is defined as a condition of traffic delay (i.e., when traffic flow is slowed below reasonable speeds) because the number of vehicles trying to use a road exceeds the design capacity of the traffic network to handle it (Weisbrod et al., 2003). A conference of European Transport Ministers defined that traffic congestion is the impedance vehicles impose on each other in conditions where the use of a transport system approaches capacity (ECMT, 2007). Congestion is also defined as a relative phenomenon that is linked to the difference between the roadway system performance that users expect and how the system actually performs (Tortore, 2011).

1.2.2 Impact of Public Transport on Traffic Congestion

In order to minimise the effect of traffic congestion, a number of measures have been proposed. The traditional response to congestion is to invest in more road capacity but, despite considerable investments, highway capacity has not kept pace with the growth in vehicle miles travelled (Parry, 2002). Thus, appropriate policies can be another solution considered by transport professionals to mitigate congestion (such as congestion charges or higher fuel taxes) (Maitra et al., 1999). However, according to Parry (2002), these solutions have several drawbacks and are widely recognised as only short term measures to deal with traffic congestion problems.

The awareness of these limitations has centralised the role of public transport as a key factor to alleviate the effect of traffic congestion. Public transport is recognised to be a sustainable solution because it can attract a number of car users to reduce car use and if a public transport system is improved, its attractiveness can also be a long-term solution aimed at mode shift. In 2005, Americans took 9.7 billion trips on public transport - 15 times the number of trips they took on domestic airlines (APTA, 2007). In Melbourne, Australia, more than 1.8 million journeys were made on Melbourne's trains, trams and buses every weekday in 2015 (Public Transport Victoria, 2015a). Schrank and Lomax (2009) estimated that Americans living in areas served by public transport can save more than $US 13 billion in congestion costs annually. The benefits of public transport affect everyone, even those who may not ever use a bus or a train. Public transport can help a community expand business opportunities, reduce urban sprawl, and create a sense of community through transit-oriented development (FHWA, 2002). Thus, public transport has been encouraged and expanded in many cities around the world. According to Polzin and Baltes (2002), public transport has been receiving serious funding commitments from a number of urban areas which invested more than 50 percent of transport resources for public transport.

1.2.2.1 The Positive Effect of Public Transport in Relieving Traffic Congestion

It has been argued that public transport plays a significant role in providing mobility within urban areas, especially for work trips and trips to central areas (Pushkarev and Zupan, 1977, Cervero, 1998, Black, 1995). Public transport is said to minimise the effect of traffic congestion by offering a basic mobility service that increases person throughput (Polzin et al., 2008). For instance, it has been estimated that each train in Sydney can remove nearly 1,000 cars from the road network (TTF, 2010).

According to Litman (2007), high quality public transport systems can reduce traffic congestion in three ways:

- Public transport provides an alternative means of travel with some speed advantage, resulting in mode shift from private car and therefore reducing congestion on parallel roads.
- Public transport can stimulate transit-oriented development thereby reducing the number of vehicles owned by households in transit-oriented locations.
- A quality public transport system can reduce travel costs for public transport users due to the high cost of operating a car. Also, the effect of quality public transport on improving travel speed on parallel roads has been demonstrated by a number of prior studies

(Mogridge, 1990, Vuchic, 1999, Lewis and Williams, 1999). New Bus Rapid Transit (BRT) systems in Australia attracted nearly 12% of car drivers to use the buses on average (Currie, 2006). In addition, research in America shows that approximately 50% of new public transport users had switched to public transport from driving a car due to fare reduction/service increase policies (McCollom and Pratt, 2004).

1.2.2.2 The Negative Effect of Public Transport in Creating Traffic Congestion

There are also negative impacts that public transport itself can have on traffic congestion such as the effect of at-grade rail crossings, the stop operations of buses and trams. This congestion is expected to rise in the future as public transport service frequencies increase to adapt to the growth in the number of people using the public transport system (Hakkert and Gitelman, 1997).

At-grade rail crossings have an effect on road traffic when a train passes through an intersection with a roadway. With the introduction of trains with higher speed and faster acceleration, boom gate closure times at at-grade rail crossings are likely to increase. This could further contribute to the level of congestion. Melbourne, Australia has a relatively large number of at-grade railway crossings (around 175) distributed throughout the metropolitan rail and road network (VicRoads, 2014). They are considered a major contributor to congestion on Melbourne's road network. Due to the impacts of at-grade rail crossings, many projects for grade separating these crossings have been carried out and are planned for the future (Andrews, 2014). A key concern for planners is the effect which at-grade crossings have on traffic in terms of delay and how these vary at different locations for differing rail service frequencies.

The operation of tram or streetcar systems can also act to create negative effects on vehicle traffic in terms of travel time and reliability (Currie and Shalaby, 2007). Streetcars run on tracks along public urban streets (called 'street running'), and also on segregated rights of way. Streetcars running on public streets without any separation share the street with vehicle traffic and pedestrians. This results in delays to vehicle traffic; these problems become more serious when the frequency of trams and traffic volumes increase. On the other hand, trams with priority run on a separated lane (semi-exclusive right-of-way) often located in the middle of road. The reallocation of road space to provide priority for trams can increase tram speed and reliability (Currie et al., 2007) however it also reduces the capacity of roads and can increase the level of congestion (Kittelson, 2003). Melbourne has the largest operating tram system as well as the largest streetcar system in the world (Currie and Smith, 2006). It carried a total of around 177 million passenger trips in 2015 (Yarra Trams, 2015). However, with around 180 kilometres of tram tracks located in the centre lanes of roads and nearly 1,200 curbside stops on these routes (Delbosc and Currie, 2013), they are considered to be a major contributor to traffic congestion on Melbourne's road network.

Buses play a very critical role in the public transport context, often carrying many more passengers per vehicle than a private car for a given amount of road space. However, bus operations may result in traffic congestion creation in two ways:

- Delay caused by midblock bus stops when passengers board and alight at these locations.
- The reduction of road capacity due to the occupation of bus priority lanes.

There are several types of bus stop designs in Melbourne. Curbside bus stops reduce the capacity of roads due to temporary reduction of carriageway width since buses stop for passenger boarding and alighting. Bus bays are primarily used on high volume or high speed roads. However, bus bays also conflict with passing vehicles once buses manoeuvre to pull into and out of the bus stops (Kwami et al., 2009, Koshy and Arasan, 2005). As a result, traffic congestion at bus bays can increase with traffic volume. Bus bays can also interfere with vehicle movement if bus demand exceeds the bus bay's capacity, resulting in some buses waiting in the traffic lane until the buses occupying the bay exit the bay (Kwami et al., 2009). In addition, bus lanes were designed to ensure buses were not delayed by traffic. However, bus lanes can increase traffic congestion on adjacent lanes if they replace traffic lanes acting to reduce road capacity. Bus lanes can also result in congestion for other roads as motorists change their route and use parallel roads.

1.2.3 Measures of Congestion Impacts Associated with Public Transport

There have been a number of studies that have explored the benefit of public transport in urban areas. A benefit-cost analysis framework including congestion relief benefits is often used in these studies (Litman, 2004b, Litman, 2003, ATC, 2006, Beimborn et al., 1993, Nelson et al., 2007). However, studies focusing on traffic congestion impacts associated with public transport are seldom carried out, yet congestion impacts are considered one of the main rationales for providing public transport in cities (Larwin, 1999, Gray, 1992, Nielsen et al., 2005, Vuchic, 2005).

In the few studies that have explored congestion relief associated with public transport, it is assumed that all or a fixed share of public transport users would shift to car if public transport was removed (Schrank et al., 2012, FTA, 2000, Aftabuzzaman et al., 2010a, Aftabuzzaman et al., 2010b). The increase in the number of car trips would lead to an increase in traffic congestion which is interpreted as the congestion relief impact of public transport.

The motivation of the current research is to investigate how to measure public transport congestion relief by considering the spatial variation of mode shift to car use among public transport users. This research also examines factors influencing mode shift to car from public transport when public transport is no longer provided in the short term. Hence, the congestion relief impact provided by public transport in various regions can be assessed more precisely. In addition, this research develops enhanced methods to determine the negative effects of public transport operations in creating traffic congestion. Thus, a more comprehensive and balanced picture of the net impact of public transport in terms of congestion impact can be achieved.

1.3 Research Aim and Objectives

The overall aim of this research is to improve methods to estimate the short-term impact of public transport on traffic congestion. Hence, it is necessary to understand both the positive and negative effects of public transport on traffic congestion in order to assess the net effect.

The main objective of this thesis is to propose and test the applicability of a general framework based on traffic network modelling to assess the net short-term impact of public transport in terms of traffic congestion in an urban traffic environment. The methodology is based on the comparison of the level of congestion between a network 'with public transport' and 'without public transport' using a conventional four step model.

In order to achieve the main objective, four sub objectives have been established:

- Identify and understand the factors influencing mode shift from public transport to car when public transport is unavailable.
- Develop improved methods to estimate the positive impact of public transport on relieving traffic congestion.
- Develop improved methods to assess the net impact (including both positive and negative impact) of individual public transport modes (bus, tram and train) on traffic congestion.
- To understand the net short-term impact of the entire public transport system on traffic congestion.

1.4 Contribution and Implication

The major contribution of the research is the development of a more comprehensive methodology that can be used to measure the net traffic congestion effect associated with public transport in the short-term. Understanding the congestion impacts associated with public transport can help traffic authorities to identify the effectiveness of a public transport system in relieving congestion on congested routes or corridors. From that, policies or improvement projects related to public transport can be proposed to seek a desired level of congestion relief.

1.5 Scope of the Study

In this study, Melbourne is chosen as a case study to develop a methodology for exploring public transport congestion impacts. Melbourne has a population of 4.42 million people over nearly 2,000 km^2 (ABS, 2016b). There are 31 Local Government Areas (LGAs) in Melbourne (VicRoads, 2005) which are commonly grouped into three categories (inner, middle and outer). Melbourne has an integrated public transport system that extends from the city centre in all directions, with trains, trams and buses offering comprehensive public transport services. Melbourne's public transport system consists of tram, heavy rail and bus which carries 9% of all trips within the metropolitan area, or 11% when expressed in terms of passenger kilometres (Currie and Burke, 2013).

In order to investigate the congestion impacts associated with public transport, an existing strategic transport modelling platform (the Victorian Integrated Transport Model) is used to compare the congestion measures in two scenarios 'with public transport' and 'without public transport'. The increase in the level of traffic congestion is considered to represent the public transport congestion relief impact. This thesis does not attempt to create a new transport modelling platform. The Victorian Integrated Transport Model (VITM) is a conventional four-step model which has already been created to estimate travel demand in Victoria, Australia. The model is implemented in a CUBE software platform. VITM contains a number of sub-models which work together to create the required output for each link such as actual speed, volume and travel time. In this thesis, the benefit of public transport on traffic congestion is assessed in the morning peak hours (7am-9am) as the highest level of congestion is expected in this period. Thus, the greatest impact of public transport on traffic congestion can be investigated.

1.6 Outline of Thesis Structure

The thesis is structured into ten chapters including this introduction (Chapter 1), as shown in Figure 1.1. They are now described.

Chapter 2 – Literature Review, gives an overview of existing literature and highlights the key findings. The review focuses on knowledge in the field including: (i) measuring traffic congestion, (ii) assessing traffic congestion relief impact associated with public transport and (iii) estimating traffic congestion creation caused by public transport. Current gaps in knowledge are also identified in this chapter.

Chapter 3 – Research Methodology, provides the proposed framework for understanding the net effect of the entire public transport system in relieving traffic congestion. The framework includes four major stages: (i) an understanding of behavioural response of public transport users if public transport is unavailable in the short-term; (ii) a development of method estimating mode shift from public transport to private car for different regions and an estimation of congestion relief impact of public transport, (iii) an exploration of the net traffic congestion effect associated with individual public transport modes and (iv) the integration of both positive and negative impacts of the entire public transport system on traffic congestion.

Chapter 4 – Behavioural Modelling, give a better understanding on mode shift from public transport to alternative transport modes, particularly to private car, when public transport is not available in the short-term. A qualitative survey with 30 public transport users is first conducted to obtain an in-depth understand of why public transport users choose an alternative mode and explore factors affecting their choices. A field survey of 648 public transport users is then carried out to verify which factors have more significant influence on the mode shift than others.

Chapter 5 – Congestion Relief Modelling, develops methods for estimating the share of mode shift from public transport to private car for different regions using data obtained from the field survey and the secondary data. These mode shifts are then adopted in a transport network model to assess the positive effect of public transport on reducing traffic congestion by contrasting the congestion levels in two scenarios: ‘with public transport’ and ‘without public transport’.

Chapter 6 – Bus Impact Modelling, investigates the net network-wide impact of bus operations on traffic congestion. In this chapter, the effects of buses on generating congestion (the effects of bus stopping operations at bus stops and intersections) are assessed with the help of both micro-simulation and macro-simulation. These negative impacts are integrated with positive impact examined by adapted mode shift from bus to car in order to estimate the net congestion effect of buses.

Chapter 7 – Tram Impact Modelling, explores the net network-wide impact of tram operations on traffic congestion. In this chapter, the effects of trams on generating congestion (the effects of the slow speed of trams, the stop operations at curbside tram stops and intersections and the occupation of priority tram lanes) are assessed with the help of both micro-simulation and macro-simulation. These negative impacts are integrated with positive impact examined by adapted mode shift from tram to car to estimate the net congestion effect of trams.

Chapter 8 – Train Impact Modelling, examines the net network-wide impact of train operations on traffic congestion. In this chapter, the effects of trains on generating congestion (the effects of at-grades rail crossings) are assessed with the help of both micro-simulation and macro-simulation. These negative impacts are integrated with positive effect examined by adapted mode shift from train to private car to assess the net congestion effect of trains.

Chapter 9 – Integrated Modelling, integrates both positive and negative impacts of the entire public transport system on traffic in order to achieve a more comprehensive picture of the net impact of public transport in terms of congestion relief. In a scenario 'with public transport', a conventional four step model (VITM) which adopts the congestion generation impacts of individual public transport modes is used to estimate the level of congestion. In a scenario 'without public transport', the mode shifts from public transport to private car for different regions are adopted to represent the increase in the number of car trips on the road network. The level of congestion in two scenarios is contrasted to assess the net impact of public transport on traffic congestion.

Chapter 10 – Conclusions, provides a synthesis of key findings and the contribution of the research. Additionally, a critique of the research is presented and areas for future research are identified.

Table 1.1 List of papers related to the thesis

Chapter	No.	Publication title	Journal	Publication status
2	Paper 1	Traffic congestion relief consequent on public transport: The state of the art	Transport Reviews	*Returned for revision*
4	Paper 2	Understanding public transport user behavior adjustment if public transport ceases - A qualitative study	Transport Research Part F	*Published*
	Paper 3	Transit user reactions to major service withdrawal – A behavioural study	Transport Policy	*Published*
5	Paper 4	Congestion relief and public transport: An enhanced method using disaggregate mode shift evidence	Case Studies on Transport Policy	*Under review*
6	Paper 5	Net impact of bus operations on traffic congestion in Melbourne	Transportation Research Part A	*Returned for revision*
7	Paper 6	Local and system-wide traffic effects of urban road-rail level crossings: A new estimation technique	Journal of Transport Geography	*Published*
8	Paper 7	Net traffic congestion impacts of street car operations in Melbourne, Australia	Transportation Research Record	*Published*
9	Paper 8	Quantifying the net traffic congestion effect of urban public transport – Including both negative and positive effects	Public Transport	*Under review*

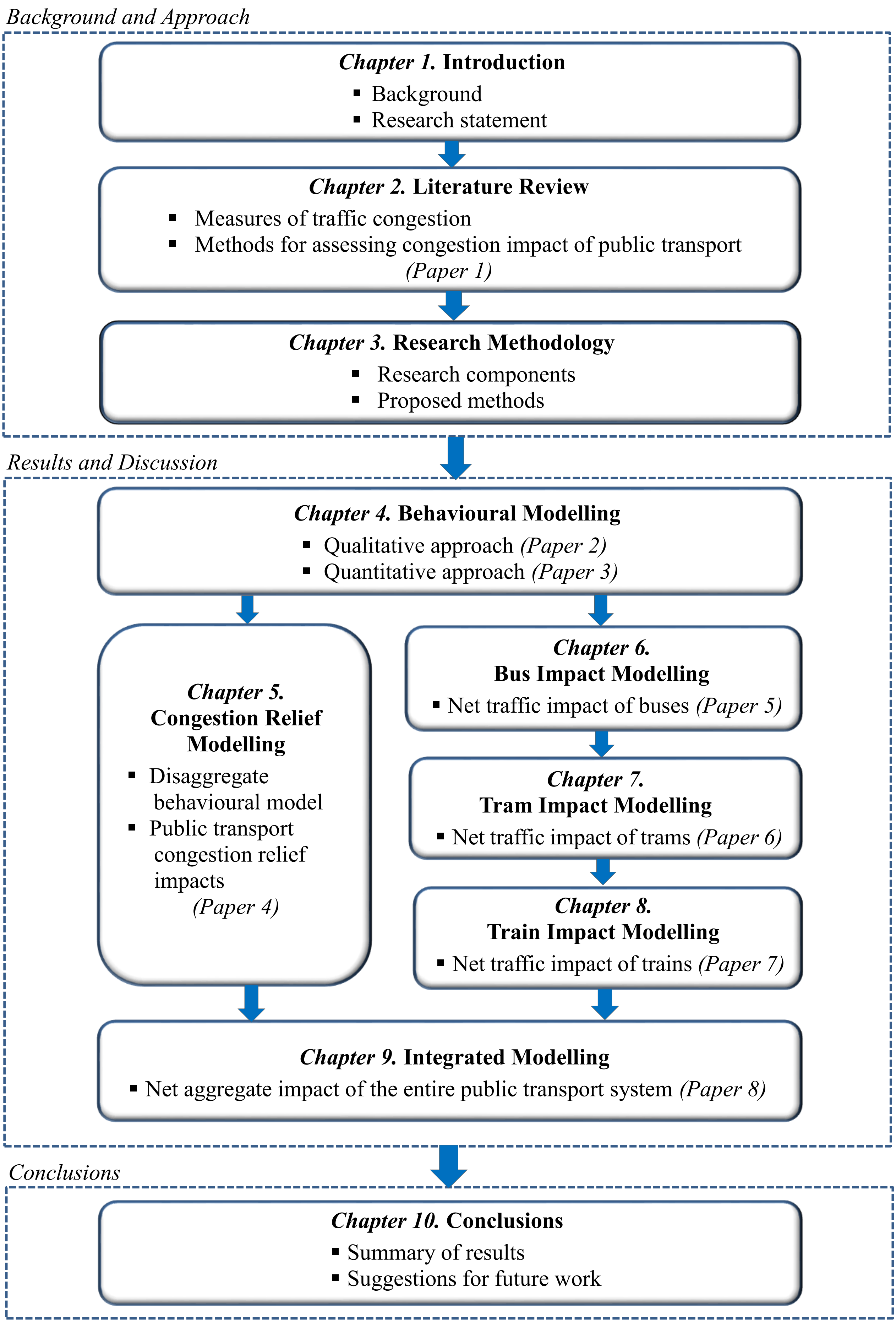
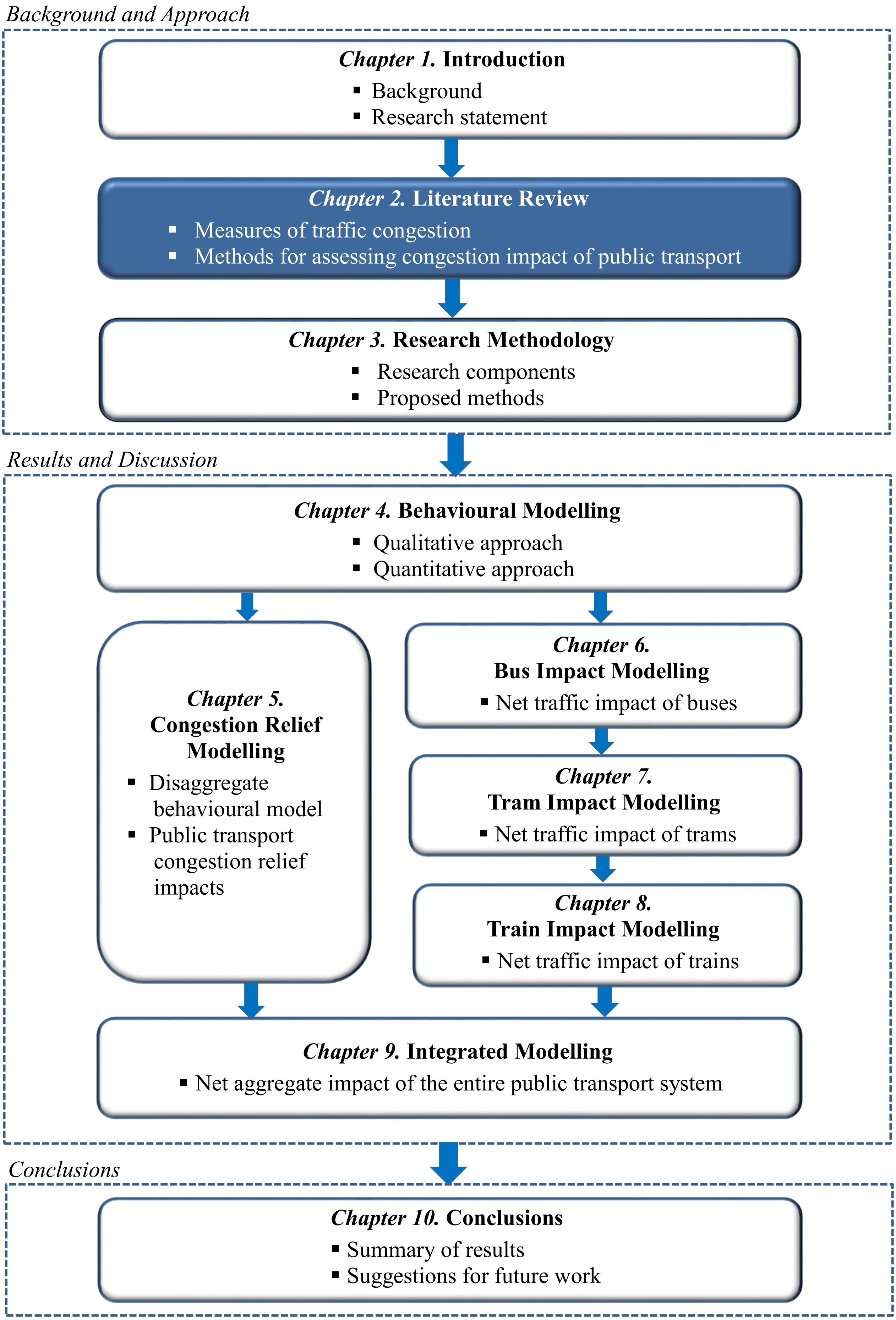


Figure 1.1 Structure of the thesis


Background and Approach
Chapter 1. Introduction
Background
Research statement
Chapter 2. Literature Review
Measures of traffic congestion
Methods for assessing congestion impact of public transport
Chapter 3. Research Methodology
Research components
Proposed methods
Results and Discussion
Chapter 4. Behavioural Modelling
Qualitative approach
Quantitative approach
Chapter 5. Congestion Relief Modelling
Disaggregate behavioural model
Public transport congestion relief impacts
Chapter 6. Bus Impact Modelling
Net traffic impact of buses
Chapter 7. Tram Impact Modelling
Net traffic impact of trams
Chapter 8. Train Impact Modelling
Net traffic impact of trains
Chapter 9. Integrated Modelling
Net aggregate impact of the entire public transport system
Conclusions
Chapter 10. Conclusions
Summary of results
Suggestions for future work

Chapter 2
LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of literature pertinent to the study of assessing the impacts of public transport on traffic congestion.

Investigating traffic congestion impacts associated with public transport requires a good understanding of two major areas:

- The measurement of traffic congestion; and
- The impact of public transport on traffic congestion.

Traffic congestion is a major urban transportation problem as it can be a barrier to economic growth (Douglas, 1993). The identification of the level of traffic congestion on a corridor or a road network can help road managers in the selection of appropriate mitigation measures. An efficient public transport system can be one of solutions for dealing with traffic congestion since it can reduce a number of car trips on the road network. However, some researchers have argued that current transportation evaluation practices tend to overlook and undervalue the benefits of public transport (Litman, 2015, Rubin and Mansour, 2013) due to the negative impacts that PT can have on creating congestion such as the operation of at-grade rail crossings (Okitsu and Lo, 2010, Taggart et al., 1987a), tram priority, bus stop operations (Chandler and Hoel, 2004, Rymer et al., 1989). In addition, it has been suggested that investments on PT are ineffective at reducing traffic congestion and financially wasteful (O'Toole, 2004, Stopher, 2004, Taylor, 2004). They believed that when a vehicle driver shifts mode to PT, another driver uses this open road space. In order to compare these arguments, understanding the net traffic congestion impact associated with PT is important. From that, routes or corridors facing congestion can be targeted for attention to obtain a desired level of congestion relief and appropriate public transport policies can encourage desired development in designated locations to achieve congestion relief. However, there are a limited number of studies assessing the impacts of public transport on traffic congestion.

In order to explore traffic congestion impacts associated with public transport, a review of the literature was undertaken with the objective of understanding:

- Definitions of traffic congestion (Section 2.2);

- Measurement of traffic congestion (Section 2.3);
- Major benefits of public transport (Section 2.4); and
- Prior studies on the impacts of public transport on traffic congestion (Section 2.5).

A journal paper was conducted based on the literature review of this research area as follows:

Paper 1 *Nguyen-Phuoc, D.Q., Currie, G., De Gruyter, C. & Young, W., 2017, 'Traffic congestion relief consequent on public transport: The state of the art',* ***Transport Review (under review, pass the 1st round, submitted the revision).***

Based on the above objectives, this chapter is organised as follows. Firstly, a review of various definitions of traffic congestion is presented. Following this, an account of indicators and thresholds used for assessing congestion measures is described. The benefits of public transport, particularly the contribution to congestion reduction, are then outlined. This is followed by a review of findings on public transport congestion impacts explored from previous studies. Finally, the chapter concludes with the identification of gaps in knowledge of public transport congestion relief impact and a discussion on available opportunities to advance knowledge in the areas identified.

2.2 Definitions of Traffic Congestion

In order to measure the level of traffic congestion, an understanding of definitions of traffic congestion is important. There have been a variety of congestion definitions proposed by scholars however none of them have been accepted as a universal definition (Downs, 2004). These definitions of traffic congestion can be categorised into four groups:

- Delay related;
- Demand related;
- Cost related; and
- Others.

Table 2.1 summarises the definitions of traffic congestion presented in published books and journals. There is no definition that presents the whole picture of traffic congestion. In terms of cause-effect, definitions related to demand can be considered the cause of congestion (demand exceeds capacity) while delay related definitions and cost related definitions can represent the effect of congestion.

Table 2.1 Definitions of traffic congestion

	Author	Definition
Demand related	Rosenbloom (1978)	Traffic congestion occurs when travel demand exceeds the existing road system's capacity.
	Pucher et al. (1979)	Congestion denotes any condition in which demand for a facility exceeds free-flow capacity at maximum design speed.
	Rothenberg (1985)	Congestion is a condition in which the number of vehicles attempting to use a roadway at any time exceeds the ability of the roadways to carry the load at generally acceptable service levels
	Vaziri (2002)	Congestion occurs when traffic demand approaches and exceeds highway capacity.
Delay related	Meyer (1997)	Congestion means there are more people trying to use a given transportation facility during a specific period of time than the facility can handle with what are considered acceptable levels of delay or inconvenience.
	Lomax (1997)	Traffic congestion is travel time or delay in excess of that normally incurred under light or free-flow travel conditions.
	Weisbrod et al. (2001)	Traffic congestion is a condition of traffic delay (when the flow of traffic is slowed below reasonable speeds) because the number of vehicles trying to use the road exceeds the traffic network capacity to handle those.
	Downs (2004)	Traffic congestion occurs when traffic is moving at speeds below the designed capacity of a roadway.
	Lee and Vuchic (2005)	Congestion is the phenomenon of increases in auto travel time due to increased travel demand
	Falcocchio and Levinson (2015)	Congestion in transportation occurs when the occupancy of spaces by vehicles or people reaches unacceptable levels of discomfort and delay.
Cost related	Litman (2000)	Traffic congestion represents the incremental costs resulting from interference among road users
	Vuchic et al. (1998), Verhoef (2000), Kockelman and Kalmanje (2005)	Congestion can be viewed as the result from under-pricing of the road network and marginal cost pricing can be used to internalise the congestion externality.
Other	Homburger et al. (1996)	Congestion is the level at which transportation system performance is no longer acceptable due to traffic interference. This may vary by type of transportation facility, geographic location, and time of day.
	Naudé and Tsolakis (2005)	Congestion may be regarded as the point at which an additional road user joins the traffic flow and affects marginal cost in such a way that marginal social cost of road use exceeds the marginal private cost of road use at the "optimal" level of congestion.

Source: Author's synthesis of the literature based on citations with in the table.

According to Calderdale Council (2015), traffic congestion is an inherently difficult concept to define as it has both physical and relative dimensions. In physical terms, congestion can be explained as the way in which vehicles interact to impede other vehicles. These interactions and their influence on individual journeys usually increase as travel demand approaches the capacity of a road or when capacity itself is reduced through road works or public transport operations (such as priority tram lanes) for example. However, the physical definition ignores that congestion can mean very different things to different people. For instance, a person living in a rural area might regard an unusually long queue of traffic experienced on their daily commute as severe congestion, while someone living in an urban area might experience much longer hold-ups on a daily basis and regard the same length queue as being almost totally uncongested. In a relative perspective, congestion can therefore also be defined in terms of the difference between the expectations of road users about the road network and how it actually performs.

2.3 Measures of Traffic Congestion

2.3.1 Congestion Indicators and Metrics

Congestion can be categorised by four aspects of its occurrence: intensity, duration, extent and variability (Lomax, 1997, Systematics, 2008, Schuman, 2011).

- **Intensity**: measures the amount of congestion delay experienced at an intersection approach, sections of route, several routes or an entire urban area (Falcocchio and Levinson, 2015). Its metrics are expressed as a rate (e.g. minutes/km) and consist of: congestion travel delay, vehicle-hours of delay, person-hours of delay, a travel time index or a travel rate index.
- **Duration**: reflects the amount of time that a road or system is congested. The duration of congestion depends upon the types of congestion (recurring or non-recurring). City size and type of roadways also impact congestion duration. Congestion is generally of long duration on major roadways in large urban areas due to high traffic volume. In contrast, duration is less frequent in small urban areas. The amount of congested time (e.g. hours or minutes) is one of key metrics used to measure this perspective of traffic congestion.
- **Extent**: measures how far congestion spread (the length of roads, the number of roads, the percentage of roads that are congested), and how many system users or components (vehicles, roads etc.) are influenced by congestion. The extent of congestion varies by the size of urban areas and the type of roadways. Freeways generally experience more delay

than other types of road as it usually accounts for about half of all urban travel in US (Schrank et al., 2012).

- **Variability:** accesses the variation in the amount, duration and extent of congestion over time.

Table 2.2 summarises congestion indicators and their metrics for measuring traffic congestion. There are a variety of congestion metrics which represent different perspectives and assumptions. Some metrics are used on route-based or whole area-based analysis. Some metrics reflect per capita or per vehicle impact and others reflect the gross impact. Hence, based on the objective of measuring congestion and the availability of the required data, appropriate measures will be used.

Table 2.2 Overview of congestion indicators and their metrics

Congestion aspect	System type		
	Single roadway	Corridor	Area wide network
Intensity (e.g., level or total amount of congestion)	Travel rate; delay rate; relative delay rate; minute-miles; lane-mile hours	Average speed or travel rate; delay per PMT; delay ratio	Accessibility; total delay in person-hours; delay per person; delay per PMT
Duration (e.g., amount of time system is congested)	Hours facility operates below acceptable speed	Hours facility operates below acceptable speed	Set of travel time contour maps; “bandwidth” maps showing amount of congested time for system sections
Extent (e.g., number of people affected or geographic distribution)	% or amount of congested VMT or PMT; % or lane-miles of congested road	% of VMT or PMT in congestion; % or miles of congested road	% of trips in congestion: person-miles or person-hours of congestion; % or lane miles of congested road
Variability (e.g., variation in the amount of congestion)	Average travel rate or speed ± standard deviation; delay ± standard deviation	Average travel rate or speed ± standard deviation; delay ± standard deviation	Travel time contour maps with variation lines; average travel/time ± standard deviation; delay ± standard deviation

Note: VMT: vehicle-miles of travel, PMT: person-miles of travel
Source: NCHRP 398, Vol. 1, Table S-5, p7 (Lomax et al., 1997)

2.3.2 Congestion Thresholds

Traffic congestion reflects the difference between road traffic conditions (such as travel time, volume/capacity) during busy traffic periods and when the road is lightly travelled. In order to identify the traffic congestion of a roadway or an area, threshold values have been introduced.

According to Falcocchio and Levinson (2015) traffic congestion thresholds can be defined of as follows:

i. Using free-flow speed as a congestion threshold or,
ii. Establishing acceptable minimum speed for various types of facilities and operating environs.

Using free-flow speed as a threshold for congestion might be suitable for rural areas and off-peak periods. In large urban areas where traffic congestion occurs frequently, particularly in peak hours, the toleration of travellers with congestion can be higher than those in rural areas, so free-flow speed might not be appropriate to use as a congestion threshold. The thresholds for 'tolerable' congestion levels can be set by traffic authorities for each type of roadway (Falcocchio and Levinson, 2015). Fox example:

- Lindley (1987) used a volume to capacity (V/C) ratio of 0.77 as a threshold for congestion (or the speed of 55 mph corresponding to V/C ratio of 0.77).
- Lomax et al. (1999) used the 85^{th} percentile speed in the off-peak period as the free-flow speed.
- Hall and Vyas (2000) considered the posted speed limit as the nominal free-flow speed for comparing with congested speed.
- Lomax and Schrank (2005) used 60 mph for freeways and 35mph for arterial roads as free-flow speed.
- According to WSDT (2011), congestion thresholds were established as 75% of posted speed limits.
- SEMCOG (2011) also used V/C ratio to identify the traffic congestion on roadway links. SEMCOG (2011) considers a roadway link congested if the V/C ratio is greater than 0.80. The relationships between V/C ratio and different levels of congestion are shown in Table 2.3:

Table 2.3 Congestion threshold (SEMCOG, 2011)

V/C Ratio	Congestion level
V/C <= 0.8	No/low congestion
V/C > 0.8 and <= 0.9	Moderate congestion
V/C > 0.9 and <= 1.0	High congestion
V/C > 1.0	Severe congestion

2.4 Benefits of Public Transport

Public transport is a shared passenger-transport service which is available for use by the general public. It consists of a variety of transport services such as trams, buses, trains or ferries. The services of public transport provide various benefits for the modern transport system such as relieving traffic congestion, increasing traffic safety, reducing air and noise pollution, improving accessibility (Litman, 2015). It is sometimes suggested that investments on public transport are ineffective at reducing traffic congestion and financially wasteful (O'Toole, 2004, Stopher, 2004, Taylor, 2004). They believed that when a driver shifts onto public transport, another one quickly grabs the open road space. However, some authors have suggested that high quality, grade-separated public transport would reduce traffic congestion and that improvement in urban public transport can be a cost-effective investment when considering all economic effects (Litman, 2007).

In terms of relieving traffic congestion, Winston and Langer (2006) indicated that there is a reduction in motorist and truck congestion costs in a city when the rail network is expanded. Castelazo and Garrett (2004) found that the establishment of new light rail service in several US cities resulted in the decline in traffic congestion growth rates. By using a regional transport model, Nelson et al. (2007) found that the Metro rail service in Washington DC created congestion-reduction benefits that exceeded rail subsidies. Other research by Litman (2004b) indicated that per capita congestion delay was significantly lower in cities with high quality rail transit systems than in others with little or no rail service.

Other benefits of public transport were also investigated in a series of studies;

- The effect of public transport on reducing road accidents was explored by Karim et al. (2012), Lalive et al. (2013) and Stimpson et al. (2014). Karim et al. (2012) found that crash rates decreased significantly with the increase in transit commute mode share, percentage of transit-km traveled relative to total vehicle-kms traveled and bus stop density. Lalive et al. (2013) found that if rail service frequency increased by 10%, road accidents reduced by around 4.6%. Another study analyzing data from 100 cities in America showed that each 10% increase in public transport's share of urban passenger travel was associated with 1.5% reduction in motor vehicle fatalities (Stimpson et al., 2014).
- An individual's health can benefit from the use of public transport. Walking to a train or bus stop can increase the amount of daily exercise undertaken which reduced a large number of health risks such as diabetes, hypertension, obesity, and some cancers. MacDonald et al. (2010) estimated the public health cost savings caused by a new light rail transit system in Charlotte, North Carolina. They found that the light rail system could save $12.6 million in

public health costs over nine years.

- Public transport was also recognised to be an efficient solution to reduce energy consumption and pollution emissions (Chester and Horvath, 2008, Davis and Hale, 2007, Gallivan et al., 2015, Potter, 2003). High benefits result if public transport is designed for efficiency such as public transport was provided on major urban corridors or public transport where traffic priority measures were applied. According to Shapiro et al. (2002), urban public transport operations consumed about half the energy and produced approximately 5% as much CO, 50% the CO_2 and NO_x emissions per passenger-mile as an average automobile. Bailey (2007) stated that by switching from automobile-dependent to transit-oriented development, a typical household can reduce its energy consumption and pollution emissions by approximately 45%. Bailey et al. (2008) found that public transport in US can reduce about 37 million metric tons of CO_2 equivalent emissions annually by reducing vehicle miles travelled.

Table 2.4 summarises the benefits that public transport services can provide (Litman, 2004b, Litman, 2004a, Litman, 2015). It can be seen that, the operation of public transport can results in a number of positive effects in different areas such as economy, society, land use and environment.

Table 2.4 Summary of public transport benefits

Benefits	Description
Congestion reduction	Reduced traffic congestion
Facility cost savings	Reduced road and parking facility costs
Consumer savings	Reduced consumer transportation costs
Transport diversity	Improved transportation options, particularly for non-drivers
Road safety	Reduced per capita traffic crash rates
Environmental quality	Reduced pollution emissions and habitat degradation
Efficient land use	More compact development, reduced sprawl
Economic development	Efficiencies of agglomeration, increases productivity and wealth
Community cohesion	Positive interactions among people in a community
Public health	More physical activity (particularly walking) increases fitness and health

Source: Litman, 2004b, Litman, 2004a, Litman, 2015

2.5 Impacts of Public Transport on Traffic Congestion

Public transport has both positive and negative impacts on traffic congestion. A description of each of these impacts is provided in the following sub-sections, including methods used for assessing them and their associated results.

2.5.1 Impact of Public Transport on reducing Traffic Congestion

The value of public transport in terms of traffic congestion relief is often demonstrated by contrasting the level of congestion in two scenarios: 'with public transport' and 'without public transport'. In the scenario of 'without public transport', it can be seen that the public transport withdrawal would result in mode shift from public transport to car which increases the level of congestion. The increase in the congestion level is considered the benefit of public transport in acting to reduce traffic congestion. Thus, mode shift to car when public transport is removed is recognised to be a key parameter used to estimate public transport congestion relief impact.

2.5.1.1 Mode Shift when Public Transport is unavailable

There are a number of studies investigating mode shift to car from public transport (Hagman, 2003, Mann and Abraham, 2006, Beirao and Cabral, 2007, Guiver, 2007, Gardner and Abraham, 2007). However, only a few published studies focus on the travel mode shift of users when public transport withdrawal occurs. Mode shift is often explored in the event of public transport strikes. Exel and Rietveld (2001) reviewed 13 studies of public transport strikes between 1966 and 2000 in Europe and the United States to explore the behavioural response of public transport users. The impact of public transport strikes varied depending on the type of strike, travel patterns and policy responses. They found that when public transport ceased, public transport travellers would switch to car (ranging from 20%-67% of public transport users), switch to other modes (23%-51%) or cancel their trips (15%-67%). In 2003, HLB Decision Economics developed a methodology to estimate the economic value of public transport trips by comparing the difference between this value in two situations, 'with public transport' and 'without public transport' (WDOT, 2003). A field survey was conducted in Wisconsin, America to examine the choices that public transport riders might make if all public transport was unavailable. The findings showed that 3.7%-14.6% of public transport users would shift to car as a driver while 9%-14.8% would switch to car as a passenger in the absence of public transport. These figures varied depending on trip purposes.

Table 2.5 summarises the literature-identified behavioural response of users for a number of public transport strikes around the world. It shows that there is a wide range in the mode shift to car as a driver (5%-50%), which would directly contribute to an increase in traffic congestion. This can be due to the difference in demographic and trip characteristics of public transport users in a particular area. For example, in the event of a urban public transport strike in Leeds (UK) in 1978, only 5% of users shifted to a car as a driver (Exel and Rietveld, 2001). This was due to the low rate of household car ownership in the UK at the time (55%) and a majority of public transport users who had no car in their households (Exel and Rietveld, 2001). The difference in the accessibility of information regarding public transport disruptions can result in difference in mode shift. Papangelis et al (2016) found that this information had strong impact on alternative mode choice during public transport disruptions. The data in Table 2.5 shows that the share of trip cancelling during public transport disruptions from 1966 to 1998 was very low (5%-10%). However, this proportion was much higher (44%-67%) when travelers have accessed to more information regarding public transport withdrawals such as information that was provided by social media. With the accessibility of relevant information, travelers had more time to arrange their work prior to the occurrence of public transport disruptions. They can change the trips to other days or work from home.

Table 2.5 Evidence of mode shift when public transport was unavailable

Source	Year	Location	PT mode removed	Mode shift to car		Cancel trip
				As a driver	As a passenger	
Exel and Rietveld (2001)	1966	New York, USA	All	50%	17%	10%
	1974	Los Angeles, USA	Bus	50%	25%	---
	1978	Leeds, UK	All	5%	60%	15%
	1981	The Hague, Netherlands	All	10%	25%	5%
	1995	Ile-de-France, France	All	28%	21%	11%
	1995	The Netherlands	Bus	30%		10%
	1998	Norway	Bus	20 %[a] , 40 - 60%[b]		---
HLB Decision Economics (2003)	2001	Wisconsin, USA	All	8%[c] (3.7%-14.6%)	12%[c] (9%-14.8%)	56%[c] (52%-67.3%)
Exel and Rietveld (2009)	2004	The Netherlands	Train	24%	14%	44%

[a] Urban traffic
[b] Interurban traffic
[c] Average value
Source: Author's synthesis of the literature based on citations with in the table.

More recently, only two studies have explored factors affecting mode shift from public transport in the event of public transport cancellations (Table 2.6). Exel and Rietveld (2009b) carried out secondary analysis on data collected from 976 people who had planned to travel by train on the day of a national rail strike in the Netherlands in 2004. The study aimed to investigate the actual behavioural reactions of train travellers to the rail strike and explored the characteristics of travellers and trips that affect chosen alternatives. They found that 24% of the train travellers shifted to a car as a driver, 14% shifted to another mode and 18% decided to reschedule their trips to another day. Overall, 44% of trips were cancelled on that day. A multinomial logit regression showed that age, gender, trip distance, frequency of train use and trip purpose had an impact on the behavioural response of users when train operations ceased. However, the analysis in this study focused only on a limited number of variables that were available through secondary data and did not include important variables such as driver license holding, car ownership, or accessibility.

More recently, Pnevmatikou et al. explored the changes in travel patterns of metro users during and following a 5-month metro disruption (Pnevmatikou et al., 2015). Data was collected from two surveys (revealed preference and stated preference) carried out in Athens, Greece in 2011. Only three major alternative modes were considered in this study: bus, private car and taxi. Cancelling the trip was not considered because the proportion choosing this option was low (less than 2%) as the metro disruption was programmed for a long period. A multinomial logit model and a nested logit model were developed to analyse the travellers' behaviour and mode choice during metro disruptions. They found that gender, income, trip purpose, travel cost and transfer inconvenience were important factors impacting mode decisions.

Table 2.6 Factors affecting mode shift when public transport was unavailable

Source	Location	Public transport mode removed	Method	Survey data	Factors affecting mode shift
Exel and Rietveld (2009b)	The Netherlands	Train	Quantitative	Secondary	Age, gender, trip distance, frequency of train use and trip purpose
Pnevmatikou et al. (2015)	Athens, Greece	Train	Quantitative	Primary	Gender, income, trip purpose, travel cost, transfer inconvenience

Source: Author's synthesis of the literature based on citations with in the table.

2.5.1.2 Reductions in Traffic Congestion due to Public Transport

Traffic congestion relief of public transport was first explored by Lo and Hall (2006). In order to investigate the benefit of public transport systems, they explored the impact of transit strikes that took place in Los Angeles over a 35-day period in October and November, 2003. Traffic conditions during the strike were measured to understand how transit actually affects congestion experienced by drivers. They measured traffic speed on freeways before and after the strike by using various sensors. They found that there was a traffic speed decrease of 20% during the strike. Parry and Small (2009) estimated the optimal transit operating subsidy by developing an analytical model of a transportation system. One input of the model is the impact of public transport on reducing traffic congestion. In order to determine this effect, they assumed that each passenger mile travelled on public transport diverts nearly 0.9 passenger miles from roadways. The outcome from their model suggests that the public transport system reduces the travel delay by 5%. In 2012, the annual urban mobility report from the Texas Transportation Institute explored the effect of public transport on saving road travel time for 498 urban areas in America (Schrank et al., 2012). In this report, all commuter rail travellers were assumed to shift to private cars travelling on freeways if a public transport service shutdown occurs. The report showed that if a public transport service is eliminated, the riders would contribute an additional 865 million hours of delay or approximately a 15% increase in the total delay in the 498 urban areas. Another study that measured the congestion relief benefit of public transport at a corridor level came from Washington, D.C (FTA, 2000). Both of these studies are aggregated in nature (citywide and/or corridor level), and their fundamental assumption for measuring congestion relief benefit is that all public transport users switch to private vehicle when the public transport service does not exist. These methodologies might be considered limited or simplistic as there are still many alternative transport modes that public transport riders can choose other than a car.

Anderson (2013) explored whether public transport generates a much larger congestion relief impact than earlier estimates. Using a choice model and data from a sudden strike in 2003 by Los Angeles transit workers, he predicts that public transport travellers are likely to drive on routes with the most travel delay. A regression discontinuity design is then used to calculate the travel delay if public transport is not available. He found that the average highway delay would increase by 47% when public transport ceases. Ewing, Tian and Spain (2014) investigated the effects that Salt Lake City's University TRAX light-rail system has on vehicle traffic on parallel roadways. This rail system began operating in 2001 and expanded over the following decades with new lines and stations. It currently carries about 53,000 average daily passengers. The study found significant declines in roadway traffic after the LRT line was completed, despite significant development in the area. The study estimates that the LRT line reduced daily vehicle traffic on the study corridor about 50%, from 44,000 (if the line did not exist) to 22,300 (current travel).

More recently, Moylan et al. (2016) investigated the impacts of rapid transit in the San Francisco Bay Area region on roadway travel demand and travel time when the public transport services are suspended during a strike. Thus, the benefits of public transport experienced by drivers could be examined. In order to estimate the lower bound of the impact, they compared traffic volumes, which were collected from a system of 2,000 buried-loop-detector stations on freeways during strikes, against observations from the same time and day of week throughout the year. The upper bound of the impact was measured using a non-parametric modelling technique to compare the travel time distributions associated with the current traffic volume and increased demand. They assumed that <u>all</u> public transport users with access to a car would shift to driving alone. They found that at the network level, the impacts of the transit strike were <u>not</u> significant. However, on roads running parallel to public transport services, there were significant delays, particularly in the peak periods. Morning peak conditions on a parallel road (Highway 24) were nearly at the 80th percentile of annual volume-weighted travel times.

Aftabuzzaman et al. (2010a) demonstrated that in practice not all public transport users would shift to use a car if public transport is removed. Indeed, they assembled real world evidence that only a share of public transport riders could switch to private car. From a study of secondary research, they suggested that on average 32% of public transport users would shift to car use. They adopted this as a fixed value for all trips and applied it to a transport network model in Melbourne to estimate the congestion relief impact associated with public transport. Some 32% of public transport trips was added to the existing car trip matrix and this was then assigned to the road network. They applied this on a fixed basis for all trip ends in the model. Results found that removing public transport is estimated to increase the number of congested links by about 1,400 or 30%. A summary of research on assessing public transport congestion relief is presented in Table 2.7.

Table 2.7 Traffic congestion relief associated with public transport

Source	Location	Method	Mode shift to car	Other results
Crain and Flynn (1975a)	Los Angeles	Observing the traffic condition during the strike		On one important freeway, the additional delay was 10-15 min in morning peak
Lo and Hall (2006)	Los Angeles	Observing the traffic condition during the strike		A traffic speed decrease of 20% during the strike
Parry and Small (2009)		Developing an analytical model of a transportation system		Public transport system reduces the travel delay by 5%
Aftabuzzaman et al. (2010a)	Melbourne, Australia	Comparing the level of congestion in two scenarios: “with” and “without” public transport using a regional transport network model	32%	Removing public transport is estimated to increase the number of congested links by about 1,400 or 30%
Schrank et al. (2012)	498 urban areas in America	All commuter rail travellers are assumed to shift to private cars travelling on freeways if a public transport service shutdown occurs	100%	The total delay increases 15%
Anderson (2013)	Los Angeles	Using a choice model and data from a sudden strike		The average highway delay would increase 47% when public transport ceases
Ewing, Tian and Spain (2014)		Comparing vehicle traffic before and after the operation of a LRT		Daily vehicle traffic on the study corridor reduces about 50%
Adler and Van Ommeren (2015)	Rotterdam, Netherlands	Observing the traffic condition during multiple PT strikes	-	Average car speed on highway ring road decreases 3%, on inner city roads reduces 10%. Car speed was measured by independent speed measurements

Moylan et al. (2016)	San Francisco	Comparing travel time before and during the public transport strike using data from detectors and a non-parametric modelling technique	100%	Morning peak conditions on a parallel road were nearly at the 80th percentile of annual volume-weighted travel times

Source: Author's synthesis of the literature based on citations with in the table.

Mode shift from public transport to car is considered a key parameter used for estimating the public transport congestion relief impact (Aftabuzzaman et al., 2010a, Aftabuzzaman et al., 2010b). Most previous studies assessing public transport congestion relief impact used a simplistic assumption, a fixed share of mode shift to car if public transport was not available. However, the literature shows that the mode shift to car varies for cities around the world and is influenced by demographic and trip characteristics of public transport users. Thus, identifying factors affecting mode shift is needed. A better understanding can help to vary the share of mode shift to car when public transport is unavailable for different areas (e.g. inner, middle and outer city). Hence, a more precise methodology for estimating the impacts of public transport on relieving traffic congestion can be developed. This gap will be addressed in Chapter 4 and Chapter 5.

2.5.2 Impact of Public Transport on creating Traffic Congestion

Although public transport is often considered to be an effective measure to mitigate traffic congestion, the operation of public transport also has some negative effects on traffic flow. In this sub-section, a detailed literature review of academic research papers and industry reports relating to the impact of bus operations, tram operations and train operation is undertaken.

2.5.2.1 Negative Traffic Impact of Bus Operations

The effect of bus operations on creating traffic congestion includes the effects of bus stop operations and the impacts of priority bus systems such as exclusive bus lanes and priority signal for buses.

The effect of bus stops on traffic flow has received a great deal of research attention. Table 2.8 summarises research on estimating traffic delay resulting from bus stop operations (at both curbside stops and bus bay stops). In the literature, there are a wide range of parameters explored to assess traffic delay caused by bus stop operations such as dwell time, bus frequency, the location of bus stops, the type of bus stops, the number of lanes and the components of the heterogeneous traffic flow. However, most studies have only considered selected parameters in their research. Theoretical models such as Cellular Automata (CA) models have been frequently used to simulate the impact of bus operations at bus stops on traffic flow (Zhao et al., 2007, Yuan et al., 2007, Tang et al., 2009, Xia and Xue, 2010). Other researchers investigated bus stop impact on vehicle traffic by collecting field data and using statistical models to find the relationship between the impact and bus parameters (such as bus frequency, bus dwell time) (Kwami et al., 2009). However, the wide range of data related to bus stops is very difficult to collect in the field. Traffic simulation is therefore recognised as an effective method to analyse the effect of a wide range of parameters on traffic flow near bus stops (Fitzpatrick and Nowlin, 1997, Koshy and Arasan, 2005, Ben-Edigbe and Mashros, 2011).

From the literature review, bus stops have been recognised to have impacts on the traffic flow and these impacts are different regarding to the type of bus stops, traffic conditions and bus parameters. Most studies have considered dwell time as one of key parameters to estimate the impact of bus stops. The effect of bus arrival frequency, bus speed, traffic volume and stream speed have not been received much consideration. Therefore, a model that can consider the impact of a wide range parameters on the assessment of traffic delay associated with bus stops is needed.

Table 2.8 Traffic delay caused by bus stopping operations

Authors	Parameters used to estimate the impact of bus stop operations	Type of bus stops considered	Methodology	Findings
Fitzpatrick and Nowlin (1997)	- Dwell time - Type of bus stops - Traffic volume	- Curbside - Bus bay	Use traffic simulation program (TexSIM) to determine the impact of bus design on traffic operation around bus stops	The average vehicle speed in midblock bus bay design is higher than that in curbside design from approximately 2 to 19 km/h The average vehicle speed in far-side bus bay design is higher than that in curbside design from approximately 0 to 15 km/h
Koshy and Arasan (2005)	- Dwell time - Traffic volume	- Curbside - Bus bay	Develop a microscopic simulation model (Hetero-Sim) to analyse the impact of bus stops on heterogeneous traffic flow	The results are graphs that show the reduction in traffic stream speed on a 7.5 wide road near curbside stop and bus bay for various bus dwell times and traffic volumes
Zhao et al. (2007)	- Distance from bus stops to intersections - Dwell time - Traffic light cycle	- Curbside - Bus bay	Use cellular automaton (CA) model and simulation to explore the combined effect of signal controlled intersection and near-	For cubside bus stops, the road capacity decreases when the distance from bus stops to intersections decreases, the dwell time and traffic light cycle

			by bus stop	increase Bus bay stops reduce road capacity less than curbside bus stops. The capacity of approaches with near-side bus bay stops is appreciably less than that with the far-side bus bay stops
Yuan et al. (2007)	- Density - Number of bus stops	- Curbside	Use modified comfortable driving (MCD) model and simulation to investigate a two-lane traffic system consisting of a mixture of buses and cars	A fundamental diagram showing the dependent of road capacity on the number of bus stops
Kwami et al. (2009)	- Bus arrival frequency - Bus impact time (time taken by the bus to decelerate to bus bay stop and stop + time taken by the bus to accelerate to re-enter or join the traffic at the curb lane)	- Bus bay	Develop a statistical relationship between average bus impact times and average bus arrival frequencies using field data collected from 15 bus bay stops in Beijing, China	The increase in bus arrival frequency results in the decrease in the actual curb lane traffic capacity. A formula which predicts the actual curb lane traffic capacity with bus bay stops based on the bus arrival frequency was also conducted.
Tang et al. (2009)	- Arrival rate of passengers - Bus density - Number of bus stop on road section	- Curbside	Develop one car-following model and one macro numerical model to study traffic interruption based on the effects of the traffic interruptions probability on the car-following behaviour	Numerical results showed that bus density and the arrival rate of passengers are important factors contributing to the interruption probability of traffic causes by bus stops. Initial density and the number of bus stops were found to have significant impacts on traffic flow
Yong-Sheng et al. (2010)	- Bus frequency - Dwell time - Traffic flow	- Curbside	Use traffic flow, cellular automata (CA) theory and simulation to examine the effects of transit stops on vehicle speeds and conversion lane numbers in a mixed traffic lane	They found that bus dwell time is an important factor effecting the traffic flow near bus stops

Yang et al. (2011)	- Dwell time - Flow rate of bus and bicycle	- Curbside	Use a theoretical approach developed on the basic of additive-conflict-flows (ACF) procedure to determine the impact of curbside bus stops on car capacity with mixed traffic	Numerical results showed that car capacity decreases with the increasing flow rates of bus stream and bicycle stream
Sun (2011)	- Safe margin distance.	- Curbside	Use a simulation model exploring the traffic flow characteristics on road section and a discrete-time simulation method to estimate the effect of bus stopping	The results provide a suitable tool to understand the mechanism of traffic congestion on the blocks.
Ben-Edigbe and Mashros (2011)	- Traffic volume - Speed	- Curbside	Use field data collected in different locations in Skudai Town, Malaysia to determine capacity loss and traffic shockwaves associated with bus stop locations along the carriageway lane of a single lane highway	They estimated that curbside bus stops on a single lane highway resulted in a roadway capacity loss of 23.4 % and -25km/h propagation velocity of shock wave
Gu et al. (2013)	- Capacity of road - Distance from bus stops to intersections - Dwell time - Green time - Length of signal cycle time - Wave speed in a car queue	- Curbside	Formulate a model using kinematic wave theory to explore the impact of near-side bus stops on traffic delay	They provided a graph showing additional car delay caused by bus stops versus distance from bus stops to intersections
Chand et al. (2014)	- Bus frequency - Dwell time	- Curbside	Analyse field data collected at six-lane urban roads in New Delhi, India using videography method to investigate the impact of curbside bus stops on mixed traffic	Graphs showing the relationship between bus frequency and capacity reduction, dwell time and capacity reduction were provided. Road capacity near bus stops reduces 8% to 13% due to curbside bus stops

Source: Author’s synthesis of the literature based on citations with in the table.

Exclusive bus lanes are one of many measures to improve the speed and reliability of public transport services (Chen et al., 2010, Deng and Nelson, 2011, Nelson et al., 1993). However, some applications are controversial as they may cause a reduction of road capacity for general traffic and increase the level of traffic congestion. The effect of bus lanes on traffic was evaluated in many studies using field survey or simulation (Chen et al., 2010, Cherry et al., 2005, Shalaby, 1999, Patankar et al., 2007, Mulley et al., 2008, Barker and Polzin, 2004). However, this effect is not considered in this thesis as the number of exclusive bus lanes accounted for a small proportion of Melbourne's bus network.

2.5.2.2 Negative Traffic Impact of Tram Operations

In terms of exploring the negative effects of tram operations on congestion, Chandler and Hoel (2004) investigated the effects of light rail crossings on average delays experienced by vehicles using microsimulation. This topic was also explored by Rymer et al. (1989). Currie and his colleagues estimated the impact of curbside stops on the efficient use of road space (Currie et al., unpublished data on VicRoads R&D Project 799, 2004). They compared tram operations on roads "with" and "without" curbside stops using traffic simulation. They found that curbside stops reduce average tram and traffic speeds by between 8% to 12%.

The provision of segregated tram lanes has been identified as an efficient means of improving transit reliability and running times when transit vehicles share road space with congested urban traffic (Vuchic, 2007). However, the reallocation of a proportion of the road space to public transport lanes reduces road capacity and can increase the level of traffic congestion (Kittelson, 2003). Cairns et al. (1998) examined around sixty locations where road space was allocated to tram lanes or bus lanes. They found that on average the traffic volume on routes affected by the reallocation of road space decreased by between 14% to 25%. In 2003, Currie and his colleagues used traffic microsimulation to investigate the on-road operational implications of alternative transit priority measures. From the findings of simulation modelling, they developed a framework to estimate the benefits and costs of priority measures to transit and traffic (Currie et al., 2007).

2.5.2.3 Negative Traffic Impact of Train Operations

The impact of train operations, particularly at-grade rail crossings, is a major concern for traffic authorities in cities with a large number of level crossings. There are a number of studies investigating the safety, social and environmental impacts of at-grade rail crossings, studies about traffic congestion impact assessment is very limited. In NCHRP Report 288, Taggart et al. (1987b) explored some formulas for calculating the travel delay experienced by each vehicle at an at-grade crossing. These equations are based on the average annual train, vehicular traffic and the closure time that is calculated from average train length and the average train speed at the crossing. Hakkert and Gitelman (1997) developed a simplified tool for evaluating level crossings in Israel. From the field data collected at the 31 most problematic locations, they calculated the cost of safety problems and travel delay and used them for comparing level crossings. Schrader and Hoffpauer (2001) created a methodology for considering the prioritization of potential highway–railway grade separation locations in Central Arkansas. In this method, delay at at-grade rail crossings is one of seven factors and estimated by a formula developed by Taggart et al. (1987b). Microsimulation is recognised to be a popular tool for assessing the travel delay of road vehicles associated with at-grade rail crossings (Chandler and Hoel, 2004, Powell, 1982, Rymer et al., 1989). Other research focusing on the delay at at-grade rail crossings was undertaken by Okitsu and Lo (2010). First, they undertook a 24-hour video recording at 33 level crossings in Los Angeles County's San Gabriel Valley. From the recording, they determined several parameters such as upstream traffic signal phasing and downstream signal green-to-cycle ratios and applied them to Webster's intersection delay model. Thus, delay caused by blockages at at-grade crossings in every individual event throughout the day could be identified. VicRoads (2010) undertook a field survey to measure travel times before and after the grade separation of a rail-road crossing in Melbourne, Australia. The results showed that travel times decreased up to 22% in peak periods following the grade separation.

As shown in previous studies, the level of traffic congestion can increase due to the operation of public transport such as the operation of at-grade rail crossings, and tram and bus operations in traffic. While there have been attempts to explore these impacts on adjacent road links or corridors, little is known about the network-wide impact of public transport in generating congestion. Indeed, the operation of public transport can result in traffic volume changes in the surrounding area because of the traffic diversion and reassignment. Assessing the negative impact of public transport operations on the road network is important because it can be integrated with the positive impact to more accurately evaluate the performance of public transport services on transport in this thesis. All prior studies assessing the impacts of public transport on congestion have just focused on the positive impact of public transport in reducing traffic congestion and not considered the negative impacts of public transport operations in creating congestion. The lack of comprehensive and balanced impact assessments on public transport congestion relief is identified as a key research gap. Chapter 6-8 will concentrate on the estimation of the positive impact as well as the negative impacts of individual public transport modes on traffic congestion and Chapter 9 will focus on the net impact of the entire public transport system on traffic congestion.

2.6 Knowledge Gaps

On reviewing the literature to date regarding the assessment of traffic congestion impacts associated with urban public transport, clear gaps in the knowledge are identified:

1. The nature and scale of the mode shift from public transport to car when public transport is unavailable in the short-term are unclear.
2. The network-wide impact of public transport operations in relieving traffic congestion is not assessed accurately.
3. The net network-wide impact of individual public transport modes on traffic congestion which considers both positive and negative impacts is not well understood.
4. The net impact of the entire public transport system on traffic congestion is not known.

2.7 Summary

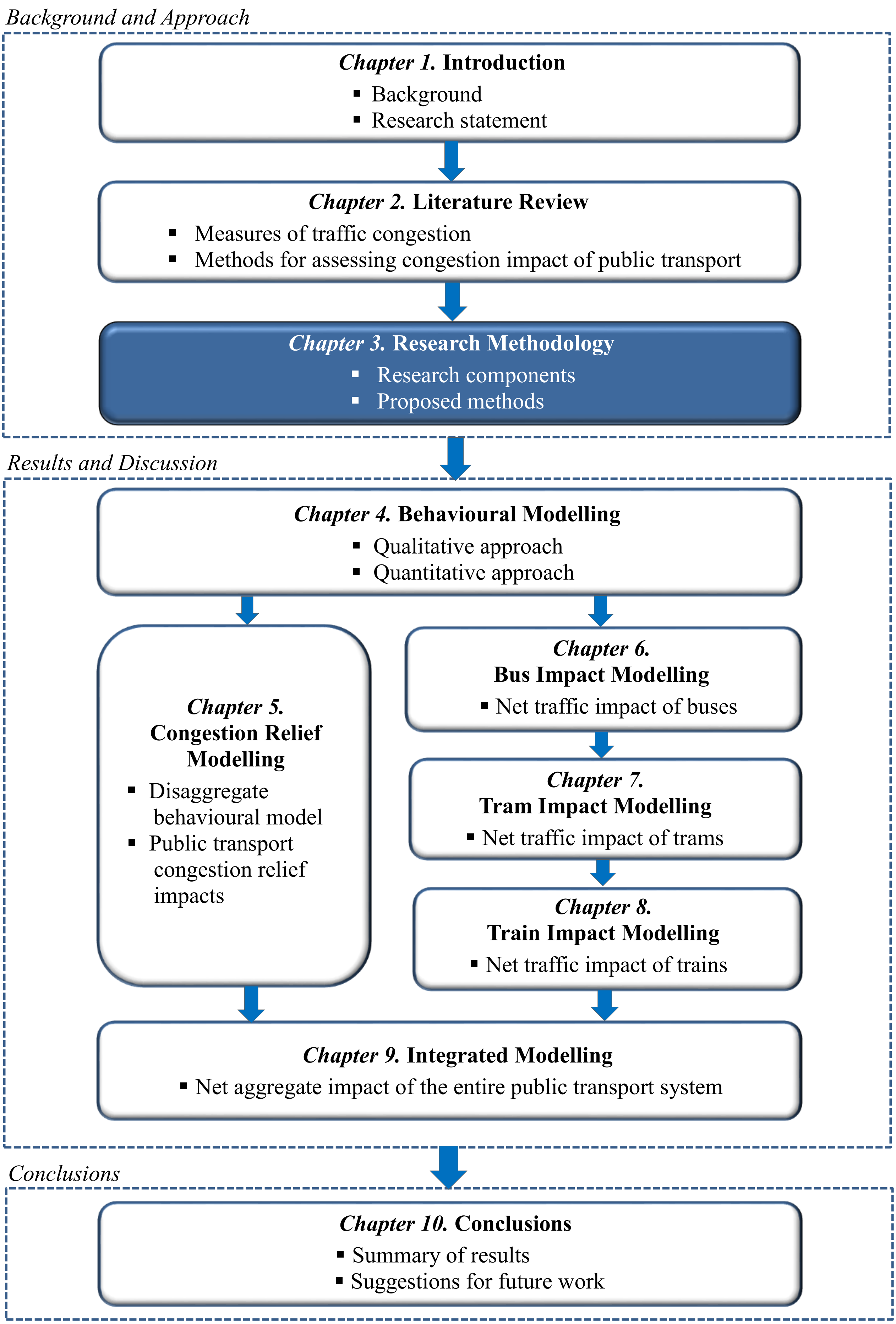
In this chapter, a review of the relevant literature was undertaken focusing on the definition of traffic congestion, the measurement of traffic congestion, the overall impact of public transport and the impact of public transport on traffic congestion. The review has identified important gaps in the existing knowledge. These gaps are summarised in Table 2.9 and the research to be undertaken to address these gaps is outlined.

This research project aims to address the knowledge gaps identified above and attempts to obtain a deeper knowledge in assessing public transport congestion relief in urban areas. In the next chapter, the research methodology will be presented in detail and the detail of data used in this research will be also provided.

Table 2.9 Existing knowledge gaps that motivate the current research

No.	Research topic	Research gaps	Research objective	Research approach
1	Factors influencing mode shift when public transport is unavailable *(Chapter 4)*	The factors influencing mode shift from public transport to car when public transport is unavailable are not clearly understood	To have better understanding of factors influencing mode shift from public transport to car when public transport is unavailable	· Conducting qualitative interview of public transport users to identify these factors · Conducting a field survey of public transport user actual behaviour to validate factors having a significant impact on the mode shift
2	Impact of public transport on reducing traffic congestion *(Chapter 5)*	The share of mode shift from public transport to car is assumed to be constant for all regions in the public transport system resulting in errors in the assessment of public transport congestion relief	To vary the share of mode shift to car for different regions	Developing a method for estimating mode shift to car when public transport is removed that varies for different regions based on traffic characteristic
		Most research on the assessment of public transport congestion relief impact adopted the fixed share of mode shift to car which might lead to inaccurate results	To assess the positive impact of public transport on reducing traffic congestion with the consideration of the various mode shift for different regions	Comparing the level of congestion in two scenarios 'with public transport' and 'without public transport' using a transport network model (VITM). Mode shift from public transport to car is adopted in the scenario 'without public transport'
3	Net impact of individual public transport modes on traffic congestion *(Chapter 6-8)*	No studies exploring the net network-wide impact of individual public transport modes (bus, tram and train) on traffic congestion to date	To assess the negative impact as well as positive impact of individual public transport mode operations on traffic congestion	Comparing the level of congestion in two scenarios 'with public transport' and 'without public transport' using a transport network model (VITM). In the scenario 'with public transport', microsimulation results representing the negative impacts of individual public transport mode operations on a road link are used to incorporate into a transport network model. In the scenario 'without public transport', the mode shift to car is adopted to model the positive effect of public transport.

4	Net impact of the entire public transport system on traffic congestion *(Chapter 9)*	No research assessing the net impact of entire public transport systems on the ability to mitigate traffic congestion. Previous studies on public transport congestion impact focused only on the positive impact of public transport on relieving traffic congestion and did not consider the impact of public transport on generating traffic congestion	To assess the net impact of the entire public transport system on traffic congestion	Modelling traffic flow on the network in a scenario 'with public transport' and 'without public transport' to estimate the net impact of the entire public transport system on traffic congestion using the mode shift data and the simulated negative impact data as inputs


Background and Approach
Chapter 1. Introduction
Background
Research statement
Chapter 2. Literature Review
Measures of traffic congestion
Methods for assessing congestion impact of public transport
Chapter 3. Research Methodology
Research components
Proposed methods
Results and Discussion
Chapter 4. Behavioural Modelling
Qualitative approach
Quantitative approach
Chapter 5. Congestion Relief Modelling
Disaggregate behavioural model
Public transport congestion relief impacts
Chapter 6. Bus Impact Modelling
Net traffic impact of buses
Chapter 7. Tram Impact Modelling
Net traffic impact of trams
Chapter 8. Train Impact Modelling
Net traffic impact of trains
Chapter 9. Integrated Modelling
Net aggregate impact of the entire public transport system
Conclusions
Chapter 10. Conclusions
Summary of results
Suggestions for future work

Chapter 3
RESEARCH METHODOLOGY

3.1 Introduction

The preceding chapter discussed previous approaches used for estimating traffic congestion impacts associated with public transport and highlighted their associated outcomes. This chapter presents a new and more complex conceptual framework for understanding the net short-term impact of public transport on traffic congestion.

Urban congestion tends to maintain equilibrium, it grows to the point that congestion delays discourage additional peak-period vehicle trips. If traffic congestion increases, some travellers will change their routes with less congestion, change travel times and travel modes to avoid delays. In contrast, if congestion decreases, travellers can take more peak-period trips. Public transport is considered the most efficient solution to reduce congestion. However, congestion relief benefits associated with public transport can be difficult to assess as urban traffic tends to maintain equilibrium. In this research, mode shift from public transport to private car in the event of a whole-day removal of the entire public transport system with advanced notification was modelled. A transport network model was then used to estimate the level of traffic congestion in two scenarios: 'with public transport' and 'without public transport'. The contrast between two outcomes is considered the short-term public transport congestion impact. This model includes an assignment process that models the change in travel behaviour when traffic volume changes. Hence, this approach is considered to be appropriate for determining the benefit of public transport on traffic congestion in the short-term.

This chapter is organised as follows. The next Section 3.2 states the research objectives of the study. Section 3.3 outlines the proposed methodology for assessing the congestion impacts associated with public transport. Section 3.4 presents the behavioural modelling approach that investigates the behavioural responses of public transport users in the event of public transport disruptions. It is followed by an overview of the congestion modelling approach that examines the net congestion impact of individual public transport modes (bus, tram and train) in Section 3.5. Section 3.6 provides an integrated modelling approach for estimating the net congestion impact of the entire public transport system. Finally, this chapter concludes with a summary (Section 3.7).

3.2 Research Objectives

To reiterate, the aim of this thesis is:

'To improve methods to estimate the traffic congestion impacts of urban public transport'

To address the aim of this research, four specific objectives were set (established in Section 1.3):

1. To identify and understand factors influencing mode shift from public transport to car when public transport is unavailable in the short term.
2. To develop improved methods to estimate the positive impact of the entire public transport system on relieving traffic congestion.
3. To develop improved methods to investigate the net impact (considering both positive and negative impact) of individual public transport modes on traffic congestion.
4. To understand the net short-term impact of the entire public transport system on traffic congestion.

3.3 Outline of the Proposed Methodology

Figure 3.1 illustrates the proposed research framework including eight components grouped into four main components: (1) behavioural modelling approach, (2) congestion relief modelling approaches, (3) public transport impact modelling and (4) integrated modelling. The first and second component are behavioural modelling approaches (qualitative and quantitative approach) which explore the behavioural responses of public transport users in the event of a whole-day removal of the entire public transport system with advanced notification. The third component is to develop a methodology for estimating mode shift from public transport to private car for different regions. This mode shift is then used to assess the congestion relief impact of public transport (the fourth component). The fifth, sixth and seventh component are congestion modelling approaches which examine the net congestion impact of individual public transport modes (bus, tram and train respectively). The integrated modelling approach, which investigates the net short-term congestion impact associated with the entire public transport system, is the final component.

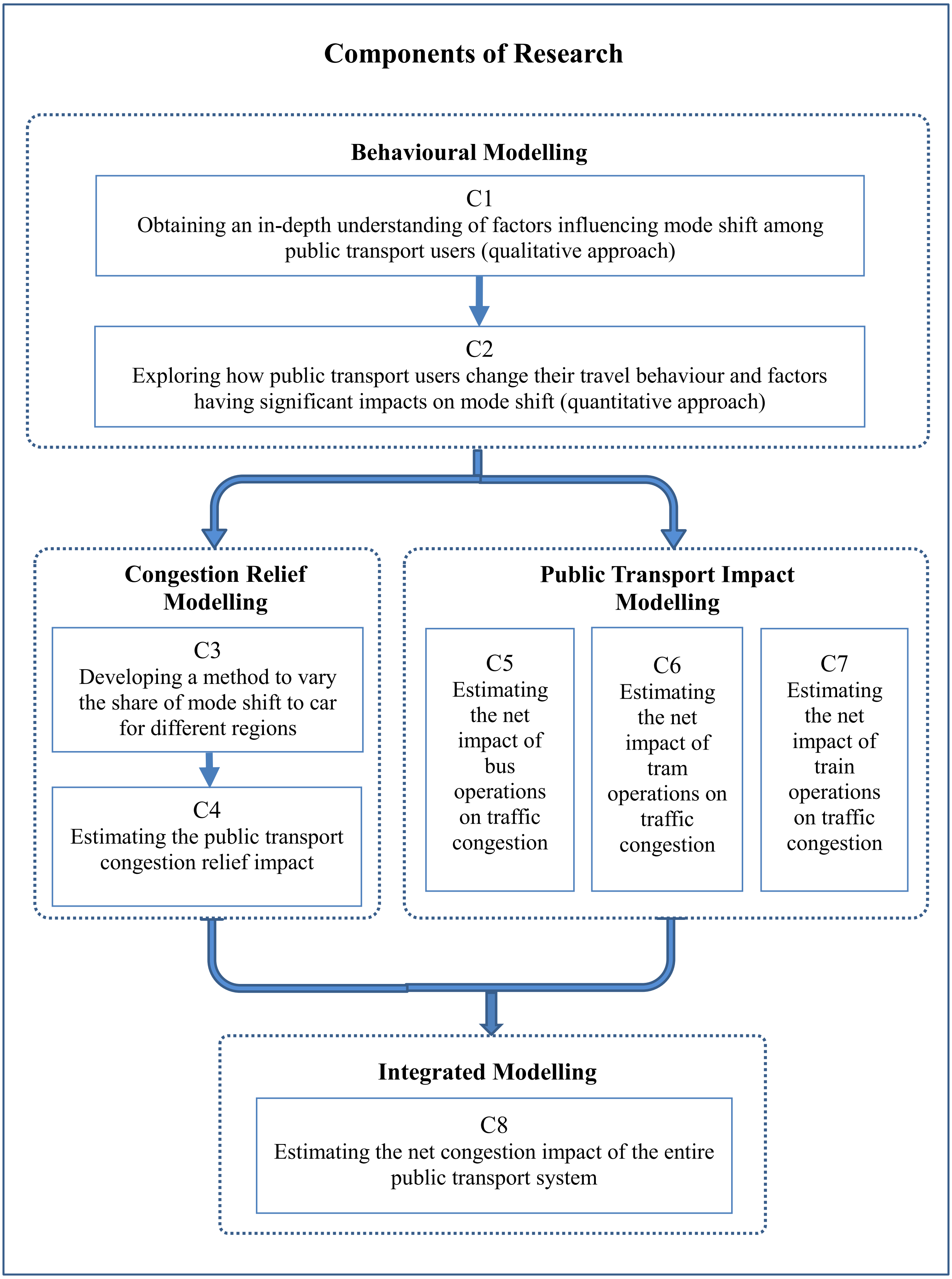


Figure 3.1 Research framework

Table 3.1 shows the relationships among the research gaps, research opportunities, research objectives and research components. The key findings from each research component are reported through Chapter 4 to Chapter 9.

Table 3.1 Relationships among research gaps, opportunities, objectives, components and thesis chapters

Research gaps	Research opportunities	Research objectives	Research components	Thesis chapters
The behavioural reaction of public transport users when public transport is unavailable is not clearly understood	Explore factors affecting mode shift from public transport to car	1. To identify and understand key factors influencing mode shift from public transport to car when public transport is unavailable	1. Semi-structured interviews with public transport users	Chapter 4: Behavioural modelling
Previous studies focused on the travel behavioural response of train users in the event of train removal. There are no studies investigating factors which have a significant influence on the travel behavioural reaction of public transport users when all modes of public transport are no longer available	Examine the effects of key factors on the mode shift of public transport users when public transport is unavailable using an analytical approach		2. Field survey with public transport users	
The share of mode shift from public transport to car is assumed to be constant for all areas. However, this mode shift varies based on the traffic characteristics of each area.	Understand how the share of mode shift to car varies for different areas	2. To develop improved methods to estimate the positive impact of public transport on relieving traffic congestion	3. Mode shift share variation	Chapter 5: Congestion relief modelling
Most research on the assessment of public transport congestion relief impacts adopted a fixed share of mode shift to car which might lead to inaccurate results	Explore the congestion relief impact of public transport using various shares of mode shift to car		4. Public transport congestion relief impact estimation	

No studies have explored the net network-wide impact of bus operations on traffic congestion	Investigate the net traffic congestion effect of bus operations by considering both positive and negative impacts	3. To develop new methods to investigate the net network-wide impact of bus operations on traffic congestion	5. Bus congestion effect estimation	Chapter 6: Bus impact modelling
No studies have explored the net network-wide impact of tram operations on traffic congestion	Investigate the net traffic congestion effect of tram operations by considering both positive and negative impacts	4. To develop new methods to investigate the net network-wide impact of tram operations on traffic congestion	6. Tram congestion effect estimation	Chapter 7: Tram impact modelling
No studies have explored the net network-wide impact of train operations on traffic congestion	Investigate the net traffic congestion effect of train operations by considering both positive and negative impacts	5. To develop new methods to investigate the net network-wide impact of train operations on traffic congestion	7. Train congestion effect estimation	Chapter 8: Train impact modelling
No research has been undertaken to assess the net congestion effect of entire public transport systems	Explore the net network-wide effect of entire public transport systems	6. To understand the net impact of entire public transport on traffic congestion	8. Net public transport congestion effect estimation	Chapter 9: Integrated modelling

3.4 Behavioural Modelling

In order to estimate the congestion relief impact associated with public transport, mode shift from public transport to private car, which is expected to occur when public transport is unavailable for a whole day, is used as an important parameter. Thus, determining this mode shift is the initial stage of estimating public transport congestion relief impact. In this section, a framework used for predicting mode shift to car for regions is presented. The first subsection describes how to gain an in-depth understanding of this mode shift using a qualitative approach. The second subsection presents a method for identifying factors which have significant impacts on mode shift using a quantitative approach. Finally, a method for predicting mode shift to car for different regions is outlined in the last subsection.

3.4.1 The Qualitative Approach (C1)

Travel behaviour is complex so an in-depth understanding of user perceptions and attitudes is necessary. A powerful tool to explore these complexities is qualitative research since it allows each individual to explain their own behaviour and attitude in choosing an alternative mode for travelling or even cancelling the trip if public transport ceases in the short-term. There are three major stages for investigating travel behaviour using a qualitative approach.

Recruitment and Sampling

A recruitment notice was published on a university website. Public transport users interested in attending the survey responded by sending an email to the researcher to indicate their interest along with information about their public transport trips that they undertook the week before (such as the origin, destination and the time of public transport trip). In order to diversify the sample, thirty interviewees from different age groups were selected from different regions of Melbourne. All participants agreed to take part in the study via consent forms and were rewarded with a gift card for their attendance.

Research Protocol and Measures

The protocol includes two parts: a semi-structured interview guide and a brief questionnaire. All interviews were recorded for the purpose of transcription. In the semi-structured interview, the first two questions concentrate on the background of interview participants which helps to provide context for the remaining questions. The remaining questions focus on mode shift from public transport to other alternative transport modes when public transport ceases, and factors influencing those choices. Additionally, the reasons of why public transport users did not choose other alternatives were also explored in the interviews. Individual interviews were held rather than focus groups because they can investigate the flexibility of each public transport user to change their behaviour if public transport was no longer available in the short term (around a day or so) and the long term (removed for 10 years or so). In particular, the interviews addressed mode shift to private car as car drivers or car passengers, since this is a major factor contributing to traffic congestion. After finishing the semi-structured interview, each participant was asked to complete a brief questionnaire covering socio-demographic information including age, income, occupation, car ownership, driving license and the origin and destination of their last public transport trip.

Data Analysis

The interview recordings were transcribed verbatim. Transcripts of the interviews were entered into NVIVO 10 software to facilitate the organisation and structuring of the process of coding and classification, and to develop relationships among concepts. Interviews were analysed independently to avoid imposing the beliefs of one participant on others. This qualitative study was based on ‘grounded theory’ (Glaser and Strauss, 1967), which provided an interactive framework for data analysis. Grounded theory is a method of analysing qualitative data which is grounded in the data without preconceived theories and is characterised by intensively analysing data, often sentence by sentence or phrase by phrase. Data obtained by the questionnaire was also entered into an SPSS file to calculate descriptive statistics.

3.4.2 The Quantitative Approach (C2)

Data Collection

The data employed in this thesis is gathered from an online survey conducted in Melbourne, Australia. This data is collected with the assistance of a market research company and targeted people who used public transport in the weekday morning peak (7-9am). This period was focused in this study since the level of traffic congestion at this time was expected to be highest. Hence, the congestion would become the most serious when there was mode shift from public transport users in the event of a public transport withdrawal.

The survey required respondents to complete a structured questionnaire with both revealed and stated preference questions. A pilot survey was conducted and corrections implemented before the full scale survey was carried out. The questionnaire was divided into three major parts: socio-economic characteristics, public transport trip characteristics and flexibility in travel behaviour.

1. The socio-economic part of the survey solicited information on gender, age, vehicle (car and bike) ownership, driver's license ownership, number of adults with a drivers' license in the household and weekly income.
2. The second part of the questionnaire was designed to gather information regarding the context of the last public transport trips that respondents undertook such as trip purpose, station accessibility and the weather conditions during their trips. Respondents were also asked to provide locations that they started and ended their trips. With this information, the researcher could estimate trip distance and identify whether a trip was to the CBD or not.
3. In the last part of the questionnaire, respondents were asked to imagine that public transport was not available for the day of their last public transport trips. Respondents are then asked about their likely behavioural reactions (a choice-set including seven options: drive a car, take a lift, take taxi/Uber, cycle, walk, cancel trip and other). In addition, respondents are asked to state the most important reasons associated with their decisions for choosing the alternative mode by rating the importance of each potential motivator affecting their choices. The motivator items were rated on a scale of 1-5, 1 being 'not important' and 5 being 'very important'. Users were also asked to rate reasons for not choosing one of the other alternative modes. These reasons provided in the questionnaire were identified from previous qualitative research.

Firstly, an email was sent to all members of a market research panel to invite them to take part in the study by answering an online questionnaire. In the invitation email, each panel member was given a link to access the questionnaire. A reminder email was sent to those who had not accessed the questionnaire one week after the initial email was sent. The data collection process stopped when the number of samples reached the target of the researchers.

Data Cleaning and Selection

In order to mitigate bias in survey response, several strategies were implemented to clean the data. Firstly, respondents who completed the survey much sooner than the expected time of completion were considered a potential 'skimmer' and data provided by them was checked carefully. Secondly, observations with no meaningful value on any of the key outcome variables were discarded from further analysis. Finally, respondents who selected the same answer value for all Likert scale questions were recognised as severe 'skimmers' and were removed from the final dataset.

Data Analysis

A Multinomial Logit Model (MLM) was used to predict categorical placement in or the probability of category membership on a dependent variable based on multiple independent variables (McFadden, 1980, McFadden and Reid, 1975, McFadden, 1976). In this study, this model was used to investigate the travel behavioural reaction of public transport users in the event of a public transport disruption and factors influencing it. It was therefore able to show when one specific factor (independent variable) changes, how a behavioural reaction would follow and whether some factors had a bigger effect on the choice than others.

There were four major behavioural reactions in the case of this study's MLM: car as a driver, car as a passenger, non-motorised modes and trip cancellation. The probability that the i^{th} public transport user would choose j^{th} behavioural reaction is given by $P_{ij} = P_r(R_{ij} > R_{ik})$, for $k \neq j, j = 0, 1, 2, 3$ ... which represent different choices, with R_{ij} being the maximum utility attainable for user i if the user chooses jth behavioural reaction and $R_{ij} = \beta_j' X_{ij} + \varepsilon_{ij}$, where β_j' is a vector of coefficients of each of the explanatory variables. If the stochastic terms ε_{ij} have the independent and Weibull distribution, the MLM can be expressed as:

$$Prob(i|Y = j) = \frac{e^{\beta_k' x_{ij}}}{\sum_{k=0}^{j} e^{\beta_k' x_{ij}}} \qquad \text{(j=0, 1, 2, 3)} \qquad (3.1)$$

The parameters (β) are estimated by maximising a log likelihood function. To standardise the model, one of behavioural reactions (j=0) is chosen as a reference case so $\beta_0' = 0$. The remaining vector coefficients $(\beta_1', \beta_2', \beta_3')$ measure the change relative to the reference case.

3.4.3 Disaggregate Approach (C3)

Mode shift from public transport to car is considered to be an important parameter for assessing traffic congestion relief impact associated with public transport. The aim of this subsection is to overview the disaggregate approach of mode shift to car based on the traffic characteristics of public transport users in a specific area. With the better understanding of the mode shift in the event of a public transport withdrawal (using qualitative and quantitative approach), there is a need to vary mode shift for different regions. The consideration of the spatial distribution of mode shift acts to increase the precision of the method assessing the congestion relief impact of public transport.

In this research, mode shift to car is varied for each LGA and as such LGA is chosen to be an analysis unit. With the primary data collected from public transport users, the share of mode shift for LGAs and the share of traffic characteristics of public transport users are determined. By conducting regression analysis, the relationship between the share of mode shift and the share of a number of traffic characteristics (P_1, P_2, …, P_n) is developed. This relationship can be used to predict mode shift to car when we know the traffic characteristics of public transport users.

In general, the multiple regression equation of the mode shift share on P_1, P_2, …, P_n is given by Equation 3.2:

$$\text{The share of mode shift to car (\%)} = \beta + \alpha_1.P_1 + \alpha_2.P_2 + \ldots + \alpha_n.P_n \quad (3.2)$$

3.5 Congestion Modelling

This section overviews the fundamental approach of the congestion modelling methodology and its application for this study. The aim of this study is to explore the network-wide impacts of public transport on traffic congestion so using macrosimulation model is considered to be an appropriate approach. Macrosimulation models are often used to simulate traffic flow without considering the interactions between individual vehicles. A number of traffic characteristics considered in these models include flow, speed and density. In macrosimulation, travel demands generated from socio-demographic and land use data are matched with road networks to present travel patterns. The simulation in a macrosimulation model takes place on a section-by-section basis rather than by tracking individual vehicles (as in microsimulation). Macrosimulation models are recognised to be suitable for testing the effects of new policies, new roads, new public transport routes on many aspects of travel demands such as land use strategies, mode choice, route selection or broad-level intelligent transport system applications.

In this study, the Victorian Integrated Transport Model (VITM) was used to investigate the congestion impacts associated with public transport. VITM is a conventional four-step model which is created to estimate travel demand on the road network in Victoria, Australia. The model is implemented in CUBE. In VITM, the road network that is considered as the input of this model is presented by a set of links and nodes and divided into 2,959 zones. Each zone is represented by a centroid node that is a point inside the zone. Nodes usually represent an intersection or a change in road characteristics. Links represent the segments of actual roads in the network or centroid connectors. Road links are coded with various road characteristics such as length, posted speed or capacity. VITM contains a number of sub-models which work together to create required outputs for each link such as actual speed, traffic volume or travel time (as seen in Figure 3.2). The first step is trip generation which uses eight trip purposes for home based trips and six trip purposes for non-home based trips to define the magnitude of total daily travel in the network. Trip distribution, the second step, distributes trips from a particular zone to all possible destination zones according to travel time. The third step is mode choice which splits trips into each available mode between each zone pair. A hierarchical binary logit structure is utilized to develop a choice model for each trip purpose. The last stage of VITM is trip assignment. In this stage, predicted model flows between each O-D pair are taken and assigned to actual routes on Melbourne's road network using an equilibrium assignment process. Speed-flow curves which vary by the type of road are used to calculate travel time.

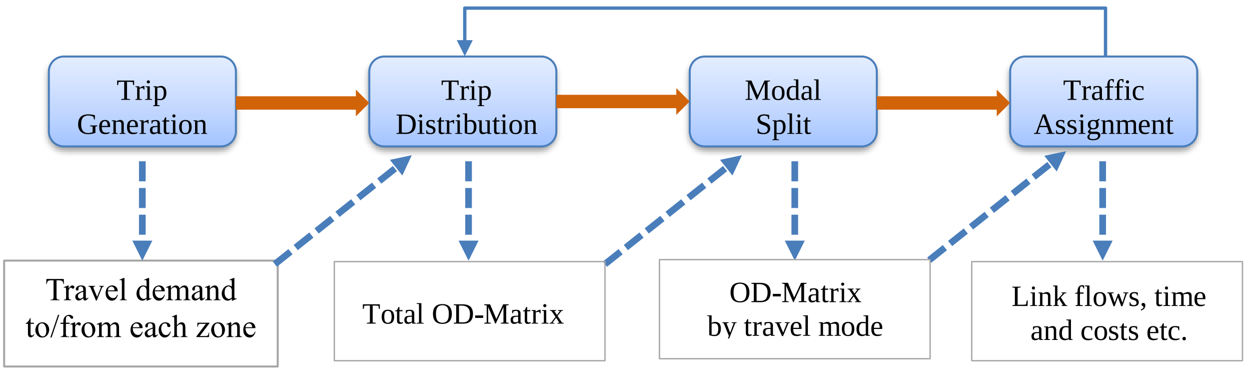


Figure 3.2 Schematic diagram of a traditional four step transport model

In the next subsections, the description of approaches to implement the modelling in the research is presented. Firstly, a method for assessing the congestion relief impact of the entire public transport system is presented. In the second, the third and the fourth part, methods for exploring the net impact of individual public transport modes (bus, tram and train) on traffic congestion is outlined. Finally, a modelling procedure for assessing the net traffic congestion effect associated with the entire public transport system is presented.

3.5.1 Modelling the Congestion Relief Impact of the Entire Public Transport System (C4)

A modelling procedure adopts an assumption regarding public transport user diversion to private car and a four step transport model to assess the positive impact of public transport on traffic. The modelling analysis was carried out for an average weekday morning peak (7am-9am) as the highest level of congestion is expected in this period. In this research, a decrease in the number of car trips due to the operation of public transport represents the positive effect of public transport. Hence, in order to assess this effect, it is assumed that there is a mode shift to car if public transport is removed. The number of public transport users shifting to car in the case of public transport removals represent the number of car users attracted by public transport operations.

The modelling procedure comprises three major steps:

- The level of congestion of the road network in the scenario ‘with public transport is estimated with the help of VITM.
- In the scenario ‘without public transport, the car trip matrix is added with a modified public transport trip matrix (public transport trip matrix is multiplied with mode shift to car which varies for LGAs (refer to 3.4.3)) to obtain a modified car trip. This matrix is then assigned into the road network to explore the level of congestion in the case of public transport withdrawal.
- The level of congestion in two scenarios ‘with public transport and ‘without public transport are contrasted to investigate the congestion relief effect of public transport operations on the road network.

3.5.2 Modelling the Net Impact of Bus Operations on Traffic Congestion (C5)

The methodology for assessing the net impact of bus operations on traffic congestion is basically similar to that for assessing tram impact. The modelling procedure also adopts an assumption regarding bus user diversion to car, along with micro-simulation and a four-step transport model to incorporate both positive and negative impacts of buses on traffic. However, there is a methodological advancement from the previous research that explores the congestion impact of tram operations. Firstly, a primary survey of bus users was conducted to explore mode shift from bus to car which was used for estimating the positive effect. This mode shift was varied for different regions which have different traffic characteristics. Secondly, a more comprehensive range of factors affecting the negative congestion impact were investigated using calibrated traffic microsimulation models. They included bus service frequency, traffic volume, speed limit, dwell time, number of lanes and bus stop type.

The modelling procedure for estimating the net impact of buses on traffic flow consists of three main stages:

- Stage 1: In the ‘with bus’ scenario, the effect of bus operations on vehicle traffic flow are modelled. Firstly, the effect of bus operations on a road link is investigated by using traffic microsimulation. Then, these results are integrated into VITM to model the network-wide effect of buses.

- Stage 2: In the scenario of 'without bus', the existing car trip matrix is added to the car mode shift matrix (bus trip matrix is multiplied by the mode shift to car for inner, middle and outer areas) to obtain a modified car trip matrix. This new car trip matrix is then assigned to the road network.
- Stage 3: The congestion measures in two scenarios, 'with bus' and 'without bus', are contrasted to assess the net traffic congestion effect of bus operations on the entire road network.

3.5.3 Modelling the Net Impact of Tram Operations on Traffic Congestion (C6)

A new approach to examine the network-wide congestion impact associated with the operation of trams is outlined in this subsection. It aims to assess both the positive effect of trams on relieving traffic congestion and the negative impact of trams on generating congestion to assess a 'net' impact. In this research, a decrease in the number of car trips due to tram operations represents the positive effect of tram operations. Thus, in order to assess this positive effect, it is assumed that there is a mode shift to car if trams are removed. The number of tram users shifting to car in the case of tram removal represent the number of car users attracted by tram operations. This figure can be determined using secondary data. The negative impacts of trams in terms of their contribution to traffic congestion includes: (1) the effect of road capacity reduction due to the occupation of semi-exclusive tram rights-of-way, and (2) the impact of trams on vehicle traffic on non-exclusive tram rights-of-way due to the sharing of road space. The modelling procedure examining the negative impacts of trams is similar to the procedure used to assess the impact of buses (incorporate the results from microsimulation into a four step model).

The modelling procedure for estimating the net impact of trams on traffic consists of three main stages:

- Stage 1: In the "with tram" scenario, the effects of tram operations on vehicle traffic flow (such as the effect of tram curbside stops and low tram speeds) are modelled by integrating the results of micro-simulation into VITM. Then, based on the VITM output, the roadway travel data (traffic volume, average speed and travel time) for each road link is calculated.
- Stage 2: In the scenario of "without tram", the existing car trip matrix is added to the modified tram trip matrix (tram trip matrix multiplied by the share of mode shift to car) to obtain a modified car trip matrix. This new car trip matrix is then assigned onto the road

network. Additionally, the capacity of road links with semi-exclusive tram rights-of-way are adjusted by adding one more lane. The roadway travel performance is then determined using the VITM output.

- Stage 3: The congestion measures in two scenarios, "with tram" and "without tram", are contrasted to determine the net congestion relief effect of tram operations on the entire road network.

3.5.4 Modelling the Net Impact of Train Operations on Traffic Congestion (C7)

A modelling procedure for exploring the impact of at-grade crossings (level crossings) on generating traffic congestion is described in this subsection. In this procedure, VITM is used to determine a number of congestion measures in two scenarios 'with level crossing' and 'without level crossing'. In the scenario 'with level crossing', traffic on links with level crossings will be delayed during crossing closure times. Microsimulation models are recognised to be an appropriate method to estimate this delay. The results from microsimulation are then incorporated with VITM as input to model system-wide congestion impact of level crossings.

The modelling procedure includes three main stages:

- Stage 1: In the scenario 'without level crossing', road links with level crossings are coded with a link type which is the same as adjacent road links to represent no crossings on those links. The VITM is then run to produce a 'without level crossing' scenario.
- Stage 2: In the scenario 'with level crossing', links with level crossings are coded by a specific road link. The percentage change in travel time on those links caused by level crossings is estimated by using traffic microsimulation. The results from micro-simulation are incorporated into VITM (macrosimulation) in order to determine the impact of level crossings on the road network. In VITM, the travel time of links with level crossings is adjusted by adding normal travel time (using Akcelik's formulation) with a percentage increase in travel time caused by level crossings on each link to represent the delay generated. The VITM is run to produce a 'with level crossing' scenario.
- Stage 3: Compare the outcomes between the two scenarios, 'with level crossing' and 'without level crossing', to estimate the impact of level crossings on immediate links and on the entire road network.

The modelling analysis is carried out for an average weekday morning peak (7am-9am) as the impact of level crossings on traffic is expected to be highest in this period.

The next parts of this section detail the microsimulation approach and how to incorporate its result into VITM (macrosimulation) to assess the network-wide impact of level crossings.

Microsimulation Approach

The aim of the microsimulation models is to estimate delays associated with crossing closure times. It is costly and difficult to collect field data from existing heavy rail operations because of the varying geometry, traffic and travel behaviour of drivers at each level crossing. Vissim is the software package adopted to model the operation of level crossings and identify the impact of rail service frequencies on regular traffic flow. In this study, the effect of level crossings on a link is the focus of analysis and the main measure used is the average link travel time. That is estimated by averaging the travel time of each vehicle on a segment. The reason for choosing travel time as a major measure is that travel time is calculated on each link in VITM and used as a main criterion for assigning vehicle trips to the road network.

The analysis focusses upon one particular type of crossing, the 'isolated mid-block level crossing on a one-lane link' to develop a scenario for travel time. Firstly, this scenario is built without rail crossings to obtain a baseline average travel time on links. Next, the simulation is run with a range of input traffic volumes and different train frequencies which act to generate different crossing closure times. The simulation run is performed for each combination of input volume and train crossing frequency. Finally, the 'base case' and the 'isolated mid-block level crossing on a one-lane link' scenario are compared to obtain the relationship between the percentage change in travel time and traffic volume for each identified train frequency.

Macro-modelling Approach

VITM assigns vehicle trips on Melbourne's road network using travel time calculated for each link using Akcelik's speed-flow formula. This figure is one of the major parameters for estimating travel cost which is used in the equilibrium assignment process. In addition, to obtain an equilibration of demand, traffic volume on each link is changed after an iterative process leading to changes in travel time. Equilibrium assignment techniques explicitly recognise that transport network link costs generally depend on the volume of traffic using that link.

A major development in this research is to more accurately represent travel time on a link with level rail level crossings to crossing closure times as influenced by the frequency of rail traffic, using the simulation outlined above. In this research the travel time on the links including level crossings is adjusted by the percentage change in travel time that is estimated by microsimulation. This percentage can be adjusted based on the volume of traffic on the road link and frequency of trains at each location. When iterating to get an equilibrium value the volume is changed in each loop. Thus, the percentage change in travel time changes with the updated volume. This process is carried out by coding in CUBE as follows:

$$Travel\ time = \text{Travel time}_0 + \text{p\%} * \text{Travel time}_0 \qquad (3.3)$$

Where:

p%: is the percentage change in travel time caused by level rail crossings which is calculated using the results from micro-simulation.

Travel time_0: Travel time of links including level rail crossings when impact of rail level crossings is not considered

$Travel\ time$: Travel time of links with level rail crossings when impact of rail level crossings is considered.

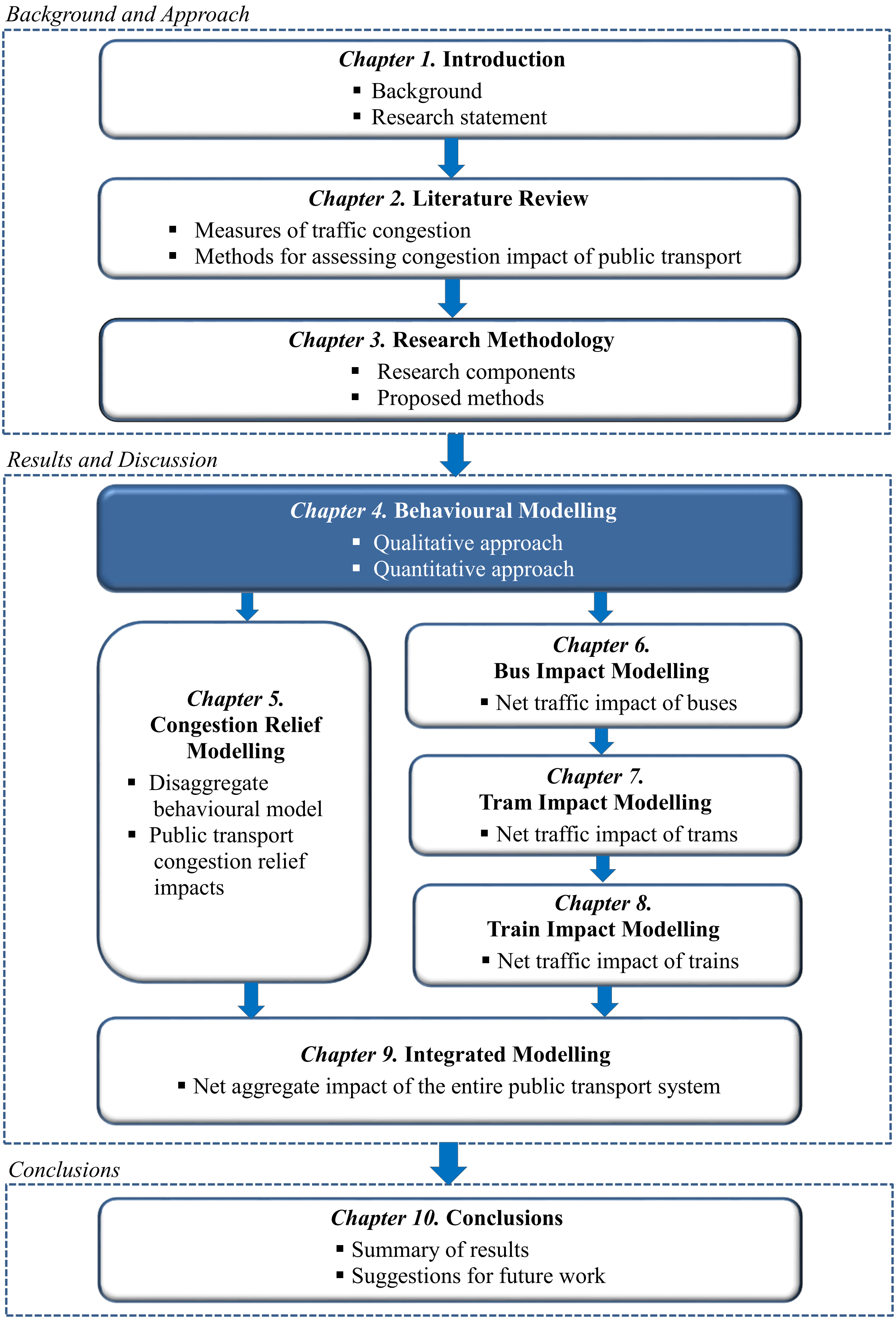
3.5.5 Integrated Modelling (C8)

This section will present a modelling procedure for assessing the traffic congestion effect associated with the entire public transport system. This model integrates both positive impact and negative impacts of public transport to estimate the net impact on traffic congestion.

VITM is used to estimate the level of congestion in two scenarios: 'with public transport' and 'without public transport'. In the scenario 'with public transport', the congestion generation impacts of the public transport system (such as the delay impacts of at-grade rail crossings, tram and bus stop operations) should be taken into consideration to model the negative impacts on traffic congestion. The procedure for modelling these impacts are presented in subsection 3.5.2, 3.5.3 and 3.5.4. In the scenario 'without public transport', mode shift from public transport to private car, which is estimated using framework outlined in subsection 3.5.1, is taken into account. The contrast between the outcomes of these two scenarios is recognised to represent the net congestion effect associated with the entire public transport system.

3.6 Summary

This chapter has outlined the overall research framework on which the following chapters are based. There are four major components in the proposed research framework: (1) the behavioural modelling approach that investigates the change in the travel behaviour of public transport users in the case of a public transport withdrawal, (2) the congestion relief modelling approach that examines the positive effect of public transport on reducing traffic congestion, (3) public transport impact modelling which explores the net impact of individual public transport modes on traffic congestion and (4) integrated modelling which investigates the net congestion effect of the entire public transport system. The detailed results of the behaviour modelling approach and the congestion modelling approaches are presented in Chapter 4 and Chapters 5-9 respectively.


Background and Approach
Chapter 1. Introduction
Background
Research statement
Chapter 2. Literature Review
Measures of traffic congestion
Methods for assessing congestion impact of public transport
Chapter 3. Research Methodology
Research components
Proposed methods
Results and Discussion
Chapter 4. Behavioural Modelling
Qualitative approach
Quantitative approach
Chapter 5. Congestion Relief Modelling
Disaggregate behavioural model
Public transport congestion relief impacts
Chapter 6. Bus Impact Modelling
Net traffic impact of buses
Chapter 7. Tram Impact Modelling
Net traffic impact of trams
Chapter 8. Train Impact Modelling
Net traffic impact of trains
Chapter 9. Integrated Modelling
Net aggregate impact of the entire public transport system
Conclusions
Chapter 10. Conclusions
Summary of results
Suggestions for future work

Chapter 4
BEHAVIOURAL MODELLING

4.1 Introduction

Chapter 1-3 detailed the background and approach of this research. In doing so, they identified a number of research gaps and opportunities and showed how each of these aligned with the research objectives and components. In this chapter, the main factors influencing mode shift, particularly mode shift from public transport to car in the event of a public transport withdrawal, will be investigated. This research fills an existing research gap identified in the Literature Review: The behavioural reaction of public transport users when public transport is unavailable is not clearly understood and there are no studies investigating factors which have a significant influence on the travel behavioural reaction of public transport users when all modes of public transport are no longer available. This is in accordance with research objective 1 which seeks to identify and understand key factors influencing mode shift from public transport to car when public transport is unavailable in the short term. Table 4.1 details the research objective, research components, research gaps and research opportunities associated with this chapter.

Table 4.1 Research gaps, opportunities and objective associated with research component 1 and 2

Research objective	Research components	Research gaps	Research opportunities
1. To identify and understand key factors influencing mode shift from public transport to car when public transport is unavailable	1. Semi-structured interviews with public transport users	The behavioural reaction of public transport users when public transport is unavailable is not clearly understood	Explore factors affecting mode shift from public transport to car
	2. Field survey with public transport users	Previous studies focused on the travel behavioural response of train users in the event of train removal. There are no studies investigating factors which have a significant influence on the travel behavioural reaction of public transport users when all modes of public transport are no longer available	Examine the effects of key factors on the mode shift of public transport users when public transport is unavailable using an analytical approach

In line with research objective 1, the research aim of this chapter is to identify factors affecting the mode shift of public transport users when pubic transport is unavailable, particularly the mode shift to private car. In order to achieve this aim, a qualitative research method is firstly adopted to gain an in-depth understanding of these factors. Then, a quantitative research method is conducted to give precise and testable expression to the findings of the qualitative research to a wider population.

The key aspects of this research component include:

- Understanding the travel behavioural response of public transport users in the event of a public transport withdrawal
- Exploring factors influencing mode shift from public transport to other transport modes, particularly to private car
- Verifying which factors have a more significant impact than others
- Proposing measures to reduce mode shift to car in the event of a public transport disruption

Two journal papers were conducted based on the findings of this chapter as follows:

Paper 2 *Nguyen-Phuoc, D.Q., Currie, G., De Gruyter, C. & Young, W., 2018, 'Understanding public transport user behaviour adjustment if public transport ceases - A qualitative study', **Transport Research Part F**.*

Paper 3 *Nguyen-Phuoc, D.Q., Currie, G., De Gruyter, C. & Young, W., 2018, 'Transit user reactions to major service withdrawal – A behavioural study'. **Transport Policy**.*

This chapter begins by describing the research methods used to gain an in-depth understanding of mode shift from public transport in the event of a public transport withdrawal. The results are then presented. The chapter concludes by discussing the implication of findings for the purpose of reducing mode shift to car when public transport is removed.

4.2 Research Methodology

In order to gain a better understanding of the behavioural reaction of public transport users in the event of a public transport withdrawal, mixed methods research is undertaken in this study. The use of qualitative and quantitative approaches in combination provides more comprehensive evidence for research problems, and helps answer questions that quantitative or qualitative methods alone cannot answer (Johnson et al., 2007).

4.2.1 Qualitative Approach

Travel behaviour is complex so an in-depth understanding of user perceptions and attitudes is necessary. One of the powerful tools to explore these complexities is qualitative research since it allows each individual to explain their own behaviour and attitude in choosing an alternative mode for travelling or even cancelling the trip if public transport ceases (Kothari, 2004).

Sampling Approach

A recruitment notice was published on the Monash University website in July 2015. Public transport users interested in participating in the survey sent an email to the researcher to indicate their interest along with information about the public transport trips that they undertook the week before (such as the origin, destination and the time of public transport trip). In order to diversify the sample, thirty interviewees from different age groups were selected from different areas of Melbourne. Most interviewees (24) were staff and students of Monash University who were living in metropolitan Melbourne. Only six participants were not from Monash University. Monash University has several campuses around Melbourne so the interviews were organised in three locations: Clayton campus, Caufield campus and the National Library in Melbourne's CBD. All participants agreed to take part in the study via consent forms and were rewarded with a $30 gift card for their attendance. The interviews were conducted from August to October 2015 (winter/spring). It is noted that the weather may have influenced public transport users' decisions during this time.

Research Protocol and Measures

The research protocol included two parts: a semi-structured interview guide (Table 4.2) and a brief questionnaire. The semi-structured interviews took 35 minutes to complete on average. All interviewees agreed to have their interview audio-taped. The first two questions concentrated on the background of interview participants which helped to provide context for the remaining questions. The remaining questions focused on mode shift from public transport to other alternative transport modes when public transport ceases, and factors impacting those choices. Additionally, the reasons why public transport users did not choose other alternatives were also explored in the interviews. Individual interviews were held rather than focus groups because they can investigate the flexibility of each public transport user to change their behaviour if public transport was no longer available in the short term (one day). In particular, the interviews addressed mode shift to car as car drivers or car passengers, since this is a major factor contributing to traffic congestion. After finishing the semi-structured interview, each participant was asked to complete a brief questionnaire covering socio-demographic information including age, income, occupation, car ownership, driving license and the origin and destination of their last public transport trip.

Table 4.2 Semi-structured interview questions

Background

1. Can you remember your last public transport trip last week that started from your home in the morning peak hours between 7am and 9am?
2. Take a moment and think. Can you please tell me about that trip?

Possible subsidiary questions:

- How long did that trip take?
- How often do you use public transport?
- Where was your destination? Can you describe your destination (e.g. traffic condition, parking...)
- Which services/modes (if you can recall) did you use to undertake this travel?
- What circumstances led to you to undertake this travel by public transport?
- Why did you choose to use public transport as opposed to other modes for this trip?
- What was the main purpose of that trip?
- How did you access public transport? If you used a car to access public transport, were you parking a car or getting a lift?
- Was there anything that you found particularly challenging about this trip?
- Have you travelled by another means for this purpose before or not?
- Will you still make this trip by public transport?

Short term impact of public transport removal

3. We would like you to imagine that the entire public transport system was no longer available for that day of your last public transport trip. How would you travel to your destination for the trip?
4. Why would you choose to travel by that mode? If you would decide not to take that trip if public transport was not available, why would you cancel the trip?
5. Of the factors affecting your mode choice if public transport was not available, which do you think are the most influential?
6. Why would you not choose to travel by other modes (e.g. bike, walk, taxi or cancel the trip)?

Data Analysis

The interview recordings were transcribed verbatim. Transcripts of the interviews were entered into NVIVO 10 software to facilitate the organisation and structuring of the process of coding and classification, and to develop relationships among concepts. Interviews were analysed independently to avoid imposing the beliefs of one participant on our interpretations of others. This qualitative study is based on ‘grounded theory’ (Glaser and Strauss, 1967), which provides an interactive framework for data analysis. Grounded theory is a method of analysing qualitative data which is grounded in the data without preconceived theories and is characterised by intensively analysing data, often sentence by sentence or phrase by phrase. Data obtained by the questionnaire was also entered into an SPSS file to calculate descriptive statistics.

According to Sandelowski (2001), the qualitative data should be reinforced by quantitative counts of participants discussing certain factors influencing their choice of transport mode. Hence, when a factor was discussed by more than 75% of participants, I refer to it as “almost all”, for between 50% and 75% I use the term “a lot of”, for between 25% and 50% I use “some” and for less than 25% I use “few”.

4.2.2 Quantitative Approach

Data collection

The data employed in this paper was gathered from a panel survey conducted in April 2016 across each of the 31 Local Government Areas in metropolitan Melbourne, Australia. This data was collected with the assistance of a market research company from people who used public transport in weekday morning peak (7am-9am). This period was focused in this study since the level of traffic congestion at this time is expected to be the highest. Hence, the congestion would become the most serious when there is mode shift from public transport users to car in the event of a public transport withdrawal. A sampling frame targeting spatial spread (across 31 LGAs) and demographics characteristics (gender and age) was used to insure the representativeness of the collected sample. Thus, a number of screening questions related to the origin and age of participants were designed to collect the needed sample.

The survey required respondents to complete a structured questionnaire designed by the candidate with both revealed and stated preference questions. A pilot survey was conducted in March 2016 and corrections effected before the full-scale survey was carried out in April 2016. The questionnaire was divided into three major parts: socio-economic characteristics, public transport trip characteristics and flexibility in travel behaviour. This questionnaire was designed based on the results of a qualitative research investigating the mode shift of public transport users in the event of a public transport withdrawal (refer to section 4.2.1). It covered the following areas:

1. The socio-economic part of the survey solicited information on gender, age, vehicle (car and bike) ownership, driver’s license ownership, number of adults with a drivers’ license in the household and weekly income.
2. The second part of the questionnaire was designed to gather information regarding the context of the last public transport trip that respondents undertook such as trip purpose, station accessibility and the weather conditions during their trip. Respondents were also asked to provide locations that they started and ended their trips. With this information, the researcher could estimate trip distance and identify whether a trip was to the CBD, the area which is expected to have a high level of traffic congestion and high parking costs, or not.

3. In the last part of the questionnaire, respondents were asked to imagine that the entire public transport system (including train, bus and tram) was not available for the whole day of their last public transport trip and that they were given prior-notification about this disruption. Respondents were then asked about their likely behavioural reactions (a choice-set including seven options: drive a car, take a lift, take taxi/Uber, cycle, walk, cancel trip and other). In addition, respondents were asked to state the most important reasons associated with their decision for choosing this alternative mode by rating the importance of each potential motivator affecting their choices. The motivator items were rated on a scale of 1-5, 1 being 'not important' and 5 being 'very important'. Users were also asked to rate reasons for not choosing one of the other alternative modes. These reasons provided in the questionnaire were identified from previous interviews with public transport users conducted in July 2015 in Melbourne, Australia (refer to section 4.2.1). Additionally, respondents were also asked to imagine that individual public transport modes (train, bus and tram) were not available for the whole day of their last public transport trip. In this case, public transport users were able to switch to alternative public transport modes.

Firstly, an email was sent to all members of a market research panel to invite them to take part in the study by answering an on-line questionnaire. In the email invitation, each panel member was given a link to access the questionnaire. A reminder email was sent to those who had not accessed the questionnaire one week after the initial email was sent. Data was collected over a 3-week period during autumn and reflects autumn travel behaviour. A total of 3,559 people accessed the survey in which 670 respondents (18.8%) passed a screening process and completed the questionnaire.

Data Cleaning and Selection

In order to mitigate bias in the survey response, several strategies were implemented to clean the data. Firstly, respondents who completed the survey much sooner than the expected time of completion (20 minutes) were considered a potential 'skimmer' and data provided by them was checked carefully. Secondly, observations with no meaningful value on any of the key outcome variables were discarded from further analysis. Finally, respondents who selected the same answer value for all Likert scale questions were recognised as severe 'skimmers' and were removed from the final dataset. After removing a number of skimmers who might have accessed the survey with the purpose of getting monetary benefits (22 respondents), a total of 648 respondents were used for the analysis.

Data Analysis

A Multinomial Logit Model (MLM) was used to predict categorical placement in or the probability of category membership on a dependent variable based on multiple independent variables (McFadden, 1980, McFadden and Reid, 1975, McFadden, 1976). In this study, this model was used to investigate the travel behavioural reaction of public transport users in the event of a public transport disruption and factors influencing it. It was therefore able to show when one specific factor (independent variable) changed, how a behavioural reaction would follow and whether some factors had a bigger effect on the choice than others.

There were four behavioural reactions in the case of this study's MLM: car as a driver, car as a passenger, non-motorised modes and trip cancellation. The probability that the i_{th} public transport user would choose j_{th} behavioural reaction was given by $P_{ij} = P_r(R_{ij} > R_{ik})$, for $k \neq j, j = 0, 1, 2, 3$, which represent different choices, with R_{ij} being the maximum utility attainable for user i if the user chooses j_{th} behavioural reaction and $R_{ij} = \beta_j' X_{ij} + \varepsilon_{ij}$, where β_j' is a vector of coefficients of each of the explanatory variables. If the stochastic terms ε_{ij} have the independent and Weibull distribution, the MLM can be expressed as:

$$Prob(i|Y = j) = \frac{e^{\beta_k' x_{ij}}}{\sum_{k=0}^{j} e^{\beta_k' x_{ij}}} \qquad (j=0, 1, 2, 3) \qquad (4.1)$$

The parameters (β) are estimated by maximising a log likelihood function. To standardise the model, one of behavioural reactions (j_0) is chosen as a reference case so $\beta_0' = 0$. The remaining vector coefficients $(\beta_1', \beta_2', \beta_3')$ measure the change relative to the reference case.

4.3 Results

4.3.1 Qualitative Results

Table 4.3 details the characteristics of the interview participants (16 males and 14 females, aged between 18 and 50 years). All participants lived in metropolitan Melbourne with incomes of up to $1999 per week.

The following results present an outline of key findings including verbatim quotes from the participants identified by individual participant number (e.g. P29). Where applicable, results are compared to known findings in the published research literature to assess their place within the context of previous research.

The results show that the choice of mode shift among public transport users is influenced by several factors; after consideration these were classified into three major categories:

- 'individual-specific factors',
- 'context-specific factors' and
- 'journey-specific factors'.

Individual-specific factors included car ownership, driving license ownership, number of cars available in the household, number of adults in the household, and income. Context-specific factors consisted of travel distance, travel time, travel cost, trip destination, weather and flexibility. Journey-specific factors included accessibility to public transport stations and trip purpose. Results under each of these headings are now discussed.

Table 4.3 Profile of respondents (*n*=30)

No	Age	Gender	Employment status	Income ($/week)	Residential area
Participant 1	25-30	M	Student	1-399	Monash
Participant 2	31-40	F	Unemployed	0	Monash
Participant 3	25-30	F	Student	400-699	Yara
Participant 4	25-30	F	Employed full-time	1400-1999	Knox
Participant 5	18-24	F	Student	400-699	Whitehorse
Participant 6	31-40	M	Employed full-time	1400-1999	Monash
Participant 7	18-24	F	Unemployed	0	Glen Eira
Participant 8	41-50	M	Employed casual work	700-999	Glen Eira
Participant 9	31-40	M	Employed full-time	1400-1999	Boroondara
Participant 10	25-30	M	Student	400-699	Monash
Participant 11	18-24	F	Student	1-399	Darebin
Participant 12	18-24	M	Student	1-399	Port Phillip
Participant 13	18-24	F	Student	1-399	Casey
Participant 14	31-40	M	Student	400-699	Monash
Participant 15	18-24	M	Student	1-399	Casey
Participant 16	25-30	F	Employed full-time	1000-1399	Stonnington
Participant 17	18-24	M	Student	1-399	Monash
Participant 18	25-30	M	Unemployed	1-399	Mornington Peninsula
Participant 19	18-24	M	Student	0	Monash
Participant 20	18-25	F	Student	1-399	Mornington Peninsula
Participant 21	25-30	M	Employed part-time	1-399	Monash
Participant 22	31-40	M	Student	400-699	Monash
Participant 23	25-30	F	Student	400-699	Monash
Participant 24	25-30	M	Student	400-699	Monash
Participant 25	25-30	F	Student	400-699	Monash
Participant 26	31-40	M	Employed full-time	1400-1999	Darebin
Participant 27	41-50	F	Employed part-time	400-699	Darebin
Participant 28	31-40	M	Employed full-time	400-699	Mornington Peninsula
Participant 29	25-30	F	Employed full-time	1-399	Boroondara
Participant 30	41-50	F	Employed full-time	400-699	Yara

4.3.1.1 Individual-specific Factors

Availability

When public transport users choose an alternative mode in the event of a public transport strike, they have to be aware that a particular mode is possible to use and is available as an alternative option. Several sub-factors were found to affect the availability of a particular mode, as discussed below.

Car and driving license ownership

Some participants mentioned that they would choose to drive a car if public transport did not work in the short term because they already have a driving license and were able to access a private car.

> P29: "I have a car, I have a license so I will use it to travel if public transport ceases."

Students who were interviewed had a reduced ability to switch to a car because driving license and car ownership rates were lower for this group. Hence, a lot of them stated that they would cancel their education-based trips as they are not able to find any appropriate alternatives.

> P20: "I am student. I don't have a car and a license so I can't drive."

The influence of the availability of transport options on mode choice is supported by previous studies. Exel and Rietveld (2009a) stated that the ability to use particular modes may also play a major role in mode choice. Ewing et al. (2004) showed that public transport users tend to use private cars than walk and bike if they are licensed drivers and cars are available in their households.

Number of available cars in a household

Few interviewees expressed that the number of cars available in their household might impact on car mode shift. They mentioned that they have only one car in their household but had to share this car with their partners on the day they took public transport. Thus, they could not access a car if public transport was not available.

> P18: "I share a car with my partner so when they use the car, I am not able to use it. But if they aren't using the car that day and I need it, I could take it."
>
> P28: "We have only one car in my house so we have to share it. If public transport is not available, I would drive. I would have to take my wife to her workplace and drive to here."

Another participant who had a driving license but did not own a car thought that she could borrow a car from her relatives or friends in her household if it was available.

> P30: "I don't have a car but I can borrow it from my husband."

The number of available cars in a household has been identified as having a significant relationship with car mode choice. Limtanakool et al. (2006) stated that car availability has a strong influence on mode choice for every trip purpose. Kim and Ulfarsson (2004) found that the number of available vehicles significantly reduces the propensity to select public transport as a travel mode and increases the propensity toward private vehicles.

Number of adults in a household

Few public transport users participating in an interview believed that car mode shift can be affected by the number of adults in a household. They mentioned that they do not have a driver's license yet, but relatives or friends in their household could access a car so they could ask them to provide a lift if public transport was not available.

> P20: "(if the entire the public transport system is removed) My dad has to drop me then, both my mum or my dad can drop me."
>
> P25: "I believe my husband or my house mates would give me a lift. They have cars and can drive."

The number of adults in a household has been found to influence mode shift to car as a car passenger. Kim and Ulfarsson (2004) argue that small households are therefore less likely to carpool or vanpool, given them have less opportunity to travel by private vehicle with their own household members.

Income

A relationship between income and mode shift of public transport users was discussed by some interviewees. Lower incomes were found to limit the flexibility that individuals have to consider using other (more expensive) modes.

> P12: "I am a student. I don't have any money to pay for a car. I don't have a license."

In contrast, people with higher incomes were more likely to choose more expensive transport modes such as driving.

> P28: "I can pay for parking. It's not a problem."

Income has been identified as having a significant relationship with the mode choice of car in previous studies. The probability of taking the car for chained trips increases with household income (Hensher and Reyes, 2000). There is also a relationship between income and car ownership (Golob, 1990, Dargay, 2001). Kim and Ulfarsson (2004) revealed that households with $35,000 or higher annual income have a greater propensity towards selecting private vehicles and a reduced propensity to use public transport as compared with walking.

4.3.1.2 Context-specific Factors

Travel distance

Almost all interviewees stated that travel distance is a critical factor affecting mode shift if public transport is unavailable. If their trip distance is longer than typical walking or cycling distances they would tend to travel by private car or even cancel the trip if public transport is no longer available.

> P27 "I have to drive, there is no other option, I can't walk. If the hospital is closer I would bike or if the distance is a walking distance I would walk. But the distance is too far to any of those things."

Trip length is considered to be an important feature in the choice of travel mode (Bergström and Magnusson, 2003, McConville et al., 2011, Müller et al., 2008). Long distances are a barrier to pedestrian and bicycle travel so travellers tend to use a car for long trips. For shorter trips, the car can be replaced by several alternatives such as public transport, walking and cycling (Carse et al., 2013). Müller et al. (2008) indicated that distance is the most important factor discriminating between modes of transport associated with higher costs (public transport and car/motorcycle) and those with lower costs (walking and cycling).

Travel time

A lot of interview participants highlighted travel time, suggesting that this might be one of the main factors affecting their mode shift if public transport is unavailable. Travel time components generally consist of in-vehicle time, out-of-vehicle time, walking, and waiting time. For long distances, they were more likely to choose the fastest transport mode, usually the private car. However, for moderate distances in the CBD, cycling may be the fastest transport mode.

> P27: "I think I would switch to bike because it is the fastest way to get to my destination. Driving a car you have to find parking. Especially in the CBD it takes a lot of time for that."
>
> P5: "I have to drive because of the distance, 30km. I want to get to work quickly. Driving is quicker than cycling, walking"

The finding is supported by existing literature. Beirao and Cabral (2007) mention that travel time is an important factor affecting mode choice. Frank et al. (2008) showed how relative associations between travel time, costs, and land use patterns where people live and work impact mode choice and trip chaining patterns.

Travel cost

Travel cost for almost all respondents was perceived as a key factor in choosing an alternative mode. If public transport ceases in the short term, they are likely to find an appropriate alternative mode with the lowest cost. Twenty five out of thirty interviewees indicated that they would not choose to use a taxi as an alternative because of the high cost. A few people would get a lift from their friends or relatives if public transport is unavailable because they can share the travel cost. For short and medium distances, walking or cycling was deemed as generally the cheapest way to travel compared to taxi or private car.

> P21: "It's much cheaper for me to ask my friend to drop me. I do pay him some money but not as much as I would pay with a taxi."
>
> P9: "I would work at home because if I want to go to my office I have to hire a car. It is costly."

The effect of travel cost on mode choice has been noted in many previous studies (Simons et al., 2013, Cervero, 2002, Johansson et al., 2006). According to Simons et al. (2013), travel cost is considered a barrier for choosing transport modes. Cervero (2002) and Johansson et al. (2006) also found that travel cost is significant.

Trip destination

It was mentioned by some participants that the destination of a trip would influence mode shift if public transport ceases in the short term. They said that in the city centre it is difficult and expensive to park. Few interviewees said they would cancel their trips because they would not be able to find any suitable alternative.

> P24: "I would cancel the trip…I can drive, I can go by car. It's possible. But the problem is the parking cost. When I go to the city I cannot find any parking and the parking cost is really very high."

Traffic congestion was also perceived as a barrier by some interviewees. They believed that congestion often occurs on the way to the city centre and this is the main reason for using public transport. If public transport is unavailable, they said they would cancel their trip. Few participants would consider driving but would leave very early to avoid peak hours.

> P15: "I can't drive to the city because I live too far, you must worry about parking in the city and traffic in the morning would probably take longer if you are travelling by car."

This finding is consistent with previous studies on how parking cost affects mode choice. According to Exel and Rietveld (2009a), trip destination is a particularly important determinant of people's mode choice set. Hess (2001) investigated the travel behaviour of commuters in Portland, Oregon and argued that parking costs have an significant influence on mode choice.

Weather

Weather also played a role in mode choice, particularly in choosing between motorised and non-motorised transport modes. Some participants felt that bad weather had a negative effect on active forms of transport (walking, cycling). However, it is noted that the interviews were conducted from August to October when the temperature was relatively cold and there were many wet weather days. Thus, participants may have been more likely to identify the influence of weather on mode selection than in other seasons.

> P3: "If it is warmer I will cycle again, if the weather is very terrible I would call a taxi or ask my friends to pick me up."
>
> P5: "The weather is a factor (affecting your choice) as well. You know, in a car you would be warmer."

Considering the effect of weather on mode choice, Sabir et al. (2008) revealed that in (extremely) low temperatures, people tend to switch from biking to car and public transport, whereas people prefer walking and biking as temperatures increase. Saneinejad et al. (2012) explored the impact of weather conditions on the transport mode choice of commuters. They found that younger individuals' tendencies to walk and bike are more negatively affected by cold temperatures than older age groups. Müller et al. (2008) examined adverse effects of school closures on transport mode choice in urban areas. The results of the multivariate analysis illustrate that weather and season have a strong influence on transport mode choice for students' travel-to-school.

Flexibility

Flexibility has a significant influence on the choice of mode. Some respondents stated that if public transport was no longer available, they would choose to use a car as it is more flexible than other modes, especially in suburban areas where congestion is less severe. In contrast, in central areas such as the CBD, travelling by car is less flexible because of congestion and parking costs. Differences in flexibility are also noted between travelling by car as a driver and a passenger.

> P26: "It's (driving a car) too convenient for time. I drop my children at school and then drive to my office and pick them up again. Another reason, I must go to my office and drive to another meeting."
>
> P13: "It is convenient because it gets me where I want to go."

Existing literature has suggested that flexibility can play a major role in influencing public transport users' mode shift. Beirao and Cabral (2007) indicated that convenience and flexibility are important influencing factors which have an impact on mode choice towards the car.

4.3.1.3 Journey-specific Factors

Accessibility to public transport stations

Public transport users can access public transport stations by walking, cycling or using a private car through Park and Ride/ Kiss and Ride (PNR/KNR). PNR schemes generally aim to reduce car use to CBDs so PNR services are often subsidised to attract car users to use public transport (Meek et al. 2008). Few public transport users who participated in an interview parked their cars at a station and took public transport to their destination because they felt that public transport is the best way to travel to their destination. However if public transport became unavailable, they may shift to car since they had already used a car for part of the trip. On the other hand, few public transport users mentioned that they used PNR because they drive their children to school on the way to work.

> P26: "I took my children to school and I parked my car at the train station and took the tram to my office". "[If public transport is removed] I would use my car, I would drop my children at school and then drive to my office and pick them up again."
>
> P25: "My husband took me to the train station and I took the train to my uni. If there is no public transport, I believe he would take me to the uni."

In this study, accessibility to public transport stations can be recognised as a new factor affecting the shift from public transport to car. This factor has not been identified in previous studies exploring mode choice.

Purpose of trip

If public transport is not available, the purpose of the trip is a key factor affecting the decision of public transport users to choose alternative modes or cancel the trip. Some public transport users recognised that they would cancel their trip if it is not too important.

> P10: "The purpose of my trip is socialisation (attending a club meeting) so I would cancel it if public transport is removed."
>
> P19: "The purpose of that trip is to sightsee in the city, that trip's not important, just for fun…I will cancel the trip (if public transport is not available)."

For education-based trips, a lot of participants who are students stated that it would be difficult to arrive on time when shifting to other modes so they would study at home instead. With trips related to work, travel decisions are more complex. Some jobs can be undertaken from home so it is possible to cancel the trip.

> P6: "I will just cancel that trip. I work in IT so it is okay if I work from home or an alternative location to the Clayton campus. I don't have to travel to my office in the city. In IT you can do that. I have a laptop all the time. I can connect to the internet from home."

However, some jobs require a face to face meeting so participants have to find an alternative mode to go to work.

> P9: "I go to work. I need to be in my office because I need to interact with other people, to talk with other people so this trip is extremely important…I would hire a car if I really really have to go to my office."

Exel and Rietveld (2009c) found that the choice to cancel the trip in the scenario of a train strike was more likely for education-based trips. Kim and Ulfarsson (2004) indicated that trip purpose impacts on mode choice. The elderly are more likely to share a ride with others when chaining trips, doing errands, or going to a medical appointment and are less likely to use public transport when going shopping or doing errands.

4.3.2 Quantitative Results

The quantitative results are presented in four main parts. First, the demographics of the sample is compared to that of the broader population. Second, respondent characteristics and travel reactions to public transport service withdrawal are presented. Third, the results of the MLM analysis that explores factors affecting the behavioural response of users are described. Reasons reported by respondents for shifting to other transport modes are then shown.

4.3.2.1 Sample Coverage

Table 4.4 shows the survey sample comprised 323males (49.8%) and 325 females (50.2%). The highest proportion (23.1%) of respondents were 30-39 year olds, closely followed by 18-29 year olds (21.8%) and 40-49 year olds (20.5%). Users aged from 50 to 59 years accounted for the lowest proportion of respondents (16.5%). A chi-squared test was conducted to compare the gender and age distribution between the sample and Melbourne's public transport user population from the 2011 Census. The results of the chi-square test showed that the sample was representative of the broader public transport user population.

Table 4.4 Comparison of gender, age ratios between sample and public transport population in census

Characteristic		Survey		Census*		Chi-squared χ^2
		Number of respondents (n)	Proportion (%)	Expected Value (n)	Proportion (%)	
Gender	Male	323	49.8	322	49.7	0.0031
	Female	325	50.2	326	50.3	0.0031
Age	18-29	141	21.8	152	23.5	0.8582
	30-39	150	23.1	127	19.6	3.5267
	40-49	133	20.5	122	18.8	0.9098
	50-59	107	16.5	102	15.7	0.2336
	60+	117	18.1	145	22.4	6.7009
Total		648	100	648	100	

* Population with a journey to work by public transport in Melbourne (2011 Census)
$\chi^2_{Gender}(0.062) < \chi^2_{Critical}(6.635)$, $\chi^2_{Age}(12.229) < \chi^2_{Critical}(13.227)$
The level of significance for this test is α=0.01

4.3.2.2 Respondent Characteristics

Table 4.5 provides a summary of respondents' demographic and travel characteristics. The number of licensed drivers was five times more than that of non-licensed drivers. There was a similar ratio of respondents owning a car and those without a car (about 5:1). More than 90% of the respondents reported that they had no health concerns preventing them from driving a car. The majority (45.4 %) of the sample had one car in their households, followed by those with two cars (31.5%). Regarding trip purpose, around 65.7% of the respondents said that they used public transport to go to work while only 7.6% of trips in the survey were related to education. In the survey, two-thirds of the respondents made trips to the Central Business District (CBD) and a third of users accessed public transport stations by car (Park and Ride (PNR) or Kiss and Ride (KNR)). Many respondents (54.3%) travelled more than 10 km for their public transport trips, nearly 18.2% travelled between 5 km and 10 km and the rest (about 27.5%) had a trip distance of less than 5 km.

4.3.2.3 Travel Reaction to Service Withdrawal

Table 4.6 presents the distribution of the behavioural reactions of public transport users as well as the average travel distance. Public transport trips which would be undertaken by car as a driver in the event of major public transport withdrawal accounted for the highest proportion (51.1%) of the sample and had the highest average travel distance (17.2 km). More than 13% of public transport trips (with an average travel distance of 17 km) would be cancelled. Short distance trips would be conducted by cycling (average travel distance of 5.6 km) and walking (average travel distance of 3.7 km). These distances, while relatively long, are considered to be reasonable for a one-day nature of the disruption. Around 5% of the respondents would switch to taxi/Uber and 2.3% would shift to other modes such as motorcycle or scooter. It can be seen that long distance trips were likely to be conducted by car or cancelled when public transport services were no longer available. By contrast, public transport users with short distance trips were likely to switch to non-motorised modes.

Due to the low frequencies recorded for some cells, the seven behavioural reactions were aggregated into four categories: car as a driver, car as a passenger (take a lift and take a taxi/Uber), non-motorised mode (cycle and walk) and cancel trip. Shifting to ‘other’ modes was not considered in the analysis as it accounted for only 2.3% of respondents. The final total sample used for statistical analysis was 633 respondents.

Table 4.7 presents the characteristics of respondents stratified by travel behavioural reactions when public transport ceases. It reveals that the majority of respondents in all age groups would shift to car as a driver (ranging from 46.6% to 63.5%). With respect to income, a higher proportion (59.2%) of respondents with average weekly income above $1,300 would shift to car as a driver whilst only 35.9% of those earning less than $250 per week chose this option. A high proportion of respondents with a driver’s license (61.8%) or a car (64.6%) would shift to car as a driver if public transport ceases. In contrast, the majority of those without a driver’s license or a car would switch to a car as a passenger, non-motorised modes or would cancel their trips. The more adults in a household with a drivers’ license, the higher share of respondents who would shift to a car as a passenger. With respect to trip frequency, the majority of respondents in all the trip frequency categories (49-56.9%) would shift to car as a driver. In terms of trip purpose, the highest proportion (59%) of trips related to work would be conducted by car as a driver while this ratio for educational trips was only 36.2%. The majority of trips related to education would be conducted by car as a passenger (25.5%) and non-motorised modes (23.4%). More trips to the CBD would be cancelled than trips not to the CBD when public transport was not available (15.5% compared to 9.4%). The majority of respondents (73.7%) accessing public transport stations by car would switch to a car as a driver while only 4.1% of those would shift to non-motorised modes. Out of the 176 respondents who travelled less than 5 km, a relatively high proportion (46%) would shift to non-motorised modes while only 9.1% would cancel their trips. In contrast, 63.8% of trips over 10 km would be undertaken by a car as a driver.

Table 4.5 Characteristics of respondents

Variables	Elements	Number of respondents	Percentage (%)
Income ($/week)	< $250/week	79	12.2
	$250 – 1,300/week	298	46.0
	> $1,300/week	271	41.8
Driver's license ownership	No	100	15.4
	Yes	548	84.6
Health concerns that prevent you from driving a car	No	595	91.8
	Yes	53	8.2
Private car ownership	No	135	20.8
	Yes	513	79.2
Number of adults with driving license in a household	None	32	4.9
	One	190	29.3
	Two	317	48.9
	More than two	109	16.8
Number of cars in a household	None	74	11.4
	One	294	45.4
	Two	204	31.5
	More than two	76	11.7
Number of bicycles in a household	None	264	40.7
	One	182	28.1
	Two	108	16.7
	More than two	94	14.5
Trip frequency	4 times per week or more	257	39.7
	1-3 times per week	205	31.6
	1-3 times per month	115	17.7
	Less than once per month	71	11.0
Weather	Hot, scorching	15	2.3
	Rainy, wet, miserable, damp	77	11.9
	Windy, dull, grey	133	20.5
	Cold, chilly	115	17.7
	Warm, mild, fine, dry	308	47.5
Trip purpose	Related to work	426	65.7
	Related to education	49	7.6
	Other	173	26.7
Trip to the CBD	No	219	33.8
	Yes	429	66.2
Accessibility PNR&KNR	No	427	65.9
	Yes	221	34.1
Travel distance	Less than 5 km	178	27.5
	5 – 10 km	118	18.2
	Above 10 km	352	54.3

Table 4.6 Behavioural reaction distribution and travel distance

Behavioural reactions	Behavioural reactions (used for analysing)	No. of respondents	Percentage (%)	Average travel distance (km)	Minimum (km)	Maximum (km)	Std. Deviation
Drive a car as a driver	Car as a driver	331	51.1	17.2	1.5	64.6	11.96
Take a lift	Car as a passenger	68	10.5	17.0	1.8	42.7	10.66
Take taxi/Uber	Car as a passenger	32	4.9	11.9	0.5	39.5	12.22
Cycle	Non-motorised mode	35	5.4	5.6	0.6	16.5	3.76
Walk	Non-motorised mode	82	12.7	3.7	0.3	13.8	3.15
Cancel trip	Cancel trip	85	13.1	17.0	0.5	49.9	11.61
Other		15	2.3	13.0	4.8	21.5	5.99
Total		648	100				

Table 4.7 Respondent characteristics by behavioural reactions

Variables	Behavioural reactions of public transport users when public transport is unavailable (%)				Total sample size (n)
	Car as a driver	Car as a passenger	Non-motorised modes	Trip cancellation	
Gender					
Female	51.4	16.4	17.0	15.1	317
Male	53.2	15.2	19.9	11.7	316
Age					
18 - 29	49.3	23.2	18.8	8.7	138
30 - 39	53.1	16.3	21.8	8.8	147
40 - 49	46.6	13.7	25.2	14.5	131
50 - 59	63.5	9.6	10.6	16.3	104
60 and over	51.3	14.2	13.3	21.2	113
Income ($/week)					
< $250/week	35.9	28.2	19.2	16.7	78
$250 – 1,300/week	50.3	13.8	17.9	17.9	290
> $1,300/week	59.2	14.3	18.9	7.5	265
Driver's license ownership					
No	2.9	39.2	25.5	25.5	102
Yes	61.8	11.3	17.1	11.1	531
Health concerns that prevent you from driving a car					
No	53.3	14.6	19.1	13.1	582
Yes	41.2	29.4	11.8	17.6	51
Private car ownership					
No	3.9	36.7	32.8	26.6	128
Yes	64.6	10.5	14.9	10.1	505
Number of adults with license in a household					
None	6.5	29.0	35.5	29.0	31
One	45.2	12.4	28.0	14.5	186
Two	60.6	14.1	13.1	12.2	312
More than two	53.8	23.1	12.5	10.6	104
Number of cars in a household					
None	1.5	23.5	45.6	29.4	68
One	50.2	13.7	20.6	15.5	291
Two	67.0	15.5	9.5	8.0	200
More than two	67.6	17.6	9.5	5.4	74
Number of bicycles in a household					
None	45.2	16.2	18.5	20.1	259
One	60.9	13.4	17.9	7.8	179
Two	56.2	17.1	14.3	12.4	105
More than two	51.1	29.0	35.5	29.0	90
Trip frequency					
4 times per week or more	49.0	16.6	21.3	13.0	253
1-3 times per week	56.9	15.3	17.3	10.4	202
1-3 times per month	49.5	11.0	18.3	21.1	109
Less than once per month	55.1	21.7	11.6	11.6	69
Weather					
Hot, scorching	38.5	23.1	30.8	7.7	13
Rainy, wet, miserable, damp	41.1	16.4	34.2	8.2	73
Windy, dull, grey	51.2	17.8	16.3	14.7	129
Cold, chilly	54.0	21.2	14.2	10.6	113
Warm, mild, fine, dry	55.4	12.5	16.7	15.4	305
Trip purpose					
Related to work	59.0	12.1	17.7	11.2	356
Related to education	36.2	25.5	23.4	14.9	47
Other	45.2	19.6	18.7	16.5	230
Trip to the CBD					
No	53.5	20.7	16.4	9.4	213
Yes	51.7	13.3	19.5	15.5	420
Accessibility PNR&KNR					
No	41.1	17.8	26.0	15.1	416
Yes	73.7	12.0	4.1	10.1	217
Travel distance					
Less than 5 km	31.8	13.1	46.0	9.1	176
5 – 10 km	49.1	14.3	23.2	13.4	112
Above 10 km	63.8	17.7	2.9	15.7	345

4.3.2.4 Model Results

Table 4.8 shows the results of the fitted multinominal logit model. The final model was selected using backwards elimination and Akaike Information Criterion (AIC) techniques. The diagnostic results of the fitted model suggest a good fit. The statistically significant, sizeable negative intercept value for "car as a driver" (-6.04, p<0.001) indicates that this behavioural response had considerably lower odds compared to the reference case 'non-motorised modes' in this sample.

Table 4.8 Multinominal Logit Model specification

Variables		Switch to car as a driver			Switch to car as a passenger			Trip cancellation		
		Coeff	p	S.E.	Coeff	p	S.E.	Coeff	p	S.E.
Age	18 - 29	Ref		-	Ref.		-	Ref.		-
	30 - 39	-0.55		0.44	-0.42		0.49	-0.17		0.57
	40 - 49	-0.64		0.45	-0.62		0.51	0.32		0.56
	50 - 59	0.75		0.54	0.32		0.62	1.78	***	0.64
	60 and over	-0.08		0.52	-0.16		0.61	1.17	*	0.63
Driver's license ownership	No	Ref.		-	Ref.		-	Ref.		-
	Yes	1.22	**	0.59	-0.26		0.49	-0.53		0.53
Health concerns	No	Ref.		-	Ref.		-	Ref.		-
	Yes	1.09	*	0.63	1.56	**	0.61	0.94		0.67
Private car ownership	No	Ref.		-	Ref.		-	Ref.		-
	Yes	1.43	**	0.67	-1.55	***	0.55	-1.03	*	0.61
Number of cars in household	None	Ref.		-	Ref.		-	Ref.		-
	One	2.90	**	1.19	1.24	**	0.57	0.87		0.60
	Two	3.45	***	1.22	1.86	***	0.66	0.68		0.72
	More than two	3.62	***	1.29	1.79	**	0.82	0.39		0.95
Number of bicycles in household	None	Ref.		-	Ref.		-	Ref.		-
	One	-0.28		0.35	-.72	*	0.41	-1.27	***	0.43
	Two	0.13		0.44	0.27		0.50	-0.18		0.52
	More than two	-1.03	**	0.46	-0.84		0.51	-1.85	***	0.61
Trip frequency	4 times per week or more	Ref.		-	Ref.		-	Ref.		-
	1-3 times per week	0.79	**	0.34	0.09		0.41	0.04		0.45
	1-3 times per month	0.53		0.45	-0.67		0.54	0.44		0.52
	Less than once per month	1.24	**	0.60	0.93		0.65	0.23		0.72
Trip purpose	Other	Ref.		-	Ref.		-	Ref.		-
	Related to education	0.44		0.64	-0.60		0.67	-0.03		0.73
	Related to work	0.36		0.36	-0.71	*	0.43	-0.48		0.46
Trip to the CBD	No	Ref.		-	Ref.		-	Ref.		-
	Yes	-0.27		0.31	-0.24		0.35	0.51		0.39
Accessibility PNR&KNR	No	Ref.		-	Ref.		-	Ref.		-
	Yes	1.12	***	0.43	0.64		0.50	0.69		0.52
Travel distance	Less than 5 km	Ref.		-	Ref.		-	Ref.		-
	5 – 10 km	1.10	***	0.36	1.13	**	0.45	1.41	***	0.48
	Above 10 km	3.10	***	0.41	3.43	***	0.47	3.78	***	0.51
Intercept		-6.04	***		-0.69			-1.82	***	

*p < 0.05, **p < 0.01, ***p<0.001
Reference case is "switch to non-motorised modes"
Model fit: Log likelihood = -531.63, AIC = 1201.3, McFadden Pseudo R^2 =0.31

The marginal effects of each variable on each behavioural reaction are presented in Table 4.9. The reference case was a passenger of 29 years or younger who has no driver's license, no car, no health issue, and no bicycle in their household. This user took a frequent public transport trip (>= 4 times/week) not to the CBD, under 5km, for ‘other’ trip purposes and did not access stations by car.

The estimated average probabilities of the four behavioural reactions to major public transport disruptions for the reference case were: 0.534 for ‘car as a driver’, 0.203 for ‘car as a passenger’, 0.115 for ‘non-motorised modes’ and 0.147 for ‘trip cancellation’. Table 4.9 shows that users aged 50 or older were more likely to cancel their trips. Users with a driver’s license were more likely to switch to a car as a driver if public transport ceases. The same is true for users owning a car, though the marginal effect is higher. Public transport users with a private car are less likely to take a lift or cancel their trips as they can use their cars as an alternative. Users living in a household with more than one car were much more likely to shift to a car and were less likely to shift to non-motorised modes and cancel their trips. Low frequent trips with work related trip purposes were more likely to be conducted by a private car when public transport was unavailable, and less likely to be undertaken by a car as a passenger. In addition, trips to the CBD were more likely to be cancelled. One possibility is that travellers decided to cancel their trips due to the expected high level of traffic congestion and high parking costs. Finally, people who had undertaken a mid (5-10 km) or long (over 10 km) distance trip by public transport, as well as accessed stations by a car, were considerably less likely to choose non-motorised modes such as cycling or walking and more likely to use a private car for their trips.

Table 4.9 Multinominal Logit Model: Marginal effects on behavioural responses

Variables		Switch to car as a driver		Switch to car as a passenger		Switch to non-motorised modes		Trip cancellation	
		dy/dx p	S.E.	dy/dx p	S.E.	dy/dx p	S.E.	dy/dx P	S.E.
Age	18 - 29	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	30 - 39	-0.056	0.538	-0.011	0.039	0.044	0.042	0.023	0.049
	40 - 49	-0.089	0.058	-0.040	0.039	0.042	0.042	0.088	0.056
	50 - 59	-0.010	0.063	-0.060	0.039	-0.083*	0.039	0.153*	0.066
	60 and over	-0.077	0.063	-0.048	0.042	-0.021	0.046	0.146*	0.066
Driver's license ownership	No	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	Yes	0.259**	0.080	-0.095	0.059	-0.038	0.049	-0.127*	0.063
Health concerns	No	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	Yes	0.021	0.068	0.090	0.056	-0.101**	0.038	-0.011	0.045
Private car ownership	No	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	Yes	0.413***	0.068	-0.313***	0.079	0.024	0.047	-0.124	0.067
Number of cars in household	None	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	One	0.268**	0.087	-0.027	0.049	-0.175**	0.051	-0.066	0.050
	Two	0.343**	0.104	-0.005	0.061	-0.200***	0.045	-0.138**	0.051
	More than two	0.315***	0.079	-0.023	0.058	-0.169***	0.032	-0.123***	0.032
Number of bicycles in household	None	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	One	0.053	0.039	-0.029	0.031	0.057	0.032	-0.080**	0.026
	Two	0.013	0.048	0.027	0.042	-0.010	0.039	-0.030	0.033
	More than two	-0.044	0.053	0.010	0.043	0.118*	0.047	-0.084**	0.029
Trip frequency	>= 4 times/week	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	1-3 times/ week	0.115**	0.038	-0.035	0.032	-0.046	0.030	-0.035	0.031
	1-3 times/ month	0.086	0.048	-0.095**	0.032	-0.024	0.037	0.033	0.040
	< 1 time/ month	0.119*	0.055	0.022	0.050	-0.084*	0.040	-0.057	0.038
Trip purpose	Other	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	Related to education	0.092	0.069	-0.070	0.037	-0.011	0.051	-0.010	0.051
	Related to work	0.125**	0.044	-0.089*	0.040	0.008	0.033	-0.044	0.036
Trip to the CBD	No	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	Yes	-0.051	0.035	-0.025	0.029	0.011	0.028	0.064*	0.026
Accessibility PNR&KNR	No	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	Yes	0.108**	0.039	-0.015	0.035	-0.085*	0.035	-0.008	0.033
Travel distance	Less than 5	Ref.	-	Ref.	-	Ref.	-	Ref.	-
	5 - 10	0.037	0.053	0.019	0.045	-0.109***	0.026	0.053	0.048
	Above 10	0.127**	0.044	0.088**	0.033	-0.329***	0.033	0.115***	0.032

*p < 0.05, **p < 0.01, ***p<0.001
Reference case: a passenger of 29 years or younger who has no driver's license, no car, no health issue, no bicycle in their household. The user takes a frequent public transport trip (>= 4 times/week) not to the CBD, under 5km for 'other' purpose and does not access stations by car.

4.3.2.5 Reasons for Shifting to other Transport Modes

Table 4.10 and Table 4.11 reveal the most important reasons reported by respondents for shifting and not shifting to other transport modes in the event of major public transport disruptions. Respondents who would choose to shift to a car rated driver's license ownership as the most important factor affecting their choices. The flexibility of the car and the availability of car parking were ranked as the second and the third most important reason respectively. Regarding mode shift to car as a passenger, the three most important factors were the availability of a driver, safety and travel time. The high level of concern for travel cost and travel distance by respondents who would switch to non-motorised modes indicated the importance of these factors. For those who would cancel their trips in the event of major public transport disruptions, trip distance and the unavailability of alternative modes were rated as matters that strongly influenced their decisions.

By contrast, respondents who would not shift to a car as a driver stated that they were highly concerned about the availability of parking, parking costs and traffic congestion. Long travel distances and the influence of weather were the key reasons that respondents would not switch to non-motorised modes when public transport was removed.

The coefficient of variation for each reason reported in Table 4.10 and Table 4.11 (ranging from 0.18 to 0.42) indicate a limited and acceptable range of responses (Reed et al., 2002).

Table 4.10 Importance of reasons for shifting to other transport modes

1 = not important, 5 = important				
Transport mode	Rank	Reasons	Mean	Coefficient of variation
Car as a driver (n=331)	1	I have a driver’s license	4.30	0.21
	2	I feel a car is flexible because I can travel anytime	4.02	0.24
	3	I can find a parking spot easily at my destination	3.96	0.25
Car as a passenger (n=68)	1	My relatives/friends have cars and they can take me	3.78	0.24
	2	I feel safe when travelling with people I know	3.69	0.26
	3	It is the quickest way to get the destination	3.62	0.28
Taxi/Uber (n=32)	1	I have no other alternative	4.06	0.27
	2	I am able to cover the cost of the taxi/Uber fare	3.94	0.22
	3	It is the quickest way to get the destination	3.84	0.25
Bike (n=35)	1	I can save money	4.41	0.18
	2	I can avoid traffic congestion	4.03	0.19
	3	I own a bike	4.03	0.25
Walk (n=82)	1	The distance to my destination is not far	3.95	0.27
	2	I feel relaxed when walking	3.93	0.27
	3	Facilities for walking to my destination are convenient.	3.89	0.28
Cancel trip (n=85)	1	The trip distance is too long	3.73	0.35
	2	I have no alternative travel mode	3.72	0.35
	3	I can reschedule my trip to another day	3.26	0.37

Table 4.11 Importance of reasons for not shifting to other transport modes

1 = not important, 5 = important				
Transport mode	Rank	Reasons	Mean	Coefficient of variation
Car as a driver (n=302)	1	It is difficult to find a car park	3.70	0.37
	2	Traffic congestion on my route is high	3.62	0.37
	3	The cost of parking at my destination is too high	3.59	0.39
Car as a passenger (n=565)	1	I do not want to depend on other people	3.87	0.29
	2	I cannot find anyone who has the same route as me	3.74	0.33
	3	I do not want to bother my relatives/friends	3.69	0.33
Taxi/Uber (n=601)	1	I am not able to cover the cost of a taxi	3.74	0.34
	2	Traffic congestion on my route is high	3.45	0.35
	3	Taxi drivers often choose a longer journey so I have to pay more money	3.35	0.37
Bike (n=598)	1	Travelling by bicycle is dependent on weather conditions	3.87	0.29
	2	Travel by bicycle is dangerous	3.78	0.32
	3	I have to travel a long distance	3.78	0.34
Walk (n=551)	1	I have to travel a long distance	4.30	0.33
	2	Travelling by walking is dependent on weather conditions	3.99	0.26
	3	Travelling by walking is time consuming	3.95	0.28
Cancel trip (n=548)	1	The trip is too important	4.12	0.24
	2	I have options available which I prefer to use	3.47	0.34
	3	I need to have face-to-face interaction	3.19	0.42

4.3.2.6 Behavioural response of public transport users when each public transport mode ceases in the short term

Table 4.12 provides information about the stated behavioural reactions to each public transport mode withdrawal among public transport users. In the event of a train withdrawal, a relatively high proportion of train users would shift to car as a driver (39.4%), particularly in outer areas where the mode shift is 55.0%. The number of users switching to other public transport modes (tram and bus) accounts for around 40% of train users in total. Non-motorised modes were chosen by less than 5% of train users, while 6.6% said that they would cancel their trips.

In the event of a tram withdrawal, 34% of tram users would switch to train, while only 12% would shift to bus. In the inner city, a relatively high proportion of tram users would choose to walk (25.2%), which is much higher than the proportion who would choose to walk in the event of a train withdrawal (2.7%). The number of tram users who would shift to car as a driver accounted for only 15%.

The highest share of bus users 28.9% would shift to car as a driver as a result of a bus withdrawal. This is followed by mode shift to train (23.5%) and tram (11.8%). Only 11% of bus users would choose to walk while around 9% would cancel their trips.

Table 4.12 also shows the share of mode shift to car when individual public transport modes cease. Train withdrawal is expected to generate the highest mode shift to car (42.7%). This is followed by bus withdrawal and tram withdrawal with 33.5% and 16.7% respectively. These figures are substantially different for each part of metropolitan Melbourne, reflecting the traffic characteristics of those areas. For example, in the event of a train withdrawal, mode shift to car in outer areas is nearly triple that for the inner city. In contrast, mode shift to car in outer areas is the lowest if tram operations cease, reflecting the predominance of the tram network in the inner and middle areas. These figures are used in the four-step transport model (VITM) to examine the expected changes in traffic congestion during public transport withdrawal.

Table 4.12 Behavioural response of public transport users when each public transport mode ceases in the short term

Behavioural reactions	**Train (%)** *(n=433)*				**Tram (%)** *(n=234)*				**Bus (%)** *(n=187)*			
	Inner	Middle	Outer	**Total**	Inner	Middle	Outer	**Total**	Inner	Middle	Outer	**Total**
Train	-	-	-	**-**	29.3	37.5	43.6	**34.2**	28.2	26.8	18.2	**23.5**
Tram	45.5	21.2	4.1	**20.7**	-	-	-	**-**	28.2	8.5	6.5	**11.8**
Bus	14.3	21.8	20.5	**19.4**	11.4	13.9	12.8	**12.4**	-	-	-	**-**
Car as driver	18.8	37.2	55.0	**39.4**	13.8	19.4	10.3	**15.0**	23.1	32.4	28.6	**28.9**
Car as passenger	4.5	6.4	8.2	**6.6**	1.6	5.6	5.1	**3.4**	2.6	8.5	13.0	**9.1**
Taxi/Uber	3.6	1.9	1.2	**2.1**	4.9	1.4	5.1	**3.8**	0.0	4.2	1.3	**2.1**
Cycle	6.3	1.3	0.6	**2.3**	7.3	2.8	2.6	**5.1**	7.7	0.0	2.6	**2.7**
Walk	2.7	2.6	1.2	**2.1**	25.2	11.1	10.3	**18.4**	5.1	9.9	15.6	**11.2**
Cancel the trip	2.7	7.1	8.8	**6.6**	4.9	5.6	7.7	**5.6**	5.1	8.5	10.4	**8.6**
Other	1.8	0.6	0.6	**0.9**	1.6	2.8	2.6	**2.1**	0.0	1.4	3.9	**2.1**
Total	100.0	100.0	100.0	**100.0**	100.0	100.0	100.0	**100.0**	100.0	100.0	100.0	**100.0**
Mode shift to car*	21.1	40.4	59.1	**42.7**	14.6	22.2	12.9	**16.7**	24.4	36.7	35.1	**33.5**

*Mode shift to car = mode shift to car as driver + 0.5 x mode shift to car as passenger

4.4 Discussion

This section firstly discusses the findings of the qualitative research which sought to provide an in-depth understanding of the behavioural reaction of public transport users when public transport ceases in the short term. Then, the results of the quantitative research are discussed. In the final section, policy implications regarding traffic congestion caused by public transport withdrawals is discussed.

Qualitative Results

The qualitative findings show that when public transport ceases in the short term, public transport users would switch to alternative modes such as travelling by car (as a driver or a passenger), cycling, walking or cancelling the trip. These shifts are not influenced by one factor alone but by a combination of factors. Factors influencing public transport users' mode choice when public transport ceases are categorised into three major themes: Individual-specific factors (car ownership, driver's license ownership, number of available cars in household, number of adults in household, income), context-specific factors (travel distance, travel time, travel cost, trip destination, weather, flexibility) and journey-specific factors (accessibility to public transport stations, trip purpose). Figure 4.1 proposes a conceptual model of mode shift to car among public transport users when public transport ceases in the short term based on these findings.

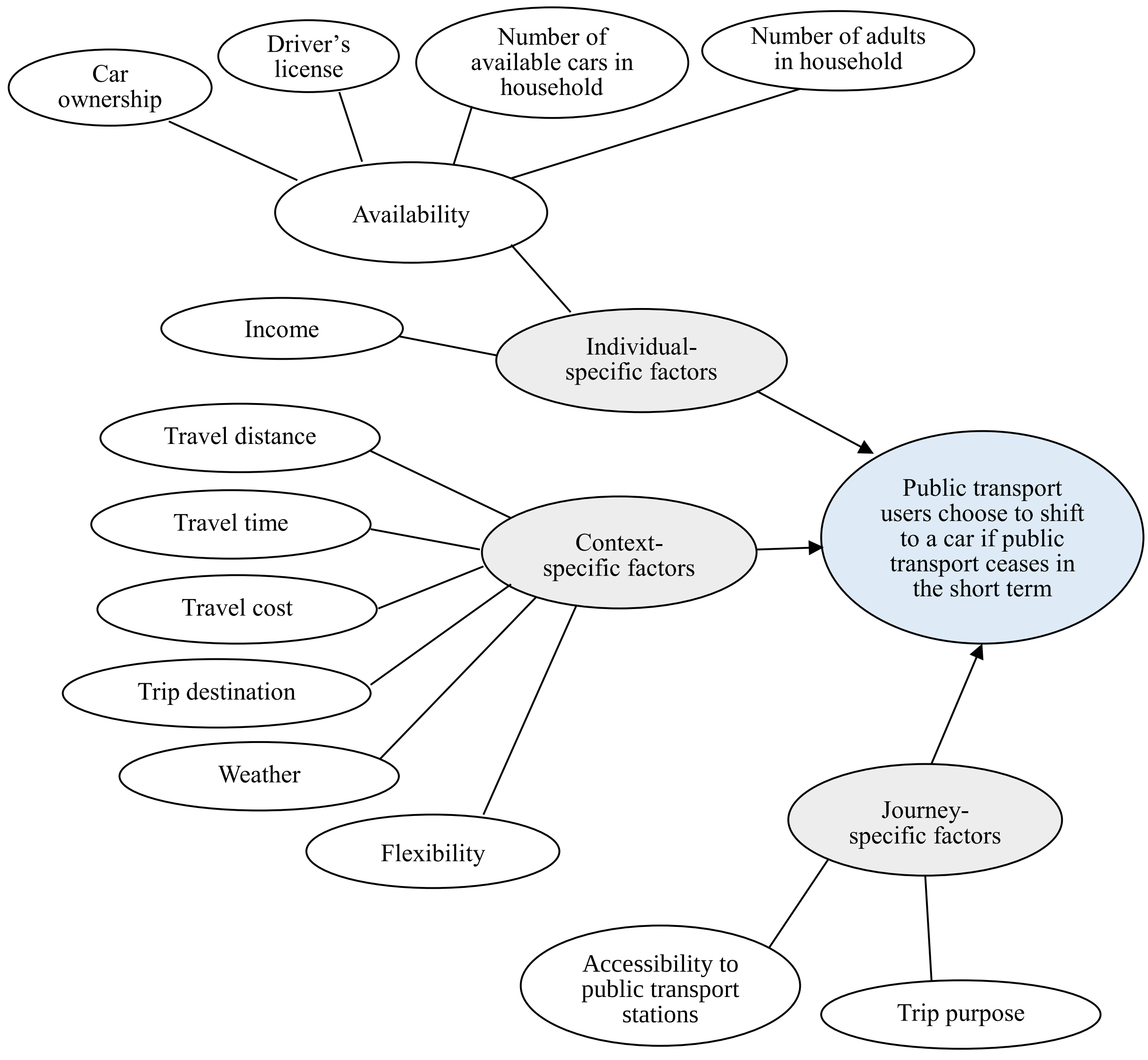


Figure 4.1 Conceptual model of mode shift to car among public transport users if public transport ceases in the short-term

Source: Authors concept based on the qualitative results

The interplay between good access to transport modes, travel time, travel cost, trip importance, non-CBD trips, weather, flexibility and PNR/KNR accessibility to public transport stations are the most important factors in favour of choosing a car if public transport is removed. In contrast, the choice of non-motorised modes (cycling and walking) is impacted by factors such as limited access to a private car, travel time and travel cost. Limited access, travel time, travel cost, trip importance, inflexibility, and safety are the most important factors affecting the decision to cancel the trip if public transport ceases in the short term.

This research found that driving was the most popular alternative transport mode that public transport users would choose. Throughout the interviews, it was clear that driving a car offered several benefits for public transport users. The main barrier for driving identified by this study is travel cost. However, a number of other factors were identified as influencing the decision of choosing a car such as the availability to access a car and accessibility to a public transport station. Someone who is accessing a public transport station with PNR or KNR would tend to use a car as an alternative if public transport ceases because they have already used it for part of their journey.

This research found that a lot of participants would choose to cancel their trips if public transport ceases in the short term. The main reason for not undertaking the trips is that they were not considered too important. Other participants felt that they could work from home so do not have to go to their workplace.

There are two key limitations to the findings reported in this research. Firstly, a large proportion of participants was students and staff from a university in Melbourne. More public transport users from other areas and backgrounds would help to establish a stronger understanding of the factors affecting mode shift to car. Secondly, the interviews were conducted during winter/spring. Ideally, the interviews should be carried out in different seasons so that the effect of weather on public transport users' choice can be understood more clearly. Further research in this area will help in developing a richer understanding of mode shift choices when public transport ceases.

Quantitative Results

An important finding of the quantitative survey was that in the event of a major public transport withdrawal, 52% of users would switch to car as a driver and 11% would shift to car as a passenger. The mode shift to car as a driver is higher than other estimates (5%-50%) explored in previous studies around the world (Exel and Rietveld, 2001) and over 20% higher than the figure estimated by Aftabbuzzaman et al. in the Melbourne context (Aftabuzzaman et al., 2010a). From secondary data, they suggested that on average, only 32% of public transport users would shift to car and then used this figure to assess the congestion relief associated with public transport. Thus, it is expected that public transport operations in Melbourne could have a much higher contribution to reducing traffic congestion than that previously determined.

The multinominal logit analysis showed that public transport users with a driver's license or a car prefer using a car than other modes if operation of the entire public transport system ceases. As expected, the more cars a household owned, the more likely an individual living in such a household would shift to a car as a driver. Trips made infrequently (once a month or less) were more likely to be undertaken by car. The same is true for trips related to work as public transport users had to be on time at their workplace. This is consistent with the findings of Exel and Rietveld (2009b). However, users with trips to the CBD were more willing to cancel their trips. One possibility is that travellers decided to cancel their trips is the expected high level of traffic congestion and high parking costs in this area. Users who accessed public transport stations by car were more likely to shift to a car in the event of public transport disruptions since they had already used a car for part of their trip. Travel distance was confirmed to have a significant correlation with mode shift (Exel and Rietveld, 2009b, Pnevmatikou et al., 2015). In particular, trips over 5 km were less likely to be conducted by non-motorised modes. These trips were considerably more likely to be made by a car as a driver or a passenger, or cancelled. New factors impacting mode shift investigated in this study are driver's license, car ownership, health concerns, the number of vehicles in household, trip destination (in the CBD or not) and station accessibility. These findings help to explain why the expected mode shift from public transport to private car when public transport in Melbourne is unavailable is higher than other cities worldwide. Melbourne has a relatively high car ownership rate, high driver licensing rate, high proportion of public transport trips related to work as well as a high proportion of public transport users accessing stations by car. A city is therefore expected to also have a high mode shift to car if it has characteristics similar to Melbourne.

In addition, the survey provided additional insight into the most important reasons for shifting and not shifting to other transport modes in the event of a major public transport disruption. The results show that the availability of parking, and parking costs, have a significant influence on the mode shift to car as a driver. Users were not likely to shift to car if their trips were to a place with limited parking availability and high parking costs, such as the CBD. These findings are consistent with previous studies on how parking costs and parking availability affect the choice of driving a car (Voith, 1998, Gillen, 1977).

As public transport removals do not occur often, the survey was carried out to investigate the behavioural reaction of public transport users if public transport was not available only for their last public transport trip in the weekday morning peak (a hypothetical situation). It is noted that the context of the termination of service - whether of limited duration and/or known in advance, and whether or not other adaptations in market choices - might affect trip making, mode choices and trip distribution patterns. In the future, the switching behaviour in actual withdrawal events should be observed in order to gain a better understanding about the mode shift of public transport users.

Policy Implications

This research has provided a better understanding of public transport users' choice of alternative transport modes when public transport is unavailable. The findings would be of interest to transport planners and decision makers for designing policies aimed at reducing the potential mode shift to car in the event of a public transport strike. For example, the following strategies could be considered:

- *Increasing the number of real time passenger information systems*. This research showed that the main reasons public transport users did not choose to shift to a car were the anticipated high levels of traffic congestion and lack of available car parking. Different types of information pre-journey, en-route and post-journey, which can be provided by using appropriate channels before and during a journey, is extremely valuable for road users as it can influence their travel behaviour (Papangelis et al., 2016, Beecroft and Pangbourne, 2015).
- *Increasing road capacity.* Allowing vehicles to travel or park in priority bus lanes or tram lanes would be an appropriate measure to increase road capacity during public transport strikes. For instance, in Los Angeles in 1974, bus lanes were opened for carpools to reduce congestion during a 10-week bus strike (Crain and Flynn, 1975b). In New York, on-street parking in the inner city was banned to ease the movement of traffic during a public transport strike (New York City Transit Authority, 1967).
- *Increasing car parking charges.* The research findings revealed that the high cost of parking was a key factor preventing respondents from driving a car. Thus, in order to limit private car use, parking charges could be increased. This measure is supported by previous findings related to the effect of parking fees on mode choice behaviour (Hess, 2001, Wilson, 1992).
- *Encouraging carpooling*. Carpooling has been successfully adopted in some cities to facilitate a mode shift from driving alone (Parkany, 1999). Carpooling could therefore be

considered when public transport is unavailable, potentially in conjunction with reducing tolls and parking charges for carpoolers.

- *Implementing flexible working times.* In Melbourne, public transport trips related to work account for approximately 80% of all public transport trips in the AM peak (Victorian Government, 2013). The findings revealed that trips related to work, considered to be important trips, were more likely to be undertaken by car if public transport was unavailable. Implementation of flexible working times at employment sites could be provided in order to reduce the number of car trips during public transport disruptions (Abkowitz, 1981).
- *Improving safety for pedestrians and cyclists*. Respondents felt that it was more dangerous to walk and cycle in areas with high levels of congestion. In order to encourage people to shift to non-motorised modes, safe walking and cycling routes should be provided. In cities which have bike-sharing systems, they could be free in the event of a public transport strike to encourage mode shift from car users and reduce the level of congestion.

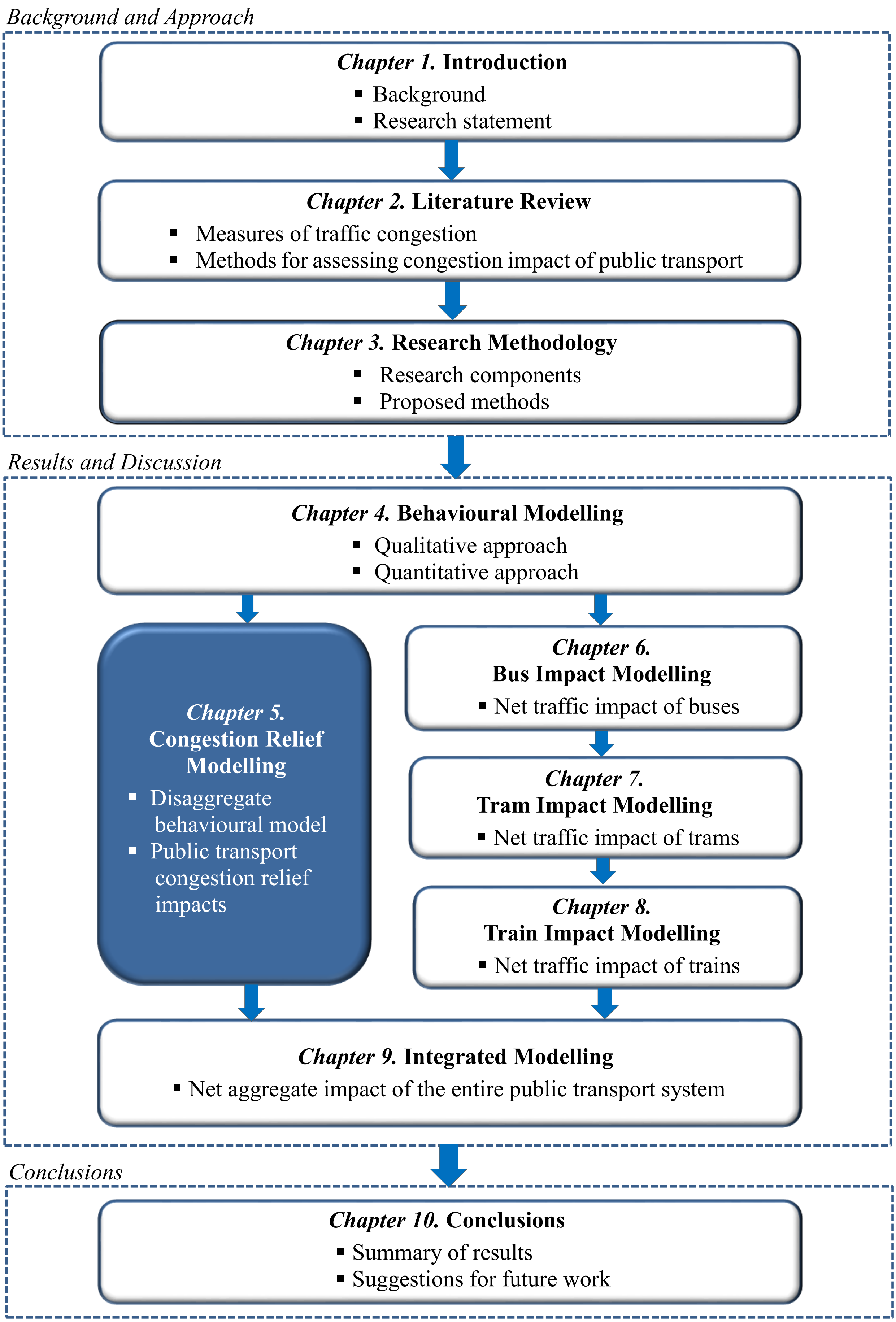
4.5 Conclusions

The aim of this chapter was to gain a better understanding of the behavioural response of public transport users if public transport withdrawal occurs in the short term. In doing so, a mixed methods research approach provided insights on factors influencing mode shift from public transport and potential solutions to reduce mode shift to car.

The findings of the qualitative research have provided a basis for developing a conceptual model that attempts to structure the public transport user's mode shift process in the event of the removal of public transport in the short term. The conceptual model consists of multi-dimensional factors which provide a tentative explanation of how public transport users switch to a car. Quantitative research was then carried out to verify the factors influencing the travel behavioural response of a larger population of public transport users.

The survey findings presented in this chapter have laid an important foundation for further chapters of this thesis. Based on a better understanding of mode shift when public transport is unavailable, particularly mode shift to private car, the congestion relief impact of public transport can be estimated.

This chapter also discussed a number of measures which can be implemented to reduce the level of congestion resulting from mode shift from public transport to car in the event of a public transport withdrawal. The next chapter presents the methodology to examine the congestion relief impact associated with public transport as well as the results.


Background and Approach
Chapter 1. Introduction
Background
Research statement
Chapter 2. Literature Review
Measures of traffic congestion
Methods for assessing congestion impact of public transport
Chapter 3. Research Methodology
Research components
Proposed methods
Results and Discussion
Chapter 4. Behavioural Modelling
Qualitative approach
Quantitative approach
Chapter 5. Congestion Relief Modelling
Disaggregate behavioural model
Public transport congestion relief impacts
Chapter 6. Bus Impact Modelling
Net traffic impact of buses
Chapter 7. Tram Impact Modelling
Net traffic impact of trams
Chapter 8. Train Impact Modelling
Net traffic impact of trains
Chapter 9. Integrated Modelling
Net aggregate impact of the entire public transport system
Conclusions
Chapter 10. Conclusions
Summary of results
Suggestions for future work

Chapter 5
CONGESTION RELIEF MODELLING

5.1 Introduction

The previous chapter provided an understanding of factors affecting mode shift from public transport to other transport modes when public transport is unavailable in the short term. In doing so, a mixed methods research approach, which integrated qualitative research and quantitative research, was undertaken with public transport users in Melbourne. This chapter expands this research by presenting improved methods to estimate the congestion relief effect of an entire public transport system. This is in accordance with research objective 2 to develop improved methods to estimate the positive impact of public transport on relieving traffic congestion. Table 5.1 details the research objective, research components, research gaps and research opportunities associated with this chapter.

Table 5.1 Research objective, gaps and opportunities associated with research components 3 and 4

Research objective	Research components	Research gaps	Research opportunities
2. To develop improved methods to estimate the positive impact of public transport on relieving traffic congestion	3. Mode shift share variation	The share of mode shift from public transport to car is assumed to be constant for all areas. However, the mode shift varies based on the traffic characteristics of each area.	Understand how the share of mode shift to car varies for different areas
	4. Public transport congestion relief impact estimation	Most research on the assessment of public transport congestion relief impacts adopted a fixed share of mode shift to car which might lead to inaccurate results	Explore the congestion relief impact of public transport using various shares of mode shift to car

In line with research objective 2, the aim of this chapter is to develop enhanced methods for estimating the congestion relief impact associated with public transport. It does this by varying mode shift from public transport to car for different regions based on their traffic characteristics.

Hence, the enhanced methods are considered to provide more precise results. The methods include two main stages. The share of mode shift from public transport to car for each Local Government Area (LGA) is firstly estimated using data from a field survey as well as secondary data (refer to section 4.3.2). These shares are then input into VITM to assess the congestion relief effect of the entire public transport system. The key aspects of these components of the research include:

- Varying the share of mode shift from public transport to car for different regions based on their traffic characteristics
- Exploring the positive effect of the entire public transport system (including train, tram and bus) on relieving traffic congestion
- Investigating the spatial congestion relief effect of public transport across Melbourne.

A journal paper was prepared based on the findings of this chapter as follows:

Paper 4 *Nguyen-Phuoc, D.Q., Currie, G., De Gruyter, C. & Young, W., 2017, 'Congestion relief and public transport: An enhanced method using disaggregate mode shift evidence',* ***Case Studies on Transport Policy (under review).***

5.2 Research Context

This section firstly provides a brief description of Melbourne and its public transport system which is used as the focus for this research. Secondly, the Victorian Integrated Survey of Travel and Activity (VISTA), which is used as secondary data in this research, is described.

5.2.1 Melbourne and its Public Transport System

Melbourne has a population of 4.53 million people over nearly 2,000 km^2 (ABS, 2016a). There are 31 Local Government Areas (LGAs) in Melbourne (VicRoads (2005)) which can be grouped into three categories (inner, middle and outer) (Figure 5.1). For this study, the central business district (CBD) plays a dominant role for many forms of retailing, employment and recreation. Melbourne has an integrated public transport system that extends from the city centre in all directions, with trains, trams and buses offering comprehensive public transport services. The public transport system in Melbourne carries 9% of all trips within the metropolitan area, or 11% when expressed in terms of passenger kilometers (Currie and Burke, 2013).

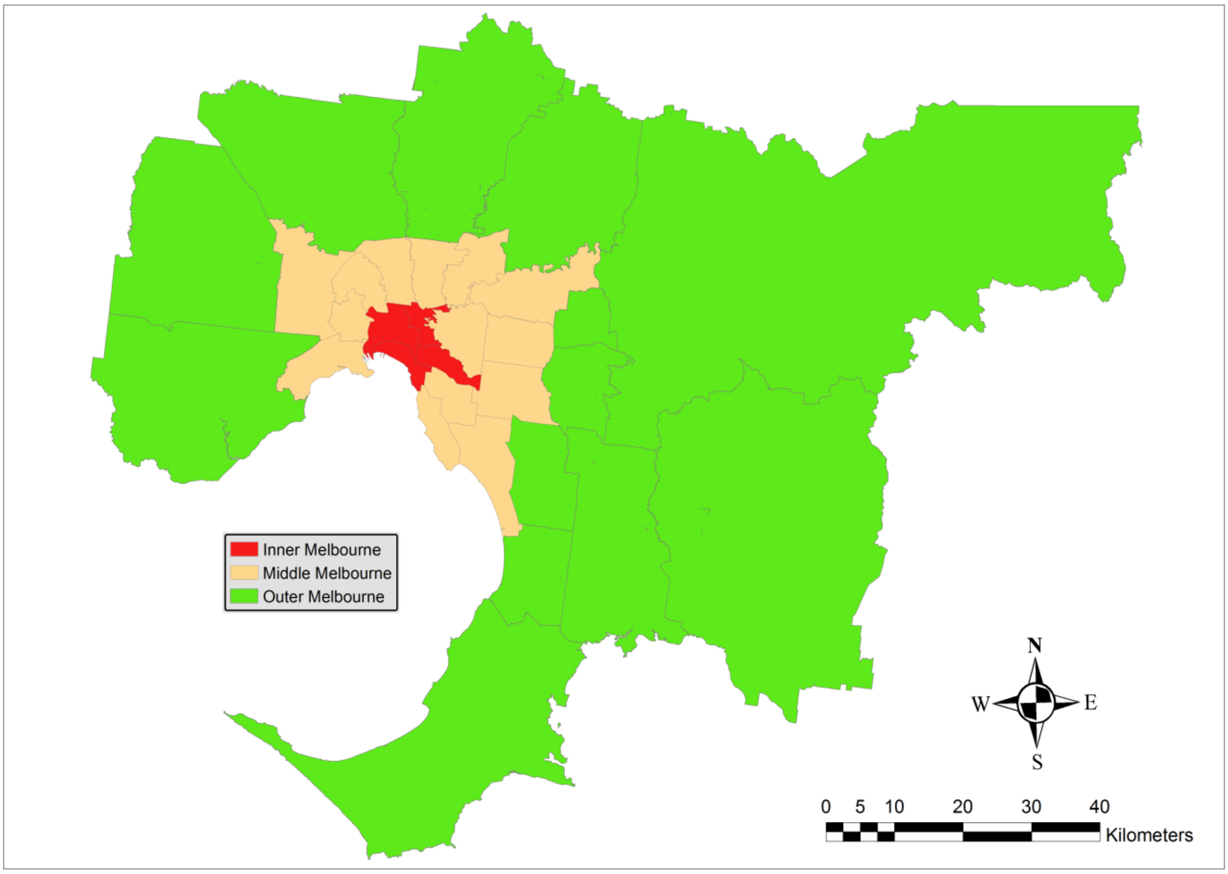


Figure 5.1 Local Government Areas in Melbourne

Melbourne's public transport system consists of heavy rail, tram and bus.

- Melbourne's heavy rail system: Melbourne's heavy rail system includes metropolitan trains, regional trains and freight trains. Melbourne's metropolitan railway network consists of 16 regular service train lines, a central City Loop subway, and 219 stations, with a total length of 830 kilometres of train track (Public Transport Victoria, 2016). The train network operates from 5:00 a.m. to midnight. The network is primarily at ground level, with more than 170 level crossings so it is not affected by road traffic. However, the exclusive right-of-way for trains may result in several impacts on vehicular traffic such as crashes or delay at at-grade railway crossings. On Melbourne's suburban railway network, there are some tracks that are shared with freight trains and V/Line regional commuter rail services. The annual report from the Victorian Department of Transport, Planning and Local Infrastructure (Public Transport Victoria, 2016) shows that the Melbourne rail network carried 233.4 million passenger trips in 2016.
- Melbourne's tram network: Tram is a major form of public transport in Melbourne. The tram network consists of 250 kilometres of double tram track, 493 trams operating across 25 routes, and 1,783 tram stops (Public Transport Victoria, 2016). It is the largest urban tram

network in the world. Tram is the second most used form of public transport in Melbourne after the commuter railway network, with a total of 203.9 million passenger trips in 2016 (Public Transport Victoria, 2016). Although tram transit has several drawbacks such as unreliability, poor running speed and safety, total tram ridership still increased by 46% between 2001-2 and 2011-12 while public transport (all mode) ridership only increased by around 9% (Currie and Burke, 2013).

- Melbourne's bus system: There are 346 bus routes in operation with a varying range of service frequencies. They are operated by 32 privately owned bus companies under a franchise from the Victorian State Government. Melbourne's bus system carries over 137.2 million passenger trips in 2016 (Public Transport Victoria, 2016). While the city relies on a radial train network and innercity tram network, the outer suburbs are primarily serviced by bus. Buses normally operate in mixed traffic conditions although there are several exclusive bus lanes provided for premium bus services.

5.2.2 Victorian Integrated Survey of Travel and Activity (VISTA)

The Victorian Integrated Survey of Travel and Activity (VISTA) conducted by the Department of Economic Development, Jobs, Transport and Resources (DEDJTR) in Victoria is an ongoing survey of household travel activity. Data is collected across the year to allow average daily travel behaviour to be measured. VISTA collects personal travel information from a sample of over 5% of Melbourne's population. The data has been weighted to match the demographics of Melbourne in the census. Recently, three surveys have been conducted including VISTA 2007-08, VISTA 2009-10 and VISTA 2012-14. In this research, all of them are used to investigate the travel patterns and personal characteristics of those who used public transport in the morning peak hour (7am-9am).

5.3 Research Methodology

There are two main steps in the research methodology. The share of mode shift from public transport to car for each LGA is firstly estimated using data from a field survey as well as secondary data. These shares are then used to assess the congestion relief effect associated with public transport with the help of the Victorian Integrated Transport Model (VITM). In order to explore the highest public transport congestion relief impact, the morning peak hour (7am-9am) was chosen as an analysis period in this research.

5.3.1 Predicting the Share of Mode Shift from Public Transport to Car

In this section, methods for estimating mode shift to car when public transport ceases are presented. Firstly, a field survey was conducted to develop a linear regression equation showing the relationship between the share of mode shift and influencing factors. Secondly, the equation was applied to the VISTA database to predict the share of mode shift to car and explore its spatial distribution across LGAs in Melbourne.

Primary Approach

The public transport user behaviour data employed in this thesis was gathered from an online survey conducted in Melbourne, Australia in April 2016 (refer to section 4.3.2). A market research company was commissioned to collect data from 648 public transport users living across Melbourne LGAs.

The field data was classified into 31 LGAs. For each LGA, the share of mode shift to car (including mode shift to car as a driver and half of the mode shift to car as a passenger[1]) was calculated. Characteristics of public transport users in each LGA were also determined such as the share of public transport users: with a driver's license (P_1), with a car (P_2), with more than one car in their household (P_3), with long public transport trip distances (more than 5km) (P_4), with a trip destination in the CBD (P_5), accessing public transport by cars (P_6), with public transport trips related to work (P_7) and the share of older public transport users (>=60 year olds) (P_8). With the figures from 31 LGAs, a linear regression relationship between the share of mode shift to car and the share of the traffic characteristics of public transport users was developed (Equation 5.1). Linear regression was chosen as this model has a good fit compared to other models. Equation 5.1 can be used to predict mode shift to car in the event of public transport withdrawal for a specific area if the values of user characteristics (P_1, P_2,…P_n) are given.

In general, the multiple regression equation of the mode shift share on P_1, P_2, … P_n is given by:

$$\text{The share of mode shift to car (\%)} = \beta + \alpha_1.P_1 + \alpha_2.P_2 + \ldots + \alpha_n.P_n \quad (5.1)$$

Secondary Approach

In order to investigate mode shift from public transport to car for LGAs in Melbourne, the VISTA database, which contains detailed travel information as well as individual information of

[1] In the case of switching to car as a passenger, this may or may not influence traffic congestion. Some car users can spend a significant amount of time for driving children to school, family members to work and elderly relatives on errands (chauffeuring trips). These trips can be particularly inefficient if drivers are required to make an empty return trip which can contribute to congestion. Thus, for the aim of modelling analysis, it is assumed that half of all car passenger trips involve chauffeuring. This is consistent with previous research exploring mode shift (Aftabuzzaman et al., 2010a).

Melbourne's public transport users, was used. From VISTA, the characteristics of public transport users for each LGA (P_1, P_2,…P_n) could be identified. By applying the linear regression equation developed from the primary survey (Equation 5.1) to these values, mode shift from public transport to car for LGAs could be predicted.

In this research, all available VISTA databases (VISTA 2007-08, VISTA 2009-10 and VISTA 2012-14) were used to get the highest available sample size (public transport users travelling in weekdays between 7-9am).

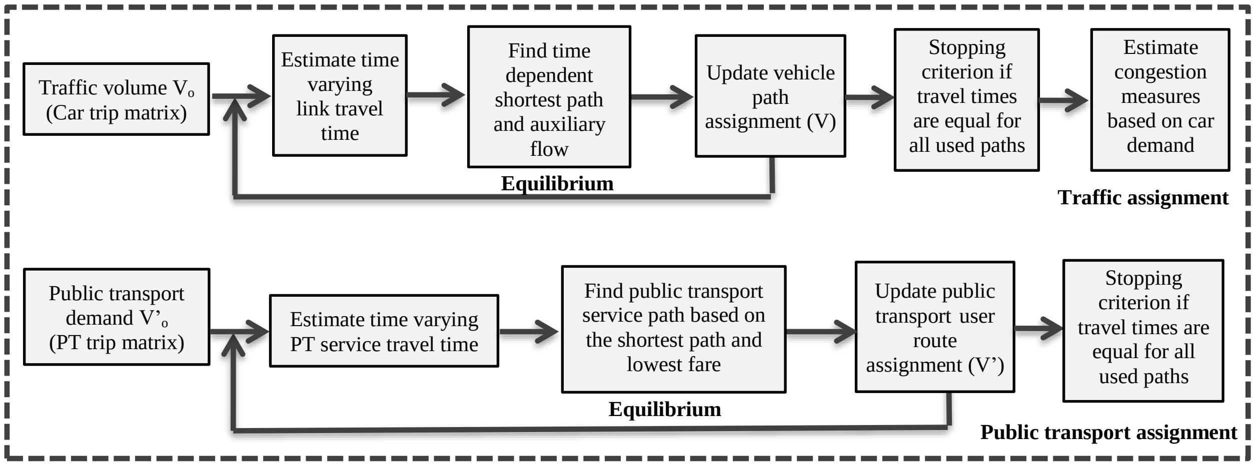
5.3.2 Modelling Traffic Congestion Relief Impact associated with Public Transport

The modelling procedure adopted an assumption regarding public transport user diversion to private car and a four step transport model was used to assess the positive impact of public transport on traffic. The modelling analysis was carried out for an average weekday morning peak (7am-9am) as the highest level of congestion occurs during this period. In this research, a decrease in the number of car trips due to the operation of public transport represents the positive effect of public transport. Hence, in order to assess this effect, it is assumed that there is a mode shift to car if public transport is removed. The number of public transport users shifting to car in the case of public transport removals represent the number of car users attracted by public transport operations.

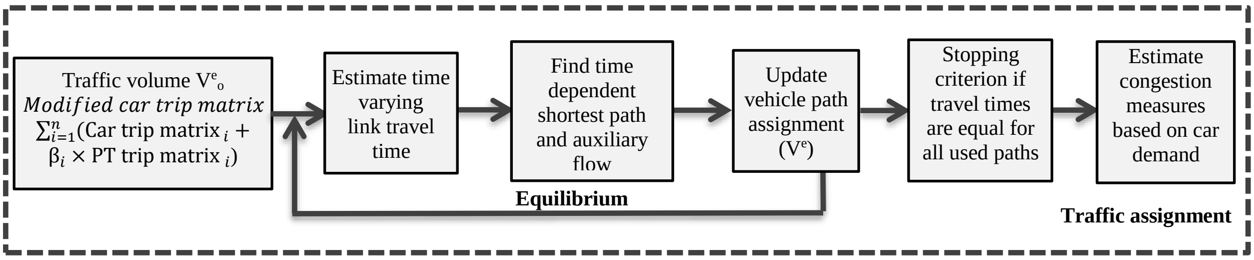
The modelling procedure comprises three major steps:

- The level of congestion on the road network in the scenario 'with public transport' is estimated with the help of VITM.
- In the scenario 'without public transport', the car trip matrix is added with a modified public transport trip matrix (public transport trip matrix is multiplied with mode shift to car which varies for LGAs) to obtain a modified car trip matrix. This matrix is then assigned on to the road network to explore the level of congestion in the case of a public transport withdrawal.
- The level of congestion in the two scenarios 'with public transport' and 'without public transport' are contrasted to investigate the congestion relief effect of public transport operations on the road network.

Figure 5.2 shows the modelling procedure for assessing the congestion relief impact associated with public transport.



(a) With public transport



(b) Without public transport

Figure 5.2 Process of estimating the level of congestion with traffic assignment in two scenarios

V_0: traffic volume from mode choice model
V: updated traffic volume
V'_0: public transport demand from mode choice model
V': updated public transport demand

β : the share of mode shift from public transport to private car (%)
V^e_0: traffic volume in the case of public transport withdrawal
V^e: updated traffic volume in the case of public transport withdrawal
n: total number of LGAs in Melbourne (n=31)

5.4 Results

This section includes two subsections. The first subsection presents the spatial distribution of mode shift to car when public transport is unavailable. The second subsection shows the positive effect of public transport on relieving traffic congestion.

5.4.1 Mode Shift to Car associated with Public Transport Removal

Primary Approach

Figure 5.3 illustrates the spatial distribution of the public transport trip origins of survey respondents. Train trips are distributed across all parts of Melbourne while a high proportion of tram trips are within the inner city. Respondents travelling by bus tend to make trips from the middle and outer areas rather than in the inner city.

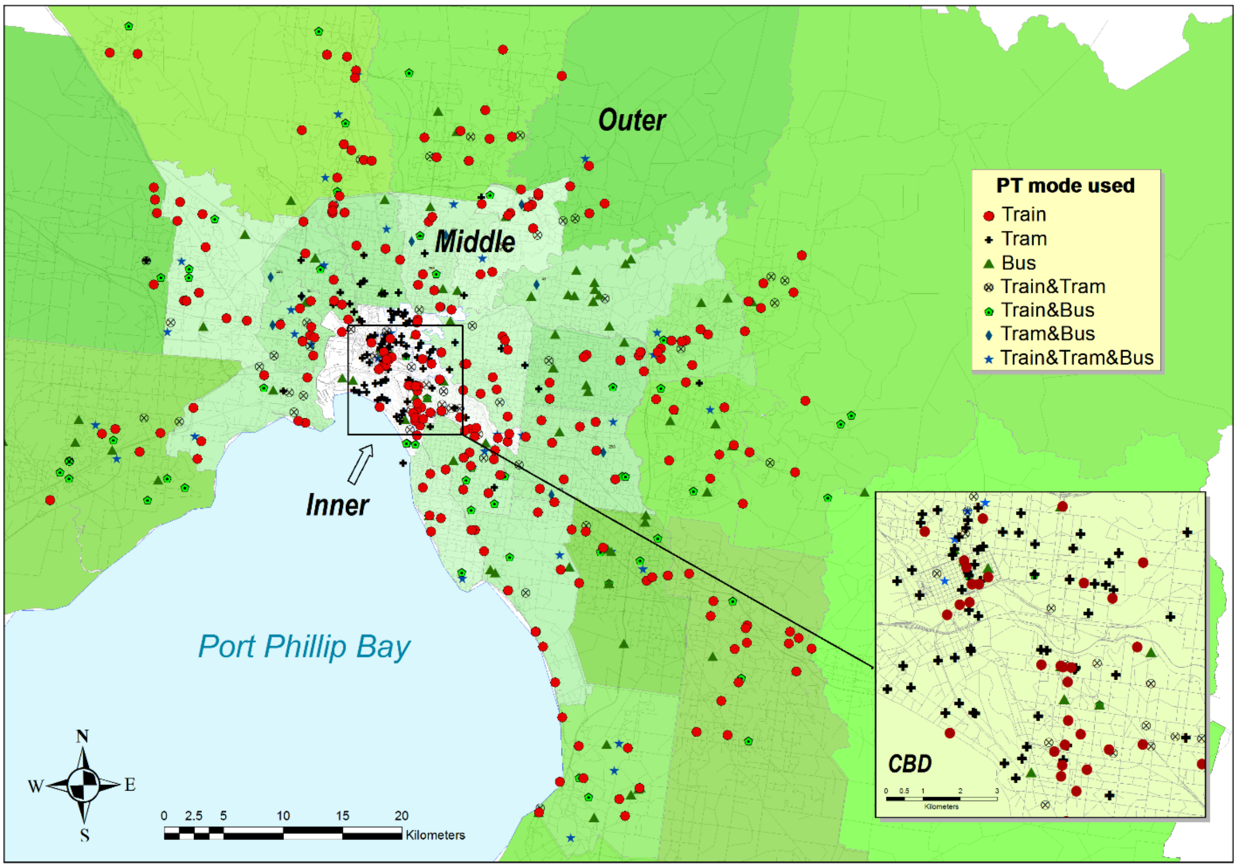


Figure 5.3 Distribution of public transport trip origins among respondents

Table 5.2 presents public transport modes used by survey respondents. As can be seen, the highest proportion of users travelled by train (68.1%), followed by tram (36.9%) and bus (29.3%). These proportions are generally consistent with the numbers of public transport users travelling between 7am-9am recorded in the VISTA database.

Table 5.2 Public transport mode distribution of users in Melbourne

Public Transport mode	Survey		VISTA**	
	No.	%	No.	%
Train	441	68.1	2,980	70.3
Tram	239	36.9	1,441	34.0
Bus	190	29.3	1,122	26.5
Total*	648		4,240	

*Total is not 100% because a number of users travelled by multiple public transport modes
**Including VISTA 2007-08, VISTA 2009-10 and VISTA 2012-14

Table 5.3 details the share of mode shift to car among public transport users in each LGA of Melbourne. Characteristics of public transport users in each LGA are also provided.

Table 5.3 Mode shift to car and characteristic of Melbourne's LGAs

	LGA	Sample size (n=648)	Car mode shift (%)	P1 (%)	P2 (%)	P3 (%)	P4 (%)	P5 (%)	P6 (%)	P7 (%)	P8 (%)
Inner	Melbourne	93	**45.7**	83.9	67.7	31.2	51.6	58.1	28.0	47.3	3.2
	Port Phillip	37	**39.2**	89.2	70.3	24.3	51.4	81.1	5.4	67.6	27.0
	Stonnington	46	**52.2**	84.8	76.1	23.9	56.5	89.1	15.2	65.2	10.9
	Yarra	32	**32.8**	68.8	68.8	28.1	15.6	84.4	0.0	43.8	18.8
Middle	Banyule	16	**62.5**	81.3	87.5	43.8	93.8	62.5	56.3	56.3	6.3
	Bayside	17	**70.6**	94.1	88.2	52.9	76.5	76.5	35.3	58.8	17.6
	Boroondara	17	**50.0**	82.4	100.0	47.1	82.4	70.6	35.3	58.8	35.3
	Brimbank	16	**68.8**	81.3	81.3	43.8	93.8	50.0	43.8	43.8	31.3
	Darebin	17	**41.2**	88.2	76.5	52.9	64.7	52.9	17.6	64.7	5.9
	Glen Eira	15	**56.7**	66.7	80.0	33.3	93.3	73.3	13.3	60.0	0.0
	Hobsons Bay	14	**60.7**	85.7	78.6	35.7	85.7	64.3	50.0	57.1	21.4
	Kingston	16	**71.9**	93.8	81.3	25.0	93.8	81.3	43.8	62.5	43.8
	Manningham	16	**81.3**	93.8	87.5	75.0	81.3	75.0	25.0	68.8	18.8
	Maribyrnong	17	**47.1**	88.2	82.4	35.3	94.1	64.7	23.5	64.7	29.4
	Monash	18	**58.3**	66.7	77.8	72.2	61.1	44.4	22.2	44.4	5.6
	Moonee Valley	16	**59.4**	81.3	81.3	56.3	56.3	62.5	18.8	43.8	31.3
	Moreland	15	**30.0**	86.7	73.3	6.7	73.3	73.3	20.0	80.0	13.3
	Whitehorse	16	**59.4**	75.0	75.0	37.5	81.3	62.5	6.3	50.0	25.0
Outer	Cardinia	15	**85.7**	100.0	85.7	71.4	85.7	71.4	71.4	71.4	14.3
	Casey	19	**78.9**	78.9	84.2	63.2	100.0	73.7	73.7	63.2	5.3
	Frankston	19	**63.2**	89.5	89.5	73.7	89.5	42.1	57.9	36.8	31.6
	Greater Dandenong	20	**55.0**	60.0	65.0	50.0	85.0	45.0	40.0	50.0	15.0
	Hume	20	**85.0**	90.0	85.0	70.0	100.0	45.0	60.0	65.0	15.0
	Knox	20	**50.0**	90.0	95.0	45.0	70.0	45.0	55.0	55.0	40.0
	Maroondah	20	**57.5**	80.0	80.0	40.0	90.0	75.0	55.0	45.0	25.0
	Melton	16	**78.1**	93.8	93.8	62.5	93.8	75.0	50.0	75.0	18.8
	Mornington Peninsula	7	**85.7**	100.0	100.0	42.9	85.7	57.1	42.9	42.9	57.1
	Nillumbik	9	**88.9**	100.0	100.0	44.4	88.9	77.8	55.6	66.7	22.2
	Whittlesea	16	**78.1**	81.3	75.0	62.5	93.8	75.0	68.8	62.5	12.5
	Wyndham	20	**62.5**	95.0	90.0	50.0	85.0	65.0	50.0	55.0	10.0
	Yarra Ranges	13	**65.2**	84.6	84.6	61.5	84.6	69.2	53.8	46.2	46.2

P1: Share of public transport users with a driver's license
P2: Share of public transport users with a car
P3: Share of public transport users with more than one car in their household
P4: Share of public transport users with long distance trips (more than 5km)
P5: Share of public transport users with trip destinations in the CBD
P6: Share of public transport users accessing public transport by car
P7: Share of public transport users making public transport trips related to work
P8: Share of older public transport users (>=60 year old)

After undertaking regression analysis, four parameters were found to be significant (p-value < 0.05) including share of public transport users with a driver's license (P1), share of public transport users with more than one car in their household (P3), share of public transport users with long public transport trip distances (more than 5 km) (P4) and share of public transport users with trip destinations in the CBD (P5) (Table 5.34). Equation 5.2 shows the relationship between the share of mode shift to car and these characteristics (P1, P3, P4 and P5). A public transport user with a driver's license and more than one car in their household, and who has a long distance trip and to the CBD is more likely to mode shift to car.

Table 5.4 Results for regression model examining the share of mode shift of public transport users

	Coefficients	*Standard Error*	*t Stat*	*p-value*
Intercept	-42.834	17.090	-2.506	0.019
P1	0.377	0.178	2.122	0.043
P3	0.501	0.111	4.498	0.000
P4	0.382	0.099	3.882	0.001
P5	0.285	0.144	1.982	0.048

R^2=0.72, adjusted R^2=0.67
P1: Share of public transport users with a driver's license
P3: Share of public transport users with more than one car in their household
P4: Share of public transport users with long distance trips (more than 5km)
P5: Share of public transport users with trip destinations in the CBD

Share of mode shift to car (%) = -42.834 + 0.377*P1 + 0.501*P3 + 0.382*P4 + 0.285*P5 (5.2)

Secondary Approach

Table 5.5 presents the distribution of the share of mode shift to car for LGAs. The mode shift for a specific area is estimated using Equation 5.2 and the values of public transport user characteristics (P1, P3, P4 and P5) in that area are determined from the VISTA database. Figure 5.4 shows the spatial distribution of four characteristics of public transport users.

Figure 5.5 illustrates considerable variation in the share of mode shift to private vehicles between inner, middle and outer Melbourne. These figures indicate the following:

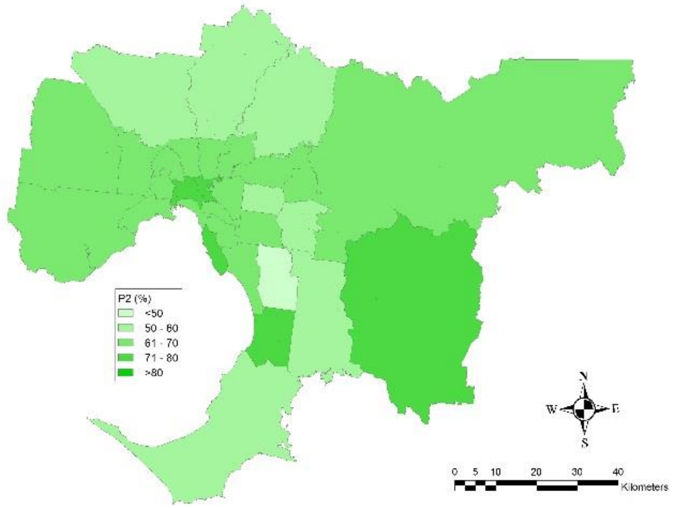
- The share of public transport users with more than one car in their household and long distance trips is lower in inner areas (such as the City of Melbourne, Port Phillip or Stonnington) and higher in middle and outer regions. By contrast, inner areas show the highest shares of public transport users with a driver's license than outer and middle areas.
- The share of mode shift to car varies considerably by LGA. This mode shift is lowest in inner Melbourne and highest in outer Melbourne.
- On average 48% of public transport users would divert to car in inner Melbourne. This figure is lowest in the city of Melbourne (38.2%). By contrast outer Melbourne has an average of approximately 67% of public transport users shifting to car, about 4% higher than middle Melbourne (63.2%) and around 20% higher than inner Melbourne. The LGA with the highest share of mode shift to private car is Cardinia (76.2%).

Table 5.5 Distribution of car mode shift for Melbourne's LGAs

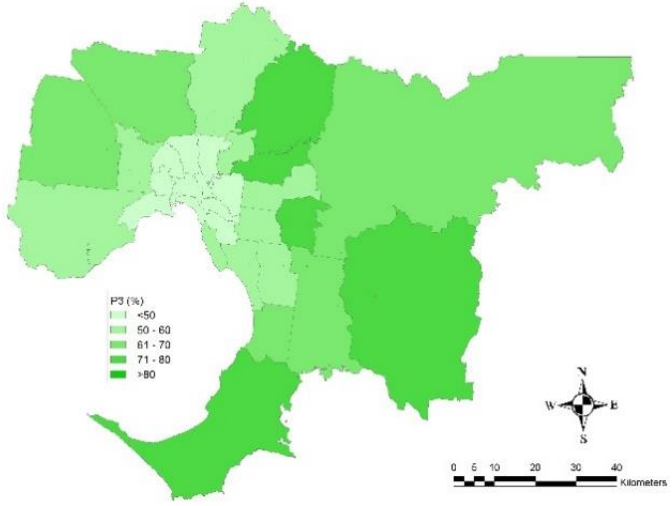
	LGA	Sample size* (*n=4240*)	P1 (%)	P3 (%)	P4 (%)	P5 (%)	Share of mode shift to car (%)	Average (%)
Inner	Melbourne	108	75.0	24.1	51.9	73.1	38.2	**48.0**
	Port Phillip	153	69.9	21.6	71.9	86.3	46.4	
	Stonnington	187	66.3	42.8	88.2	82.9	60.9	
	Yarra	180	74.4	28.3	61.7	82.8	46.6	
Middle	Banyule	150	67.3	54.0	96.0	77.3	68.3	**63.2**
	Bayside	111	72.1	52.3	94.6	79.3	69.2	
	Boroondara	243	65.4	44.4	83.5	77.4	58.1	
	Brimbank	104	64.4	58.7	98.1	72.1	68.9	
	Darebin	207	64.3	35.7	89.9	76.8	55.5	
	Glen Eira	215	65.6	49.3	94.4	80.5	65.6	
	Hobsons Bay	108	63.9	38.0	95.4	75.0	58.1	
	Kingston	172	64.5	55.2	94.8	73.8	66.4	
	Manningham	143	63.6	74.8	97.9	69.2	75.8	
	Maribyrnong	148	60.1	35.8	93.9	75.0	55.0	
	Monash	217	62.2	57.1	94.5	78.8	67.8	
	Moonee Valley	164	65.2	49.4	92.1	78.7	64.1	
	Moreland	233	61.4	36.1	87.6	71.2	52.1	
	Whitehorse	234	58.1	56.8	91.5	61.1	59.9	
Outer	Cardinia	25	72.0	76.0	96.0	60.0	76.2	**66.9**
	Casey	119	53.8	68.9	96.6	59.7	65.9	
	Frankston	72	70.8	65.3	97.2	65.3	72.3	
	Greater Dandenong	107	47.7	50.5	88.8	53.3	49.5	
	Hume	106	56.6	67.9	90.6	59.4	64.1	
	Knox	129	57.4	79.1	98.4	58.9	72.8	
	Maroondah	134	65.7	53.7	96.3	67.2	64.8	
	Melton	62	69.4	66.1	93.5	79.0	74.7	
	Mornington Peninsula	25	60.0	72.0	80.0	52.0	61.2	
	Nillumbik	84	52.4	78.6	94.0	57.1	68.5	
	Whittlesea	95	56.8	56.8	95.8	73.7	64.7	
	Wyndham	114	63.2	58.8	98.2	74.6	69.2	
	Yarra Ranges	91	60.4	68.1	98.9	50.5	66.3	

**n*=4240 users who used public transport in the morning peak hours (7am-9am). The characteristics of these users are identified using secondary data (VISTA 07-08, VISTA 09-10, VISTA 12-14)

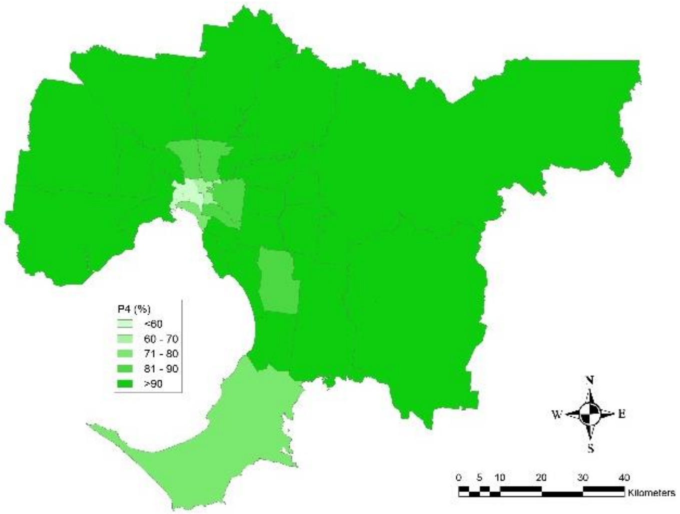
P1: Share of public transport users with a driver's license
P3: Share of public transport users with more than one car in their household
P4: Share of public transport users with long distance trips (more than 5km)
P5: Share of public transport users with trip destinations in the CBD



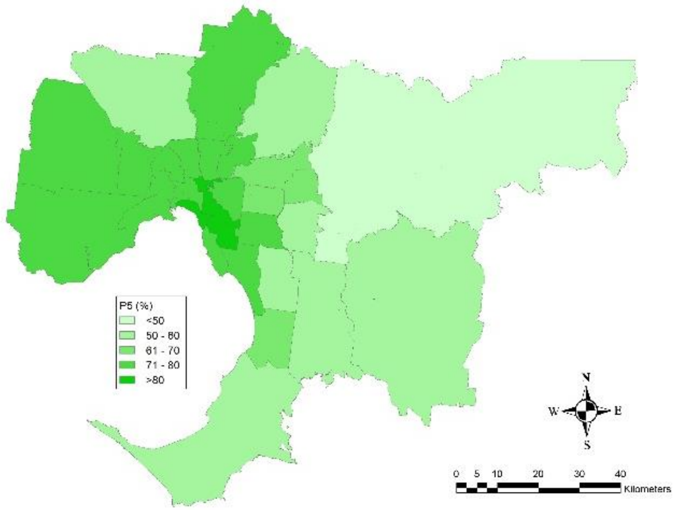
(a) Share of public transport users with a driver's license



(b) Share of public transport users with more than one car in their household



(c) Share of public transport users with a long distance trip (more than 5km)



(d) Share of public transport users with trip destinations in the CBD

Figure 5.4 Distribution of characteristics for each LGA in Melbourne

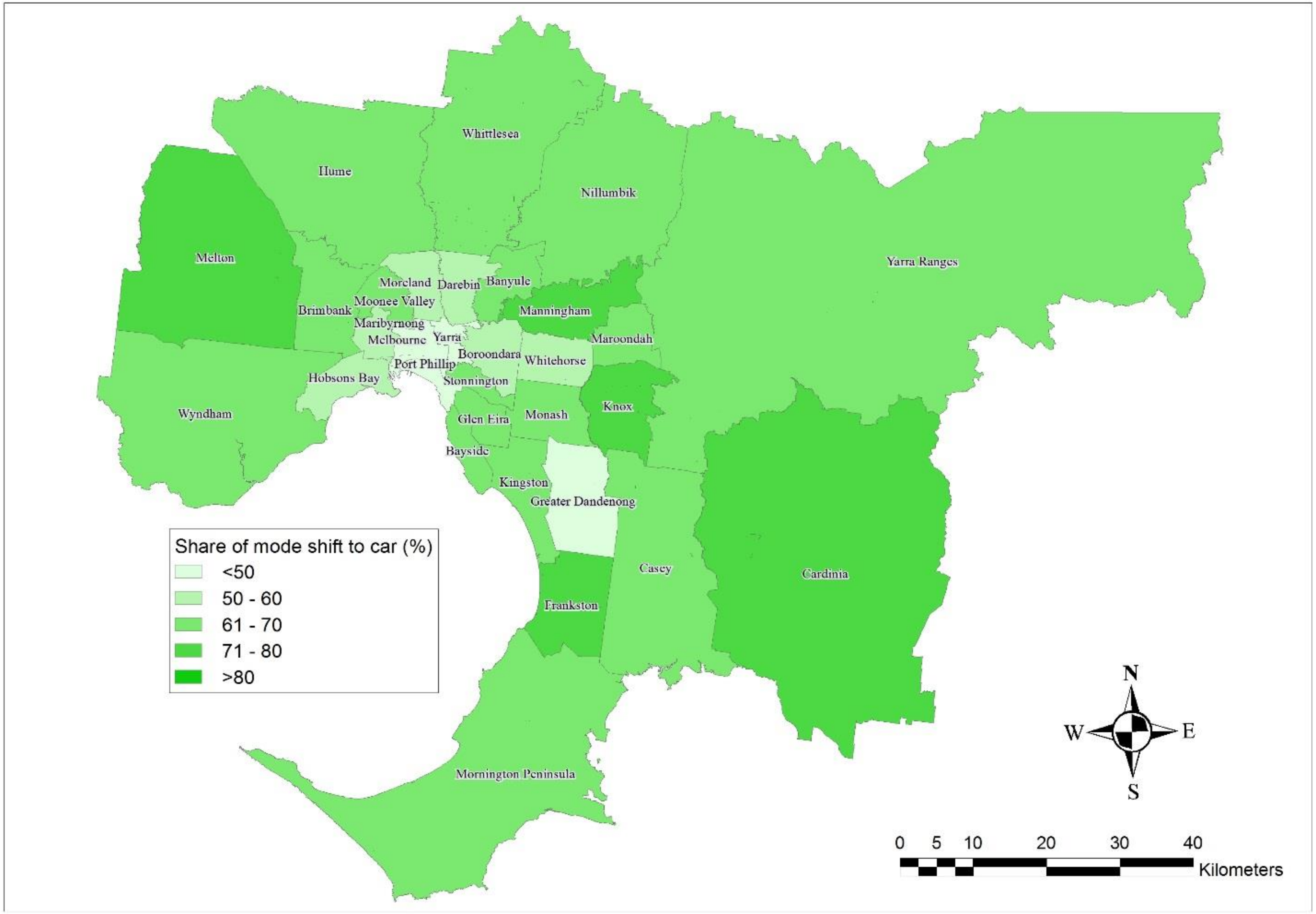


Figure 5.5 Spatial distribution of the share of mode shift to car for LGAs in Melbourne

5.4.2 Traffic Congestion Relief associated with Public Transport

Table 5.6 presents the congestion relief effect associated with the public transport system on the road network in Melbourne. The results in Table 5.6 indicate that:

- The operation of public transport contributes to reduce the number of severely congested links and moderately congested links by more than 63% and 6% respectively.
- Vehicle time travelled and total delay on the road network reduces by around 56%.
- Average travel speed increases from 36.59 km/h to 48.14 km/h (an increase of 31.6%) whilst actual travel time per km reduces by approximately 52%.

Table 5.6 Congestion relief impact of public transport on Melbourne's road network

Measure	With public transport	Without public transport	Absolute change	Change (%)
Number of severely congested links	2,075	5,718	3,643	**63.7**
Number of moderately congested links	1,999	2,125	126	**5.9**
Vehicle distance travelled (million veh-km)	15.00	17.64	2.64	**15.0**
Vehicle time travelled (million veh-hr)	0.38	0.86	0.48	**55.8**
Total delay on road network (million veh-hr)	22.55	51.23	28.68	**56.0**
Average travel speed (km/h)	48.14	36.59	-11.56	**-31.6**
Actual travel time per km (min)	1.80	3.75	1.96	**52.1**

Notes: Severely congested links are road links which have a volume to capacity (V/C) ratio equal to or greater than 0.9. Moderately congested links are road links which have a V/C ratio equal to or greater than 0.8 and lower than 0.9 (SEMCOG, 2011).

The comparison of public transport congestion relief impacts on the road network in different parts of Melbourne is detailed in Table 5.7. The results show that the public transport system in Melbourne has the highest effect in inner areas and lowest impact in outer areas. Table 5.7 shows that:

For inner Melbourne:

- The number of heavily congested links decreases by approximately 73% with public transport operations while the number of moderately congested road links decreases by around 9%.
- Total network delay and vehicle time travelled reduce by over 78%.
- Average travel speed increases by nearly 80%.

For middle Melbourne:

- The operation of public transport results in a reduction in the number of severely congested links of more than 63% and in the number of moderately congested links of 18%.
- There is a decrease in vehicle time travelled and total delay on the road network of more than 56%.

- Travel time on average decreases from 3.76 minutes/km to 1.91 minutes/km (49.2% decrease).

For outer Melbourne:

- Public transport operations contribute to reduce the number of severely congested links by 53.3% and the number of moderately congested links by 10.2%.
- Vehicle time travelled and total delay on the road network decrease by approximately 28%.
- Average travel speed increases from 49.19 km/h to 54.72 km/h (an increase of 11.2%).

Table 5.7 Congestion relief impact of public transport on Melbourne's road network in inner, middle and outer areas

Measure	Inner			Middle			Outer		
	With public transport	Without public transport	Change (%)	With public transport	Without public transport	Change (%)	With public transport	Without public transport	Change (%)
Number of severely congested links	413	1529	**73.0**	1,087	2,959	**63.3**	575	1231	**53.3**
Number of moderately congested links	407	446	**8.7**	930	1,144	**18.7**	662	737	**10.2**
Vehicle distance travelled (million veh-km)	1.63	2.17	**24.9**	6.11	7.40	**17.4**	7.26	8.08	**10.1**
Vehicle time travelled (million veh-hr)	0.05	0.23	**78.3**	0.18	0.41	**56.1**	0.15	0.21	**28.6**
Total delay on road network (million veh-hr)	3.07	14.02	**78.1**	10.42	24.66	**57.7**	9.07	12.56	**27.8**
Average travel speed (km/h)	42.31	23.44	**-80.5**	44.94	32.68	**-37.5**	54.72	49.19	**-11.2**
Actual travel time per km (min)	2.09	7.01	**70.2**	1.91	3.76	**49.2**	1.53	1.89	**19.0**

5.5 Discussion

This chapter describes an enhanced method developed in Melbourne, Australia for assessing the congestion relief impact associated with urban public transport. The approach employs travel behaviour modelling to estimate mode shift from public transport to car in the event of a public transport withdrawal and a transport network model (macrosimulation) to estimate the impact of public transport. The methodological advance compared to previous approaches (Aftabuzzaman et al., 2010b) is that the method for predicting separate levels of mode shift for regions is developed with the support of the primary data collected in Melbourne. Thus, the mode shift to car, which is a key figure for estimating the congestion relief associated with public transport, can be varied for different regions based on the particular characteristics of each region. This approach is considered to provide more precise results than the approach used by Aftabuzzaman et al. (2010b) who assembled real world evidence and suggested that on average 32% of public transport users would shift to car use for all regions.

The analysis of data derived from a field survey conducted with public transport users in Melbourne shows that there is a linear relationship between the share of mode shift to car for a specific area and a set of factors. In this research, the characteristics of public transport users obtained from the VISTA database were used to predict mode shift to car for Melbourne's LGAs. The results demonstrate that mode shift from public transport to car is lowest in inner areas (48%) as a high proportion of users in these areas have short distance trips which might be taken by non-motorised transport modes such as cycling or walking. In contrast, the mode shift is higher for regions located further from the CBD (ranging from 49.5% to 76.2%). However, the share of mode shift to car for LGAs obtained from the field survey may be biased as the sample size in a number of LGAs is very small (under 10 participants). Thus, the developed linear regression was used to predict mode shift to car for LGAs using the characteristics of public transport users derived from the VISTA database which includes a greater sample size for each LGA. This method is considered to reduce the bias in the estimation of mode shift to car in the event of a public transport disruption.

The findings from the transport network modelling show that Melbourne's public transport operations contribute to reduce vehicle time travelled and total delay on the road network by around 56%. The public transport congestion relief impact estimated in this research is much higher than that in previous research. The higher mode shift found from the survey (ranging from 38.2% to 76.2%) compared to the fixed mode shift (32.4%) used in the previous research (Aftabuzzaman et al., 2010b) is a major cause of this difference. The congestion relief impact of public transport estimated in this research is also much higher than the figures estimated by previous scholars (Parry and Small, 2009, Schrank et al., 2012, Anderson, 2013). The difference in public transport congestion impacts among cities can result from differences in public transport systems, public transport ridership or methods used for assessment.

In terms of spatial effects, the congestion relief impact of public transport is highest in inner areas and lowest in outer areas. In inner areas, the operation of public transport contributes to reduce the total network delay and vehicle time travelled of the entire road network by over 78%. However, these figures decrease to approximately 56% in middle areas and only around 28% in outer areas. The level of traffic congestion in inner areas, particularly in peak hours, is much higher in comparison to that in middle and outer areas. Hence, although the average mode shift in inner areas is lowest (48%), public transport operations still have the highest effect on reducing congestion in these regions. In contrast, the impact of public transport in outer areas is much lower than that in inner and middle areas even though mode shift is higher (66.9%). This is because of the lower level of traffic congestion in these areas as well as the ratio of the number of public transport users to total road network length.

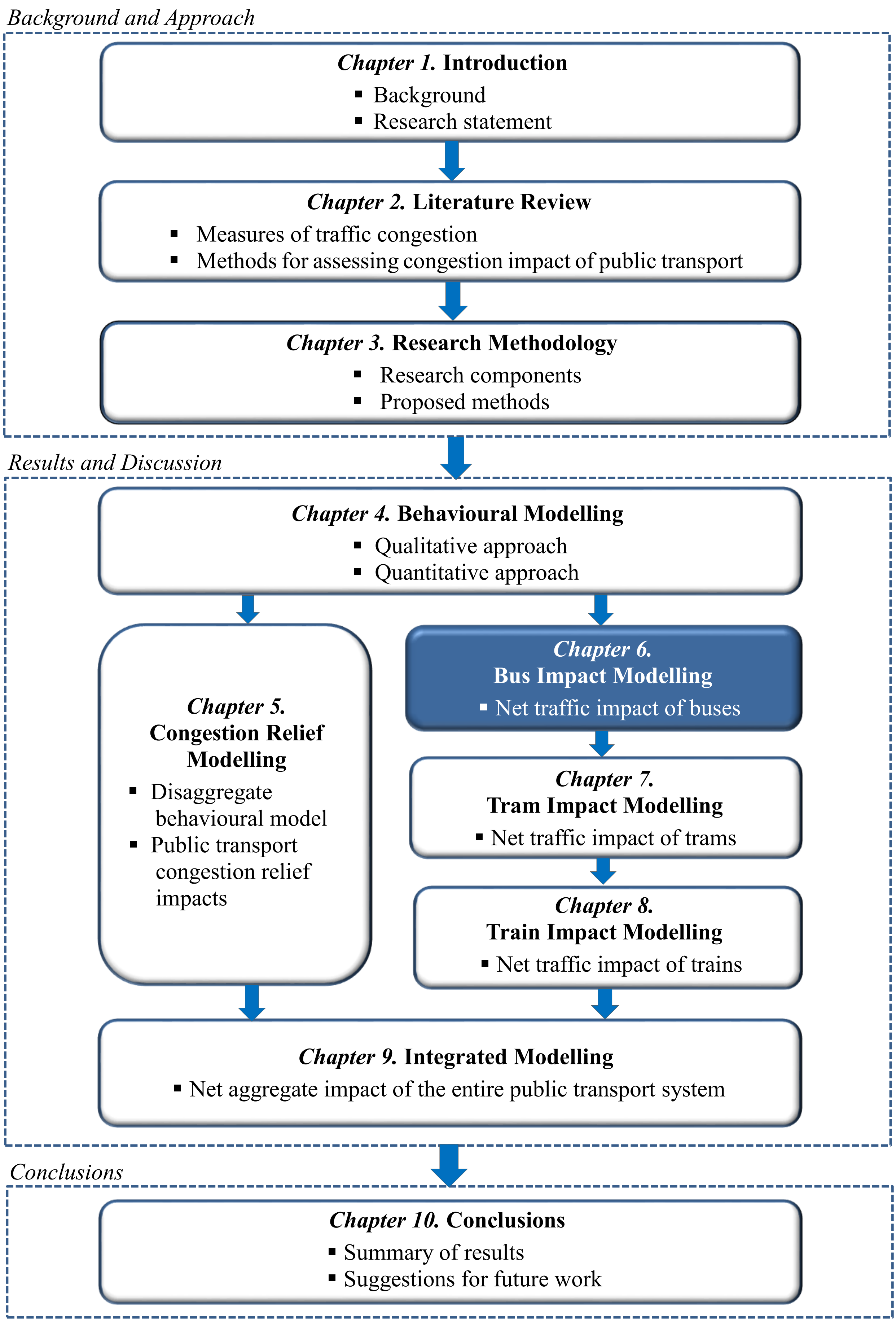
The contributions of this research include the development of an enhanced method for estimating mode shift from public transport to car when public transport ceases in the short-term and the creation of an improved method for assessing the congestion relief impact associated with public transport.

Overall, the enhanced methods described in this chapter are considered an improvement to methodological approaches to assessing one of public transport's most significant impacts on Australian cities; acting to reduce urban traffic congestion.

5.6 Conclusions

This chapter aimed to explore the congestion relief effect of the entire public transport system. In doing so, mode shift from public transport to car was estimated for various regions using both primary and secondary data. This mode shift was then used in transport network modelling (VITM) to assess the positive effect of public transport on reducing traffic congestion.

The findings show that public transport has a significant effect on reducing traffic congestion, particularly in inner areas. However, public transport itself can have negative effects on generating traffic congestion at locations like at-grade rail crossings or on roads where the frequent stopping of buses and trams might slow traffic. Removing public transport in these cases should act to reduce the level of congestion. To understand the total effects of public transport on traffic congestion it is necessary to understand both the negative impacts as well as the positive impacts discussed in this chapter. The next three chapters (Chapter 6-8) present methods to examine the net congestion impact associated with individual public transport modes (bus, tram and train) which takes into account not only the positive but also the negative effects.


Background and Approach
Chapter 1. Introduction
Background
Research statement
Chapter 2. Literature Review
Measures of traffic congestion
Methods for assessing congestion impact of public transport
Chapter 3. Research Methodology
Research components
Proposed methods
Results and Discussion
Chapter 4. Behavioural Modelling
Qualitative approach
Quantitative approach
Chapter 5. Congestion Relief Modelling
Disaggregate behavioural model
Public transport congestion relief impacts
Chapter 6. Bus Impact Modelling
Net traffic impact of buses
Chapter 7. Tram Impact Modelling
Net traffic impact of trams
Chapter 8. Train Impact Modelling
Net traffic impact of trains
Chapter 9. Integrated Modelling
Net aggregate impact of the entire public transport system
Conclusions
Chapter 10. Conclusions
Summary of results
Suggestions for future work

Chapter 6
BUS IMPACT MODELLING

6.1 Introduction

Chapter 5 explored the modelling approach used to assess the effect of the entire public transport system on relieving traffic congestion. In Chapters 6-8, the net congestion effect of individual public transport modes (train, tram and bus) will be investigated. This chapter focuses on the net congestion effect of bus operations and addresses a research gap identified in the Literature Review: No studies have explored the network-wide impact of buses on traffic congestion. This is in accordance with research objective 3 to develop new methods to investigate the net network-wide impact of bus operations on traffic congestion. Table 6.1 details the research objective, research component, research gap and research opportunity associated with this chapter.

Table 6.1 Research gap, opportunity and objective associated with research component 5

Research objective	Research component	Research gap	Research opportunity
3. To develop new methods to investigate the net network-wide impact of bus operations on traffic congestion	5. Bus congestion effect estimation	No studies exploring the net network-wide impact of bus operations on traffic congestion	Investigate the net traffic congestion effect of bus operations by considering both positive and negative impacts

Although bus services have a positive effect on reducing traffic congestion by encouraging mode shift from private car to bus, they also have negative effects on creating congestion. The frequent stopping of buses may cause delays for vehicles running behind them. In addition, the take up of road space for priority bus lanes also contributes to congestion as it reduces the capacity of roads for general traffic. The net congestion effect of bus operations will be investigated in this chapter.

Transport modelling was used to examine these effects. Firstly, traffic microsimulation is used to estimate the negative effects of buses on vehicle traffic flow on road links. These results are then incorporated into a four step model (VITM) to explore the negative effects on the entire road network. The mode shift from bus to car was also incorporated within the VITM to estimate the positive effect of buses in reducing congestion. The net impact of buses was assessed by integrating both positive and negative effects.

A journal paper was prepared based on the findings of this chapter as follows:

Paper 5 *Nguyen-Phuoc, D.Q., Currie, G., De Gruyter, C. & Young, W., 2018, 'Net impact of bus operations on traffic congestion in Melbourne',* ***Transport Research Part A (Passed the first round with minor revision, submitted the revision).***

6.2 Research Context

6.2.1 Melbourne's Bus Network

The bus network in Melbourne (Figure 6.1) consists of 346 routes operated by 32 privately owned bus companies (Public Transport Victoria, 2015b). Bus is the third most used form of public transport in Melbourne with 137 million passenger trips in 2015-16 after the commuter railway network (233 million) and tram network (204 million) (Public Transport Victoria, 2016). While the city relies on a radial train network and inner city tram network, the middle and outer suburbs are primarily serviced by buses (Currie and Loader, 2010). Buses normally operate in mixed traffic conditions although there are some exclusive bus lanes (accounting for only 0.7% of the bus network) provided for premium bus services.

There are two main types of bus stops in Melbourne: curbside bus stops (approximately 16,000 stops) and bus bays (nearly 2,800 stops). Curbside bus stops which are located adjacent to the shoulder lanes are the most common, convenient and simplest form of bus stops (Fitzpatrick et al., 1996). They provide easy access for bus drivers and cause minimal delays to buses. However, they can impede car traffic flow and encourage drivers to make unsafe lane changes to avoid delay behind stopped buses. Bus bays, on the other hand, are located separately from traffic lanes and off the normal section of a roadway, thereby allowing the through traffic behind to move freely. However, buses arriving and departing from bus bays may affect other passing vehicles as they manoeuver to pull in and out of stops. Almost all bus bays in Melbourne are located on highways in middle and outer areas.

6.2.2 Spatial Unit of Analysis

Local Government Areas (LGAs) are the spatial unit of analysis used in this study. There are 31 LGAs in Melbourne (VicRoads, 2005) which are grouped into three categories. These include inner (4 LGAs), middle (14 LGAs) and outer (13 LGAs).

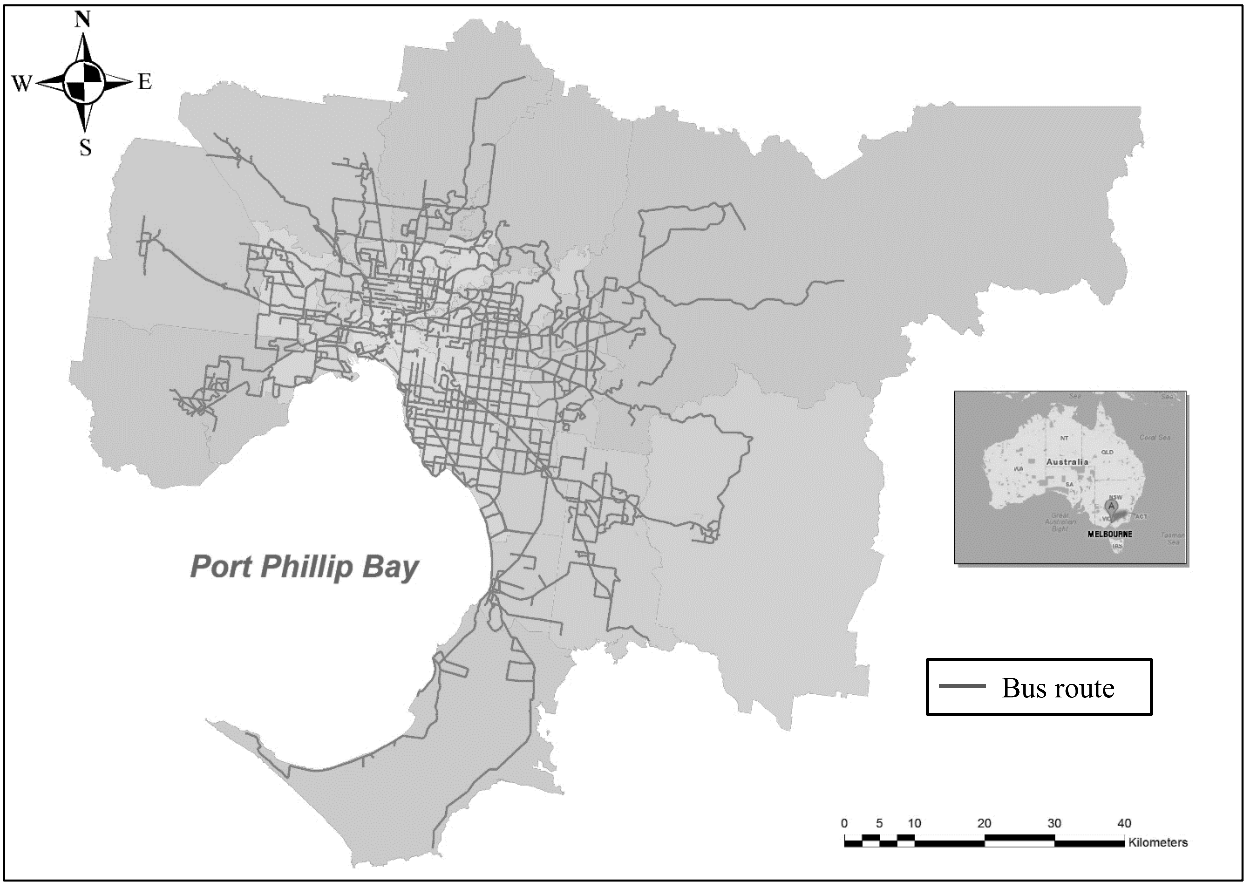


Figure 6.1 Melbourne's bus network

6.3 Research Methodology

This section describes the methodology that has been developed to assess the net traffic congestion impact of bus operations on the entire road network. In the first part, a primary survey, which aims to determine mode shift from bus to car in the event of a bus withdrawal, is presented. This is followed by description of secondary data sources relating to Melbourne's bus operations. Steps involved in assessing the net effect of buses on traffic congestion is detailed in the final part.

6.3.1 Primary Survey for Estimating the Mode Shift from Bus to Car

An online survey of bus users across metropolitan Melbourne (inner, middle and outer) was conducted in April 2016 (refer to section 4.2.2). The survey aimed to understand the behavioural reactions of bus users in the event of bus withdrawal. Respondents who used buses in the weekday morning peak (7am-9am) were asked about the impact of bus withdrawal and their likely change in travel behaviour.

Firstly, an email was sent to all members of a market research panel inviting them to take part in the study by answering an on-line questionnaire. In the email invitation, each panel member was given a link to access the questionnaire. A reminder email was sent to those who had not accessed the questionnaire one week after the initial email was sent. Data was collected over a 3-week period. A total of 187 bus passengers successfully completed the survey. These respondents were asked to describe their behavioural reactions when bus operations were unavailable. From the results of the survey, the share of mode shift to other travel modes for inner, middle and outer areas could be estimated.

This research has assumed that bus user diversion to car when bus operations cease would have an impact on traffic congestion. It is clear that a shift to 'car as driver' would directly increase the number of car trips on the road network (the diversion to other public transport modes, walking or cycling is not considered to directly influence congestion). However, in the case of switching to 'car as passenger', this may or may not influence traffic congestion. For example, Litman (2004b) argues that some car users can spend a significant amount of time driving children to school, family members to work and elderly relatives on errands (chauffeuring trips). These trips can be particularly inefficient if drivers are required to make an empty return trip which can also contribute to congestion. For the purpose of this analysis, it is assumed that half of all car passenger trips involve chauffeuring (Aftabuzzaman et al., 2010a). Thus, the mode shift to car that would contribute to traffic congestion if bus operations cease is the sum of the share of mode shift to 'car as driver' plus half of the share of mode shift to 'car as passenger'.

6.3.2 Secondary Data Sources Relating to Melbourne's Bus Operations

In this research, three datasets were used to determine the arrival frequency, dwell time and bus stop type of each bus stop in Melbourne. All of these datasets are publicly available at www.data.vic.gov.au.

- *Bus Boardings and Alightings at Bus Stops:* This dataset details the number of passengers boarding and alighting on a 'typical' weekday at each bus stop for the 7am to 7pm period. This figure is estimated for the AM peak (7am-9am) by applying the proportion of patronage for each bus route in the AM peak compared to the 7am-7pm period. The dwell time at bus stops was then estimated through a non-linear model using total passengers as the independent variable (Rajbhandari et al., 2003). By analysing data collected daily for the whole year of 2001 on a bus route in New Jersey, Rajbhandari et al. (2003) found that $\textit{Dwell time} = a(\text{total passenger})^b$ where a=7.26, b=0.738 (R^2=0.741, sample size = 8306).
- *Timetable and Geographic Information:* This dataset provides static timetable data and geographic information. It contains scheduled information for all metropolitan and regional bus services in Victoria. From this dataset, the frequency at each bus stop in the AM peak can be determined.

- *Bus Stop Infomation:* This dataset includes spatial objects (points) representing the location of public bus stops used by metropolitan bus routes, SkyBus routes, night bus routes, regional bus and regional coach routes. It does not include 'Country Free School Bus' stops. Each stop has a number of attributes including the stop ID, stop type, stop name, ticket zone and list of bus routes using the stop.

Geographic Information System (GIS) software (ArcGIS) was used to incorporate the characteristics of each bus stop (dwell time, arrival frequency and bus stop type) into the road network in the VITM.

6.3.3 Method for Modelling the Net Impact of Buses on Traffic Congestion

The modelling procedure adopts an assumption regarding bus user diversion to car, along with microsimulation and a four-step transport model to incorporate both the positive and negative impacts of buses on traffic congestion. The modelling analysis was carried out for an average weekday morning peak (7am-9am) in Melbourne which experiences the highest level of traffic congestion across the day.

In this research, a decrease in the number of car trips due to bus service provision represents the positive effect of buses. In order to assess this effect, it is assumed that there is a mode shift from bus to car when buses are removed. The number of bus users shifting to car in the case of bus removal therefore represents the number of car users attracted by bus services. The negative impact of buses in terms of their contribution to traffic congestion is represented by the effect of bus stop operations during boarding and alighting. The effect of priority bus lanes on reducing road capacity was not considered in this research since the number of bus lanes account for a relatively small proportion of Melbourne's bus network (approximately 0.7% bus network).

The modelling procedure for estimating the net impact of buses on traffic flow consists of three main stages:

Stage 1: In the 'with bus' scenario, the effect of bus operations on vehicle traffic flow are modelled. Firstly, the effect of bus operations on a road link is investigated by using traffic microsimulation. Then, these results are integrated into VITM to model the network-wide effect of buses.

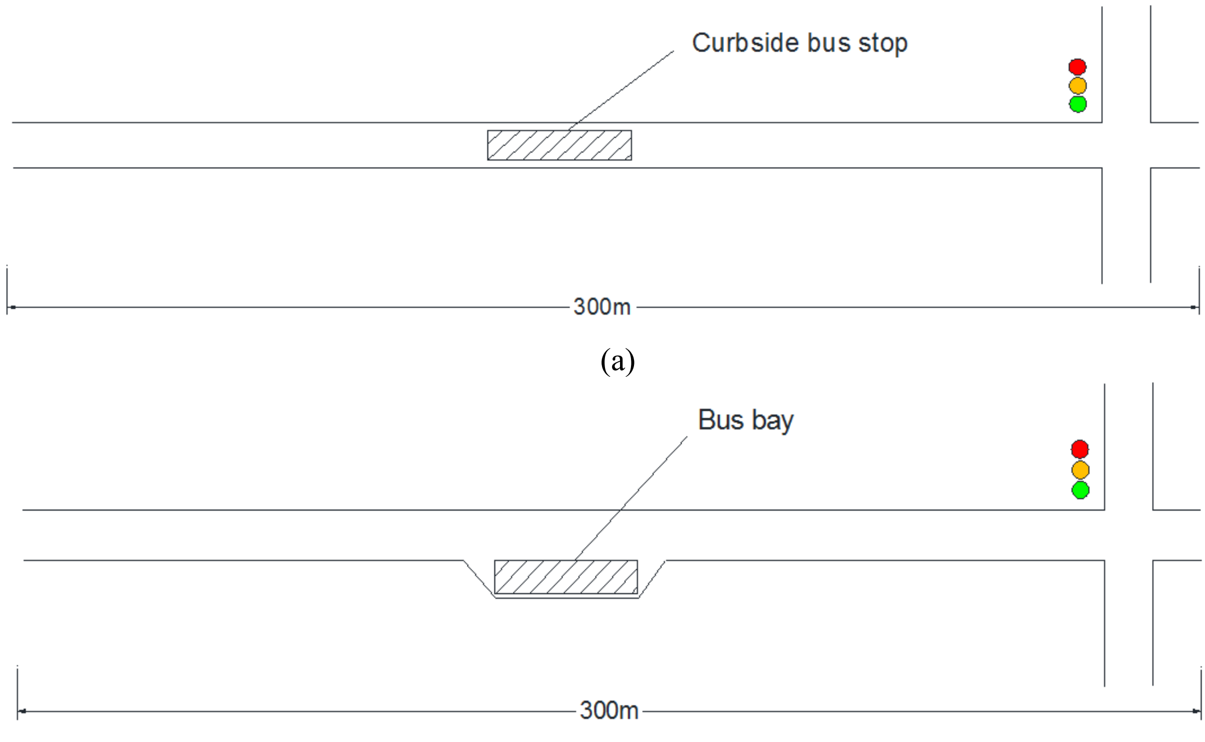
Stage 2: In the scenario of 'without bus', the existing car trip matrix is added to the car mode shift matrix (bus trip matrix is multiplied by the mode shift to car for inner, middle and outer areas) to obtain a modified car trip matrix. This new car trip matrix is then assigned to the road network.

Stage 3: The congestion measures in two scenarios, 'with bus' and 'without bus', are contrasted to assess the net traffic congestion effect of bus operations on the entire road network.

Microsimulation Approach

Traffic microsimulation (VISSIM) is used to estimate delays caused by bus stop operations at bus stops as well as at intersections (since the acceleration/deceleration of buses is lower than cars). For microsimulation purposes, the effect of buses on a particular road link is the focus of analysis. The main performance measure used is travel time. This is estimated by averaging the travel time of each vehicle on the segment. The reason for choosing travel time as a key measure is that travel time is calculated on each road link and used as the main criteria for assigning vehicle trips to the road network in VITM. Thus, the effect of buses on traffic is represented by the increase in average travel time between two scenarios: 'with bus' and 'without bus'.

The developed microsimulation model consists of a road link, a bus stop (curbside or bus bay), detectors and traffic signals. A bus stop is located at the mid-point of the road link as shown in Figure 6.2. In VITM, the average length of links with bus operations is approximately 300m, with around three intersections per kilometre. Thus, a 300m road link with a bus stop and an intersection is modelled to estimate the impact of bus operations on vehicle traffic flow. The intersection is located at the end of the link in order to be consistent with the road links with bus operations modelled in VITM (Department of Transport, 2011).



(b)

Figure 6.2 Modelled road links with: (a) curbside bus stop and (b) bus bay

In order to simplify the microsimulation, the following assumptions are adopted:

- The headway of buses on a road link is the same even if the link is shared by various bus routes.
- On road links which have more than one bus stop, it is assumed that those links have one stop with the combined total equivalent bus frequency and number of passengers boarding and alighting.
- From the dataset '*Bus Stop Information*', the number of mid-block bus stops accounts for the majority of bus stops in Melbourne (more than 80%). Thus, it is assumed that bus stops are located at the middle of road links.
- It is assumed that intersections are controlled by fixed traffic signals with a typical cycle time of 60 seconds. The all orange period and intergreen time are assumed to account for 6 seconds so the green time for each leg is 27 seconds.

Table 6.2 Parameters set in the VISSIM microsimulation

No	Parameter	Value	Detail
1	Acceleration and deceleration rate of buses	1.3m/s^2	
2	Road link length	300m	
3	Bus stop location	150m	From the beginning of the link
4	Traffic signal cycle time	60s	27s green, 27s red, 3s orange, 3s clearance

Traffic microsimulation models normally include a large number of parameters that must be calibrated before the model can be used as a tool for prediction. In order to ensure validity of the developed model, a calibration process was performed against the speed of traffic flow. In this research, field data was used to calibrate the traffic flow for the base case (without bus). In order to collect the field data, a video camera was placed on an overpass at Princess Highway, Melbourne to record traffic operations over a one-hour period. By tracking each vehicle in a real time traffic video, the speed of each vehicle was measured. Wiedemann 99, a psycho-physical perception car-following model, in VISSIM was then applied to calibrate the VISSIM models.

The number of parameters we would ideally like to calibrate is high, but this is seldom possible because of the computational effort involved and limited data availability. In this particular study, parameters such as look ahead distance (from 250m to 100m), observed vehicles (from 2 to 4), standstill acceleration (from $3.5m^2$ to $2.00m^2$), acceleration with 80km/h (from $1.5m^2$ to $0.5m^2$) were adjusted through trial and error. More importantly, the desired speed distribution also changed which has a significant influence on highway capacity and achievable travel speeds. Since the speed distribution plays a critical role in roadway capacity and travel speed (PTV, 2015), adjusting the stochastic distribution of speeds was carefully performed (Figure 6.3). The horizontal axis represents the desired speed whereas the vertical axis shows the cumulative percentage from 0 to 100. Compared to the default graph, the calibrated distribution is shown as a S-curve which can better replicate median values. As shown in Figure 6.3, intermediate points were also adjusted.

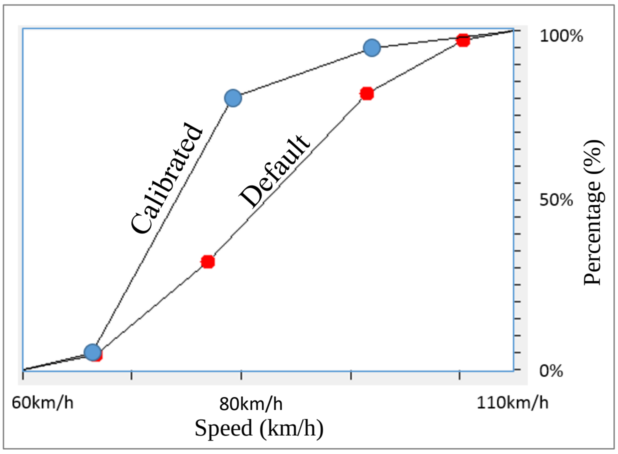


Figure 6.3 Default vs. calibrated traffic speed distribution in VISSIM

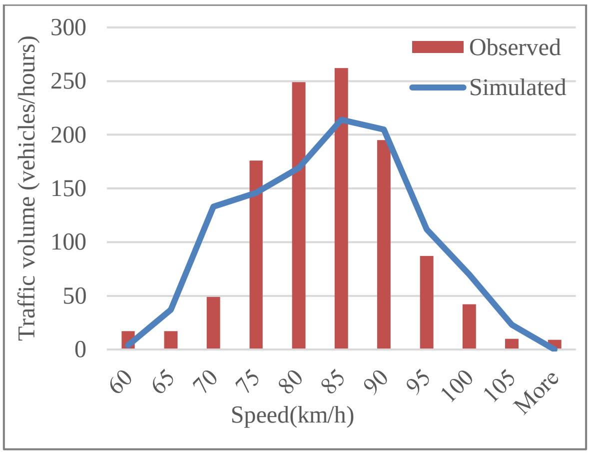


Figure 6.4 Comparison of observed (field) data and simulated VISSIM output

The Figure 6.4 plots speed against frequency for the observed data and simulated data. Intuitively, the results in simulation are generally well matched after calibration. This is supported by a statistical analysis of both datasets which shows an average speed of 80km/h with less than 10km/h standard deviation. The correlation (R^2) between two data sets is 0.97.

As with most traffic simulation software, VISSIM can be accessed by an external interface. The VISSIM COM interface defines a hierarchical model in which the functions and parameters of the simulator originally provided by the graphical interface can be manipulated by programming (Tettamanti and Horváth, 2015). With the use of the VISSIM COM interface, multi run tasks can be automated. In this research, the calibrated VISSIM models (six scenarios comprising two bus stop types and three types of road links) were run each combination of dwell time, speed limit, traffic volume, and bus arrival frequency (as shown in Table 6.3). In total, 6,408 scenarios (2*3*3*4*8*9) were created. The simulation ran for an hour (3,600 seconds) with intervals of 0.1 second. In order to consider the variability of microsimulation output, five random seeded runs were conducted for each set and the results for five runs were averaged. Hence, a total of 32,040 runs were conducted.

Table 6.3 Parameter values used in microsimulation

Characteristic	Parameter values
Type of bus stop (1: curbside stop, 2: bus bay stop)	1, 2
Number of lanes	1, 2, 3
Speed limit (km/h)	40, 60, 80
Dwell time (s)	10, 20, 30, 40
Arrival frequency of bus at stops (min)	0, 2, 4, 6, 8, 10, 20, 40
Traffic volume per lane (veh/hour)	100, 200, 300, 400, 500, 600, 700, 800, 900

The results of microsimulation were used to develop a regression model that shows the relationship between the increase in travel time caused by bus operations and a number of related characteristics for six scenarios. The model can be expressed as follows:

Increase in travel time for each scenario = f (dwell time, traffic volume, frequency, speed limit) (6.1)

The above formula was used to estimate the additional travel time (delay caused by buses) for all road links with bus operations in VITM. The negative impact of bus operations on congestion could then be determined. This process is detailed in the next section.

Macro-modelling Approach

VITM assigns vehicle trips on Melbourne's road network using travel time calculated for each link using Akcelik's formula (Akçelik, 1991). In the equilibrium assignment process, to obtain an equilibration of demand, the traffic volume on each link is changed during an iterative process, leading to a change in travel time. A major development in this research is to represent the travel time on a road link with bus operations based on bus service frequencies, traffic volumes, speed limit, dwell time, the number of lanes and the type of bus stops.

To model the negative impact of buses on congestion, in the scenario 'with bus', travel time on links with bus operations is added as a percentage change in travel time estimated using traffic microsimulation. This percentage is adjusted based on the bus service frequency, traffic volume, speed limit, dwell time, number of lanes and type of bus stop on each road link with bus operations. When iterating to obtain an equilibration, the vehicle traffic volume is changed in each loop. So, the percentage change in travel time has to be changed with the updated traffic volume. This process is carried out by coding in Cube using the following formula:

$$Travel\ time = \text{Travel time}_0 + \text{p\%} * \text{Travel time}_0 \qquad (6.2)$$

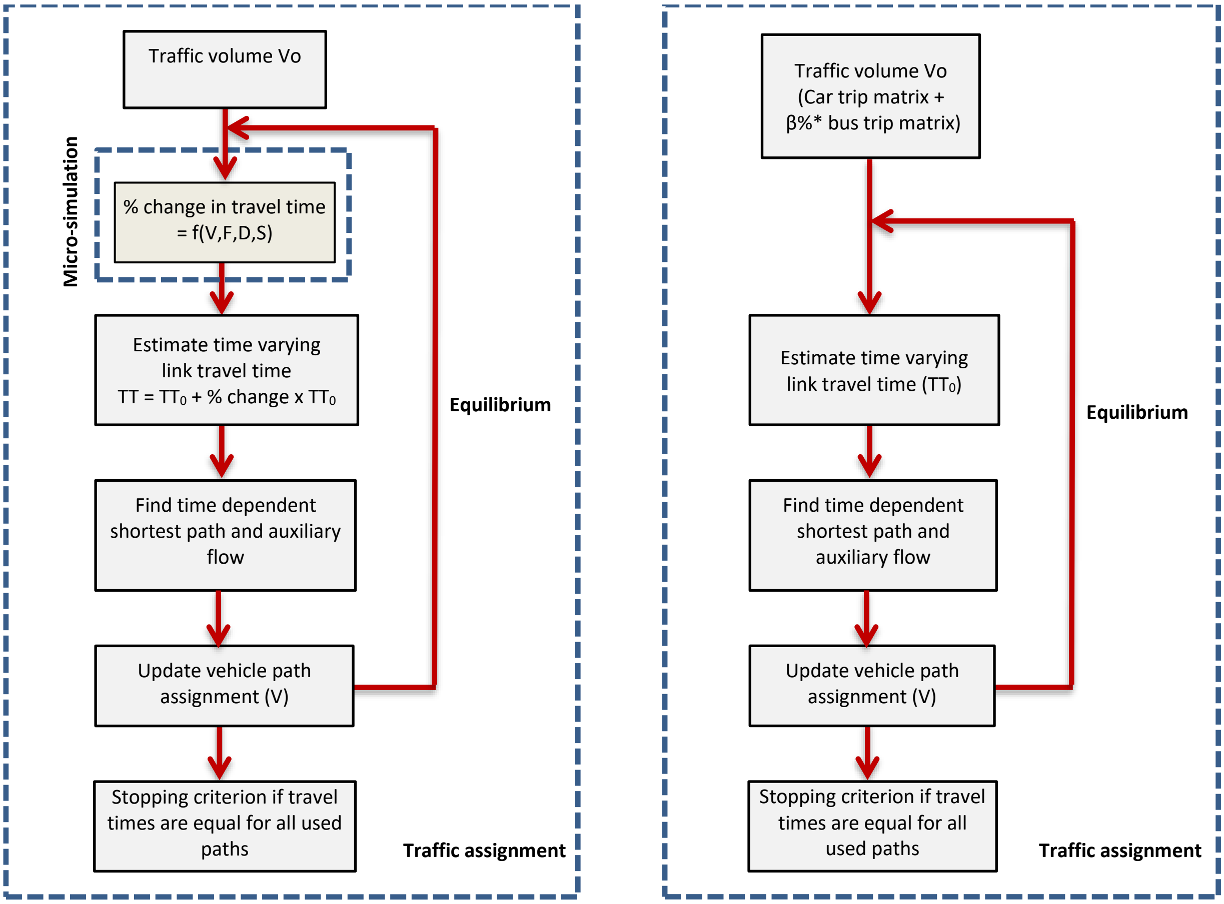
Where: p%: is the percentage change in travel time caused by bus stop operations; it is calculated using the regression functions created from the results of traffic microsimulation.

Travel time_0: Travel time on link with bus operations when the impact of bus stop operations is not considered.

$Travel\ time$: Travel time on link with bus operations.

In order to model the positive impact of buses, a bus matrix that shows the number of bus users travelling from each origin to each destination is first generated from the public transport assignment in VITM. In order to represent the increase in car trips for each area (inner, middle and outer) in the case of bus removal, the bus matrix is modified by multiplying it by the mode shift to car for each area, obtained from the primary survey. This modified bus matrix is then added to the existing car trip matrix to create an expanded car trip matrix. In the 'without bus' scenario, the expanded car matrix is assigned to the road network to estimate the increase in congestion. This increase represents the traffic congestion relief impact of bus operations.

Figure 6.5 shows the modelling process for the two scenarios: ‘with bus’ and ‘without bus’. The outcomes between the two scenarios are compared to explore the changes in congestion measures on the road network. These changes represent the net effect of bus operations on traffic congestion.



where
- V_0: traffic volume
- V: updated traffic volume
- TT_0: travel time without bus effect
- TT: travel time with bus effects
- F: bus frequency
- D: dwell time at bus stops
- S: speed limit

(a) With bus

where
- β : mode shift to private car from bus (%)
- TT_0: travel time
- V_0: traffic volume
- V: updated traffic volume

(b) Without bus

Figure 6.5 Process of estimating travel demand in the two scenarios

6.4 Results

The results of this chapter are presented in three parts. First, the mode shift from bus to car when buses are not available (obtained from the primary survey) is described. The effect of bus operations on a road link (modelled using traffic microsimulation) is then presented in the second part. The mode shift to car and the results from microsimulation are then incorporated into VITM (macro-modelling) in order to assess the net congestion relief impact associated with bus operations. These results are shown in the final part.

6.4.1 Mode Shift from Bus to Car

Primary research was conducted with bus users in Melbourne in April 2016. Table 6.4 presents the stated mode shift of bus users in the event of bus service cancellations (refer to section 4.3.2.6). Around 29% of respondents said they would drive a car while 9.1% said they would travel by car as a passenger. Approximately 24% and 12% of respondents would switch to trains and trams respectively. Bus withdrawal is expected to generate a mode shift to walking of 11.2%. Cancelling the trip was chosen by 8.6% of respondents. These figures are substantially different for each part of metropolitan Melbourne, reflecting the different traffic and land use characteristics of those. For instance, in inner Melbourne if buses are not available, the mode shift to car as a driver is lower than that in the middle and outer areas (23.1% compared to 32.4% and 28.6%). This is because people in inner areas have greater access to other public transport modes such as train or tram.

For the purpose of this modelling analysis, it was assumed that half of all car passenger trips involve chauffeuring. Hence, the mode shift to car that contributes to traffic congestion if bus operations cease would therefore be 33.5% of bus users (28.9% + half of 9.1%).

Table 6.4 Mode shift of bus users when bus services cease

Mode	Mode shift from bus (%)			
	Inner	Middle	Outer	**Total**
Train	28.2	26.8	18.2	**23.5**
Tram	28.2	8.5	6.5	**11.8**
Car as driver	23.1	32.4	28.6	**28.9**
Car as passenger	2.6	8.5	13.0	**9.1**
Taxi/Uber	0.0	4.2	1.3	**2.1**
Cycle	7.7	0.0	2.6	**2.7**
Walk	5.1	9.9	15.6	**11.2**
Cancel the trip	5.1	8.5	10.4	**8.6**
Other	0.0	1.4	3.9	**2.1**
Total	100.0	100.0	100.0	**100.0**
Mode shift to car*	24.4	36.7	35.1	**33.5**

* Mode shift to car = mode shift to car as driver + ½ mode shift to car as passenger

6.4.2 Microsimulation Results

From the results of microsimulation, six non-linear regression models were developed to predict the percentage increase in travel time resulting from bus operations for different road link types (as shown in Table 6.5). All selected parameters have a significant impact on the increase in travel time in these regression models. The R^2 values are all at least 0.80, indicating a relatively high level of correlation.

Table 6.5 Functions for estimating travel time increases caused by bus stop operations

Type of road link		Regression functions	R^2
Curbside bus stop	One-lane road link	$ITT\ (\%) = e^{0.000003*V^2-0.0029*V+0.0256*D+0.0160*S+0.0751*F+0.3337}$	0.80
	Two-lane road link	$ITT\ (\%) = e^{0.000005*V^2-0.0048*V-0.0109*D+0.0197*S+0.0705*F-0.2124}$	0.82
	Three-lane road link	$ITT\ (\%) = e^{0.000005*V^2-0.0050*V-0.01118*D+0.0183*S+0.0680*F-0.4102}$	0.82
Bus bay	One-lane road link	$ITT\ (\%) = e^{0.000005*V^2-0.0055*V-0.0149*D+0.0026*S+0.0687*F+1.8971}$	0.82
	Two-lane road link	$ITT\ (\%) = e^{0.000005*V^2-0.0055*V-0.0160*D+0.0089*S+0.0699*F+0.7111}$	0.82
	Three-lane road link	$ITT\ (\%) = e^{0.000005*V^2-0.0055*V-0.0131*D+0.0106*S+0.0687*F+0.1618}$	0.83

ITT: Increase in travel time (%)
V: Traffic volume (vehicles/lane/hour)
D: Dwell time (second)
S: Speed limit (km/h)
F: Bus arrival frequency (buses/hour)

6.4.3 Macro-modelling Results

Table 6.6 details the estimated net traffic congestion effect of bus operations in Melbourne on the entire road network as well as the bus route network. Results in Table 6.6 show that:

For the entire Melbourne road network:

- The number of severely congested links and moderately congested links decreases by 10.7% and 5.9% respectively with the operation of buses.
- Vehicle time travelled and total delay on the road network reduces by around 2.8%.
- The average road network speed increases from 46.8 km/h to 47.8 km/h (2.2%).
- Travel time on average decreases only slightly from 1.91 minutes/km to 1.90 minutes/km (0.7%).

For the Melbourne road network with bus routes:

- The operation of buses contributes to reduce more than 130 heavily congested road links (9.8%) and 134 moderately congested road links (11.7%).
- A decrease of 2.5% in vehicle distance travelled occurs with the operation of buses.
- Total network delay and vehicle time travelled decrease by 3%.
- Average travel speed increases from 40.2 km/h to 41.2 km/h (an increase of 2.5%).

Table 6.6 Net impact of bus operations on Melbourne's road network

Measures	Entire Melbourne road network				Melbourne bus route network			
	With bus	Without bus	Absolute change	Change (%)	With bus	Without bus	Absolute change	Change (%)
Number of severely congested links (V/C>=0.9)	2,198	2,462	264	**10.7**	1,198	1,328	131	**9.8**
Number of moderately congested links (0.9>V/C>=0.8)	1,993	2,117	124	**5.9**	1,013	1,147	134	**11.7**
Vehicle distance travelled (million veh-km)	15.04	15.29	0.25	**1.7**	6.69	6.86	0.17	**2.5**
Vehicle time travelled (million veh-hr)	0.397	0.409	0.011	**2.8**	0.198	0.205	0.007	**3.0**
Total delay on road network (million veh-hr)	23.64	24.34	0.69	**2.9**	11.84	12.20	0.36	**3.0**
Average travel speed (km/h)	47.8	46.8	-1.0	**-2.2**	41.2	40.2	-1.0	**-2.5**
Actual travel time per km (min)	1.90	1.91	0.01	**0.7**	2.01	2.02	0.01	**0.4**

Notes: Severely congested links are road links which have a volume to capacity (V/C) ratio equal to or greater than 0.9. Moderately congested links are road links which have a V/C ratio equal to or greater than 0.8 and lower than 0.9 (SEMCOG, 2011).

Table 6.7 compares the congestion impact of bus operations on the entire road network in various parts of Melbourne. It shows that Melbourne's bus operations have the highest impact in inner areas and the lowest effect in outer areas. Table 6.7 shows that:

For inner Melbourne:

- Bus operations contribute to reduce the number of severely congested links by 16.2% and the number of moderately congested links by 5.6%.
- Vehicle time travelled and total delay on the road network decrease by 7.3%.
- Average travel speed increases from 40.4 km/h to 42.9 km/h (an increase of 6.1%).

For middle Melbourne:

- The number of heavily congested links decreases by approximately 6% with bus operations while the number of moderately congested road links decreases by 4.9%.
- Total network delay and vehicle time travelled reduce by 2.2%.
- Average travel speed increases by 2%.

For outer Melbourne:

- The operation of buses results in a reduction in the number of severely congested links of more than 15% and in the number of moderately congested links of more than 7%.
- There is a decrease in vehicle time travelled and total delay on the road network of 2.1%.
- Travel time on average decreases slightly from 1.57 minutes/km to 1.54 minutes/km (1.5% decrease).

Table 6.7 Net impact of bus operations on Melbourne's road network in inner, middle and outer areas

Measures	Inner Melbourne			Middle Melbourne			Outer Melbourne		
	With bus	Without bus	Change (%)	With bus	Without bus	Change (%)	With bus	Without bus	Change (%)
Number of severely congested links (V/C>=0.9)	455	543	**16.2**	1,194	1,271	**6.1**	549	648	**15.3**
Number of moderately congested links (0.9>V/C>=0.8)	368	390	**5.6**	962	1,012	**4.9**	663	715	**7.3**
Vehicle distance travelled (million veh-km)	1.61	1.67	**3.7**	6.16	6.28	**1.9**	7.27	7.34	**1.0**
Vehicle time travelled (million veh-hr)	0.054	0.058	**7.3**	0.189	0.193	**2.2**	0.154	0.158	**2.1**
Total delay on road network (million veh-hr)	3.20	3.45	**7.3**	11.27	11.52	**2.2**	9.18	9.37	**2.1**
Average travel speed (km/h)	42.9	40.4	**-6.1**	44.1	43.2	**-2.0**	54.6	54.1	**-0.9**
Actual travel time per km (min)	2.16	2.28	**5.4**	2.05	2.09	**2.0**	1.54	1.57	**1.5**

Notes: Severely congested links are road links which have a volume to capacity (V/C) ratio equal to or greater than 0.9. Moderately congested links are road links which have a V/C ratio equal to or greater than 0.8 and lower than 0.9 (SEMCOG, 2011).

6.5 Discussion

This chapter explores the net effects of bus operations on traffic congestion. The research adopted microsimulation and a four-step transport model (VITM) to explore the negative effects of buses on generating traffic congestion. The positive effects on reducing traffic congestion were also examined by incorporating the diversion from bus to private car in the event of bus withdrawal.

The findings show that although there are some negative effects, the net congestion impact of bus operations on the entire road network is positive. The operation of buses in Melbourne acts to reduce the number of severely congested links and moderately congested links by approximately 10% and 6% respectively. There is a reduction of nearly 3% in vehicle time travelled and total delay on the road network. The congestion relief effect of buses on the bus route network is not much higher compared to the impact on the entire road network. Hence, it can be concluded that the operation of buses not only reduces traffic congestion on roads with bus routes but also decreases congestion on other surrounding roads.

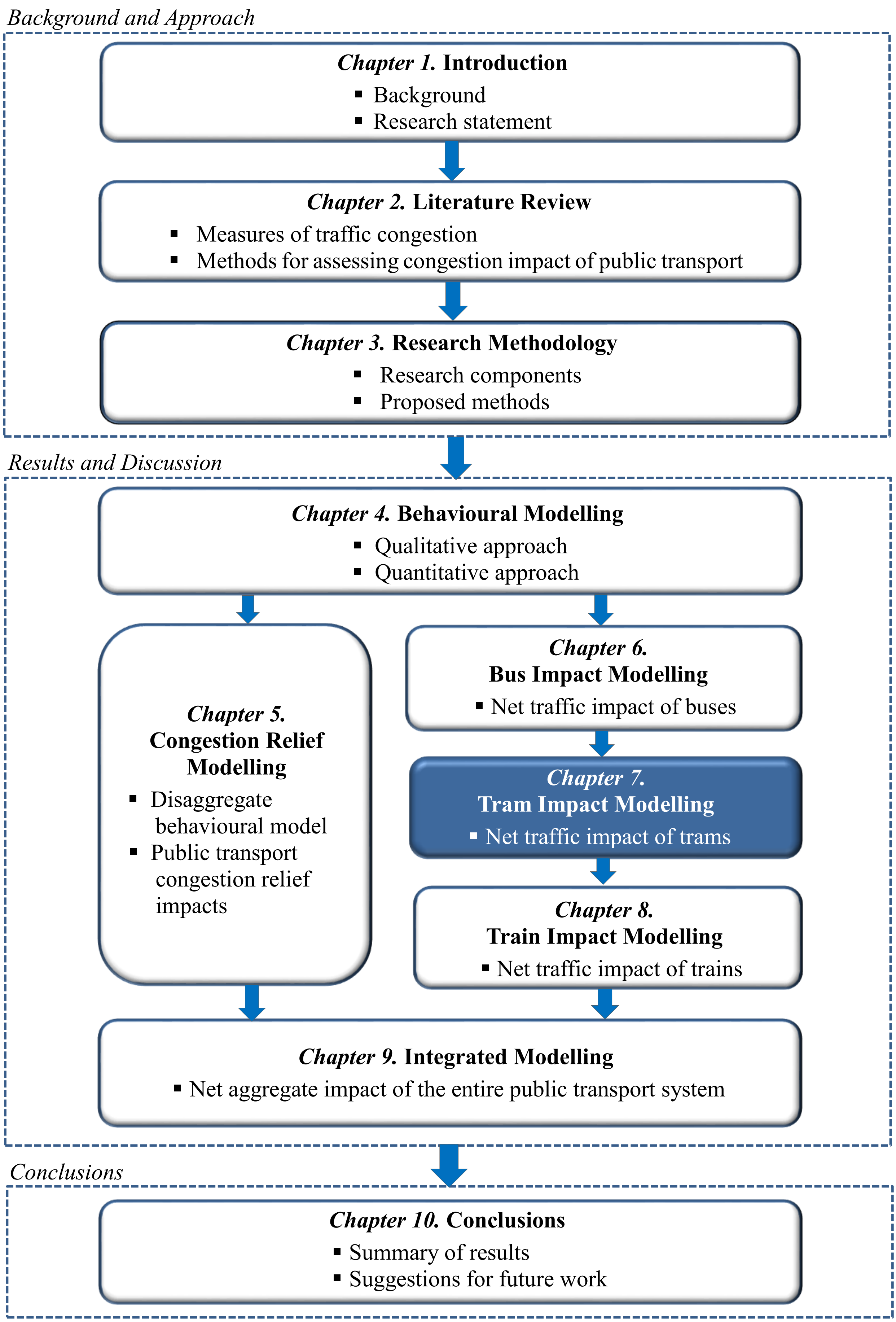
Melbourne's bus services were found to have the largest congestion effect on the road network in inner areas. Vehicle time travelled and total delay on the road network decreases by 7% due to bus operations. The operation of buses also contributes to reduce the number of heavily congested links by 16% and the number of moderately congested links by 6%. In contrast, although bus is the major public transport mode in middle and outer areas and the mode shift from car to bus is higher than that in inner areas, buses in middle and outer areas have a lower effect on reducing congestion. Bus operations in outer Melbourne reduces vehicle time travelled and total delay on the road network by only 2%. This is despite a reduction in the number of heavily congested links of more than 15%, compared to only 6% in middle areas. Indeed, the level of congestion in inner areas is expected to be highest, with many road links at capacity in peak periods, so the mode shift from car to bus (even if it is not as high as that in middle and outer areas) has a significant effect on reducing traffic congestion. This is consistent with the findings of Thomson (1968). He found that once roads reached capacity, even small reductions in traffic can reduce delays significantly.

Melbourne's bus network is spread out across the road network. When buses are removed, mode shift to car occurs across the road network and is not concentrated along specific corridors. Hence, the congestion caused by bus disruptions is not significant or it can be said that buses have a relatively small effect on reducing traffic congestion.

6.6 Conclusions

This chapter aimed to develop an enhanced method to assess the net network-wide effect of bus operations on traffic congestion. The positive effect of buses was assessed by considering the share of road users shifting from car to bus. The effect of bus stop operations (at stations and intersections) on traffic flow was recognised to be the negative effect of buses. The findings show that in terms of congestion effect, the benefit of buses outweighs the drawbacks. Although bus services cover all of Melbourne's areas and are the main public transport mode in outer areas, they have the highest congestion impact in inner areas, the traditionally highest congested areas.

The developed method for estimating the congestion relief impact of buses can be applied for other cities however there are some limitations in the method such as the lack of consideration the effect of priority bus lanes. This point need to be focused in further research. In the next chapter, the net impact of tram operations will be explored.


Background and Approach
Chapter 1. Introduction
▪ Background
▪ Research statement
Chapter 2. Literature Review
▪ Measures of traffic congestion
▪ Methods for assessing congestion impact of public transport
Chapter 3. Research Methodology
▪ Research components
▪ Proposed methods
Results and Discussion
Chapter 4. Behavioural Modelling
▪ Qualitative approach
▪ Quantitative approach
Chapter 5. Congestion Relief Modelling
▪ Disaggregate behavioural model
▪ Public transport congestion relief impacts
Chapter 6. Bus Impact Modelling
▪ Net traffic impact of buses
Chapter 7. Tram Impact Modelling
▪ Net traffic impact of trams
Chapter 8. Train Impact Modelling
▪ Net traffic impact of trains
Chapter 9. Integrated Modelling
▪ Net aggregate impact of the entire public transport system
Conclusions
Chapter 10. Conclusions
▪ Summary of results
▪ Suggestions for future work

Chapter 7
TRAM IMPACT MODELLING

7.1 Introduction

Chapter 6 explored the net effect of bus operations on traffic congestion. In this chapter, the net traffic congestion of light rail transit (trams/streetcars), a second major form of public transport in Melbourne, is investigated. The chapter addresses a research gap identified in the Literature Review: No studies have explored the net network-wide impact of trams on traffic congestion. This is in accordance with research objective 4 to develop new methods to investigate the net network-wide impact of tram operations on traffic congestion. Table 7.1 details the research objective, research component, research gap and research opportunity associated with this chapter.

Table 7.1 Research gap, opportunity and objective associated with research component 6

Research objective	Research component	Research gap	Research opportunity
4. To develop new methods to investigate the net network-wide impact of tram operations on traffic congestion	6. Tram congestion effect estimation	No studies have explored the net network-wide impact of tram operations on traffic congestion	Investigate the net traffic congestion effect of tram operations by considering both positive and negative impacts

The approaches and findings of the research in this chapter are presented in the form of a journal paper as follows:

Paper 6 *Nguyen-Phuoc, D. Q., Currie, G., De Gruyter, C. & Young, W. 2017. Net impacts of streetcar operations on traffic congestion in Melbourne, Australia.* ***Transportation Research Record: Journal of Transportation Research Board****, 2648(1), 1-9.*

Light rail transit is considered to be an effective solution to deal with traffic congestion. Light rail systems can be operated under different right-of-way types. With the flexibility of light rail systems in congested cities, they can attract a significant share of urban car trips and reduce car use on congested road networks. However, the operation of streetcar systems can also act to create negative effects on vehicle traffic in terms of travel time and reliability. Trams run on tracks along public urban streets, and also on segregated rights of way. Trams running directly along public streets without any separation have to share streets with vehicle traffic and other road users. Trams generally travel with low speeds for safety reasons and tram stops often lack platforms. Passengers may be required to wait on a sidewalk, and then board or disembark directly among mixed traffic, rather than at a curbside. This results in delays to vehicle traffic which becomes more serious when the frequency of trams and traffic volumes increase. On the other hand, trams with priority can operate in a separated lane (semi-exclusive right-of-way) often located in the middle of a road. The reallocation of road space to provide priority for trams increases tram speed and reliability; however, it also reduces the capacity of roads and can increase the level of congestion. Thus, developing a method for exploring the net congestion impact of tram operations is needed as the value of a tram system can be assessed in terms of relieving traffic congestion.

The proposed methods for assessing the net impact of tram operations is relatively similar to the methods used for estimating the net impact of buses (Chapter 6). Mode shift from tram to car in the event of a tram withdrawal was used to investigate the positive effect of trams. The negative effects of trams were explored by incorporating the results from microsimulation, which models the effect of trams on a specific road link, into a four-step model (VITM).

The results in paper 6 were selected for publication in *Transportation Research Record: Journal of Transportation Research Board.* This paper is included in the next section of this chapter.

7.2 Net Traffic Congestion Impacts of Streetcar Operations in Melbourne, Australia *(Paper 6)*

Net Impacts of Streetcar Operations on Traffic Congestion in Melbourne, Australia

Duy Q. Nguyen-Phuoc, Graham Currie, Chris De Gruyter, and William Young

Public transit is widely recognized to reduce urban traffic congestion, as it encourages automobile travelers off the road. However, streetcars have been criticized for causing traffic congestion since large trams must operate in mixed traffic on narrow, congested streets. At the same time, streetcars reduce congestion by encouraging automobile drivers to use trams. So what is the net effect of streetcars on congestion? This paper presents a new method for assessing the net traffic congestion effects associated with streetcar operations in Melbourne, Australia, which has the largest streetcar network in the world. Impacts were determined with the use of a traffic network model to compare congestion with trams and without trams. The positive impacts of trams were estimated using mode shift from tram to automobile when tram services were removed. Negative impacts were explored by considering streetcar traffic operations, the impact of curbside tram stops, and the effect of exclusive priority tram lanes on traffic flow. Findings show that the streetcar network in inner Melbourne results in a net congestion benefit to traffic; a 3.4% decrease in vehicle time traveled and total delay on the road network was established. The streetcar network also contributes to reducing the number of moderately congested links by 16%. Areas for future research are suggested, such as exploring the spatial distribution of the mode shift to automobile and the long-term effect of trams on traffic.

With the rapid growth in use of private automobiles in recent years, traffic congestion has become a major issue in many large cities, particularly in inner cities (*1*). There have been attempts to improve or create rail-based transit systems to reduce traffic congestion (*2*), and light rail transit is considered an effective solution to the problem (*3*). Light rail systems can be found in land use contexts ranging from suburbs to high-density central business districts, and they can be operated under various right-of-way types (*4*). With their flexibility in congested cities, light rail systems can attract a significant share of urban automobile trips and reduce automobile use on congested road networks. However, the operation of streetcar systems can have negative effects on vehicle traffic, such as travel time and reliability (*5*). Streetcars run on tracks along public urban streets and on segregated rights-of-way. Streetcars running directly along public streets without any separation share the street with vehicle traffic and other road users. Trams generally travel at low speeds for safety, and tram stops often lack platforms. Passengers may have to wait on a sidewalk and then board or disembark directly among mixed traffic, rather than curbside (*6*). This system delays vehicle traffic, which becomes more serious when the frequency of trams and traffic volumes increases. Trams with priority can operate in a separated lane (semiexclusive right-of-way) often located in the middle of the road. The reallocation of road space to provide priority for trams increases tram speed and reliability (*7*); however, it also reduces the capacity of the road and can increase congestion (*8*).

Melbourne, Australia, has the largest operating light rail system as well as the largest streetcar system in the world (*6*). However, with about 180 km of tram tracks located in mixed traffic in the center lanes of roads (*9*), such systems are a major contributor to traffic congestion on Melbourne's road network. A key concern for planners is the net impact of tram operations on traffic congestion and how this varies across the city.

This paper explores the networkwide congestion impact associated with the operation of trams in Melbourne. Both the positive effect of trams in relieving traffic congestion and the negative effect of trams in generating congestion are assessed to determine a net impact.

The paper is structured as follows. The next section outlines previous studies relating to the impact of trams on traffic congestion. This outline is followed by a description of the study methodology. The results are then presented. The paper concludes with a summary, concluding remarks, and areas for further study.

BACKGROUND

Few studies have attempted to assess the impacts of trams on traffic congestion. Exploring the negative effects of tram operations on congestion, Chandler and Hoel investigated the effects of light rail crossings on average vehicle delay by using microsimulation (*4*). This topic was also explored by Rymer et al. (*10*) and Cline and Urbanik (*11*). Currie and colleagues estimated the impact of curbside stops on the efficient use of road space in their work on VicRoads R&D Project 799 (unpublished data, 2004). They compared tram operations on roads with and without curbside stops by using traffic simulation. They found that curbside stops reduced average tram and traffic speeds by 8% to 12%.

The provision of segregated tram lanes is an efficient means of improving transit reliability and running times when transit shares road space with congested urban traffic (*12*). However, the reallocation of road space reduces road capacity and can increase traffic congestion (*8*). Cairns et al. examined about 60 locations where road space was allocated to tram lanes or bus lanes (*13*). They found that on average the traffic volume on routes affected by the reallocation of road space decreased by 14% to 25%. Thus, the displaced traffic resulted in less congestion than expected; however, congestion may

D. Q. Nguyen-Phuoc, G. Currie, and C. De Gruyter, Public Transport Research Group, Institute of Transport Studies, and W. Young, Department of Civil Engineering, Monash University, Victoria 3800, Australia. Corresponding author: D. Q. Nguyen-Phuoc, [redacted]

Transportation Research Record: Journal of the Transportation Research Board, No. 2648, 2017, pp. 1–9.
http://dx.doi.org/10.3141/2648-01

have been moved to roads where traffic was diverted. In 2003, Currie et al. used traffic microsimulation to investigate the on-road operational implications of alternative transit priority measures. From the findings of simulation modeling, they developed a framework to estimate the benefits and costs of priority measures to transit and traffic (*7*).

Almost all previous studies focused on the negative impacts of tram operations on a road link or corridor. For networkwide effects, there have been few attempts to estimate the positive impact of tram operations on reducing traffic congestion on the road network. Bhattacharjee and Goetz analyzed the level of traffic on highways before and after the opening of light rail corridors in Denver, Colorado (*2*). In their study, data on vehicle miles traveled collected by field surveys from 1992 to 2008 were used to explore the effect of light rail. They found that light rail had reduced the level of traffic along some of the adjacent highways for a short period.

A study that used computer models to simulate and assess the congestion relief impact of trams on the entire road network was conducted by Aftabuzzaman et al. (*14*). Their research assumed a diversion to automobiles by tram users when the tram system was removed. From secondary research, they suggested that on average 32% of public transport users would shift to automobiles. They adopted this fixed value for tram trips and applied it to a transport network model in Melbourne to estimate the congestion relief impact associated with tram operations. The contrast between several congestion measures obtained from two scenarios, with tram and without tram, was considered to represent the amount of avoided congestion associated with tram operations. They found that in inner Melbourne, tram operations contribute to reducing congested links by approximately 28% and vehicle travel delay by 66%.

GAPS IN KNOWLEDGE

Only one study has examined the networkwide effect of trams on reducing traffic congestion (*14*). In that study, the mode shift to automobile (from tram) was determined with secondary data for all public transport users, not specifically tram users. Additionally, the study estimated only the positive impact of tram operations and did not consider the negative effects of trams, such as traffic delay caused by curbside tram stops, low tram speeds, and the allocation of priority tram lanes.

This paper is the first to provide a methodology with which to assess the net impact of tram operations on traffic congestion relief. To estimate the positive impact, the assumption of tram user diversion to private automobile when trams are removed was adopted. A primary survey determining the mode shift to automobile from trams in Melbourne was conducted in September 2015. The negative impact of trams was modeled with microsimulation. Context and methodology are detailed in the following.

RESEARCH CONTEXT

Melbourne's Tram Network

Trams are a major form of public transport in Melbourne. The tram network consists of 250 km of tram track, 493 trams operating across 25 routes, and 1,763 tram stops (*15*). It is the largest urban tramway network in the world (*15*). Trams are the second most used form of public transport in Melbourne, following the commuter railway network, with a total of 182.7 million passenger trips in 2012 and 2013 (*15*). Although tram transit has several drawbacks, such as unreliability, poor running speeds, and safety issues, total tram ridership increased by 46% between 2001–2002 and 2011–2012, while total public transport ridership (all modes) increased by only 9% (*9*).

Melbourne's tram system operates on three types of right-of-way: nonexclusive, semiexclusive, and exclusive (Figure 1). On nonexclusive rights-of-way (on-street running), trams operate with vehicle traffic in the center of the road. Pedestrians must walk from a curb to tram stops in the center of a road, usually without protected crossing points. The mixed traffic track arrangement (167 km) accounts for 67% of total tram tracks in Melbourne. There are approximately 1,200 curbside stops of 1,780 tram stops (67%); most of these are on-street (*5*). Curbside stops are a major feature of on-street running of services because of their impact on the efficient use of road space. During each boarding and alighting, all road traffic behind trams must stop. Thus, tram operations at curbside stops result in delays for vehicle traffic. Furthermore, the relatively short spacing between Melbourne's tram stops (approximately 270 m) contributes to a reduction in tram operating speeds because of acceleration, deceleration, and stop dwell time (*5*).

On semiexclusive rights-of-way, trams have to share crossroads with general traffic, but tram tracks are separated from traffic lanes by lane designation, mountable curbs, or striping. In Melbourne, most semiexclusive tram rights-of-way are in the inner city, where traffic congestion generally is higher. Trams running on exclusive rights-of-way are not affected by road traffic because this type of tramway is separate from the road network.

Spatial Unit of Analysis

Local government areas (LGAs) are the base unit of analysis used this study. There are 31 LGAs in Melbourne (*16*), grouped into three categories: inner (four LGAs), middle (14 LGAs), and outer (13 LGAs).

STUDY METHODOLOGY

This section describes a new methodology that has been developed for estimating the net traffic congestion impact of tram operations on the entire road network. In the first subsection, the Victorian integrated transport model (VITM) is described. The method, including several steps for assessing the net networkwide effect of trams on reducing traffic congestion, is then presented.

Victorian Integrated Transport Model

VITM is a conventional four-step transport model used to estimate travel demand in the Australian state of Victoria. The model is implemented in a Cube software platform. In VITM, the road network is represented by a set of links (66,848 links) and nodes, divided into 2,959 zones. Nodes usually represent an intersection or a change in road characteristics, and links represent the segments of actual roads in the network. VITM contains several submodels that work together to create the required output for each link, such as speed, volume, and travel time.

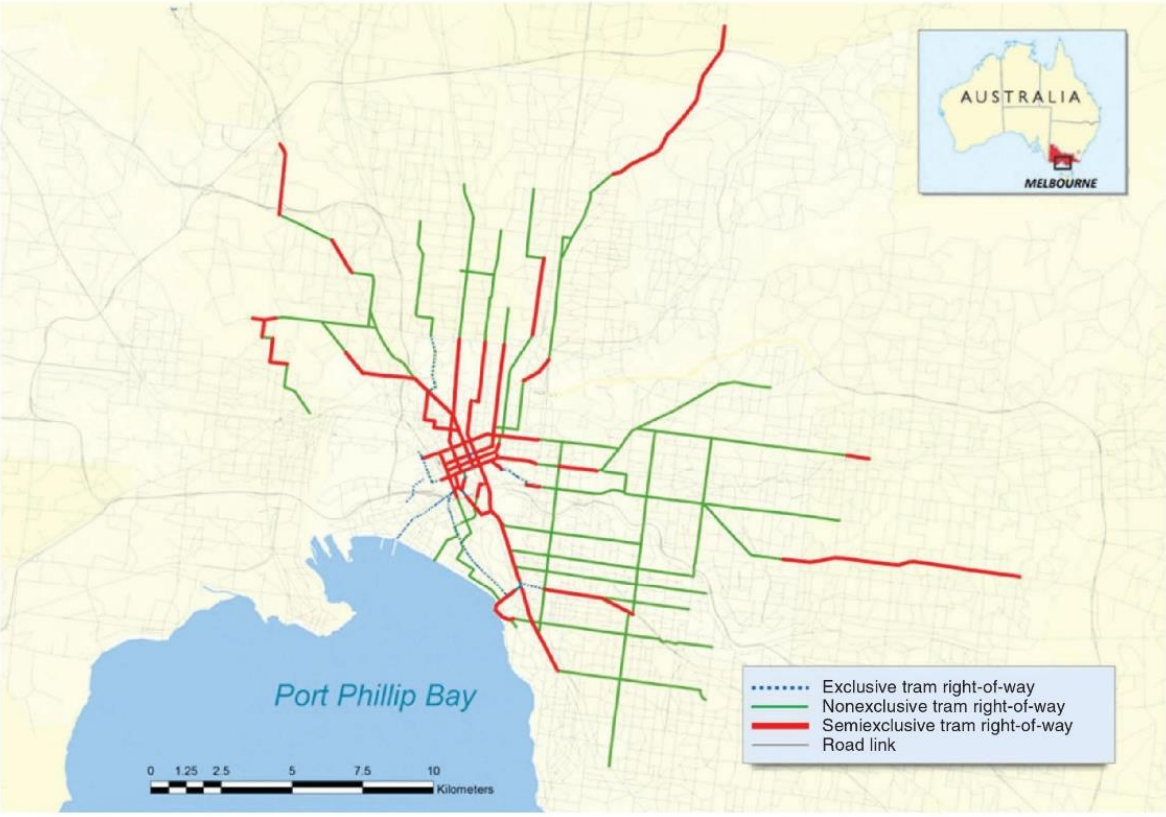


FIGURE 1 Melbourne's tram network.

Method for Modeling the Net Impact of Trams on Traffic Congestion

The modeling procedure adopts an assumption regarding tram user diversion to automobile, along with microsimulation and a four-step transport model to incorporate both positive and negative impacts of trams on traffic. The modeling analysis was carried out for an average weekday morning peak (7 to 9 a.m.).

In this research, a decrease in the number of automobile trips related to tram operations represents the positive effect of tram operations. Thus, to assess this positive effect, it is assumed that there is a mode shift to automobile if trams are removed. The number of tram users shifting to automobile in the case of tram removal is represented by the number of automobile users attracted by tram operations. The negative impact of trams relating to their contribution to traffic congestion includes (*a*) the effect of road capacity reduction related to the occupation of semiexclusive tram rights-of-way and (*b*) the impact of trams on vehicle traffic on nonexclusive tram rights-of-way related to the sharing of road space. Table 1 illustrates the methods adopted for estimating the

TABLE 1 Methodology for Assessing Negative Impacts of Tram Operations on Vehicle Traffic

Tram Right-of-Way	With Tram	Without Tram	Method for Assessing Direct Tram Effect
Exclusive	Tramway is constructed separately from road network; does not have any effect on vehicle traffic.	Does not have any effect on vehicle traffic.	Not applicable
Nonexclusive	Trams operate with vehicle traffic. Low speed of trams and tram stop arrangements may cause delay for vehicles.	Vehicles are not affected by tram operations. Speed of vehicle traffic increases.	Estimate vehicle travel delay caused by tram operations on specific link with microsimulation, incorporate this result into a 4-step model, and compare outcome of 4-step model in two scenarios: with tram and without tram.
Semiexclusive	Trams share crossroads with general traffic, but tram tracks are separated from traffic lanes.	Priority tram lanes are returned to general traffic. Capacity of road links increases.	Increase one lane for vehicle traffic on road links with trams in without-tram scenario and use 4-step model to compare congestion measures in two scenarios: with tram and without tram.

negative effect of each tram right-of-way type on generating traffic congestion.

The modeling procedure for estimating the net impact of trams on traffic consists of three main stages, as follows.

Stage 1

In the "with tram" scenario, the effects of tram operations on vehicle traffic flow (such as the effect of tram curbside stops and low tram speeds) are modeled by integrating the results of microsimulation into VITM. Then, according to the VITM output, the roadway travel data (traffic volume, average speed, and travel time) for each road link are calculated.

Stage 2

In the "without tram" scenario, the existing automobile trip matrix is added to the modified tram trip matrix (tram trip matrix multiplied by the mode shift to automobile) to obtain a modified automobile trip matrix. This new automobile trip matrix is then assigned onto the road network. Additionally, the capacity of road links with semi-exclusive tram rights-of-way is adjusted by adding one more lane. The roadway travel performance is then determined from the VITM output.

Stage 3

The congestion measures in the two scenarios, with tram and without tram, are contrasted to determine the net congestion relief effect of tram operations on the entire road network.

Primary Survey for Estimating the Mode Shift from Tram to Automobile

In September 2015, Public Transport Victoria conducted an online survey of public transport users in metropolitan Melbourne to understand the potential impact of public transport cancellations. Participants were asked about the impact of tram cancellations and about their likely travel behavior. A total of 306 users completed the online survey, in which 209 respondents (68%) reported that they regularly used trams and would be affected if tram services were cancelled in the morning peak. Survey findings are presented in the results section of this paper.

Microsimulation Approach

Vissim 7.0 is used to simulate tram operations and identify the impact of trams on general traffic flow. In this study, the effect of trams on a particular link is the focus of analysis. The main performance measure used is travel time. This figure is estimated by averaging the travel time of each vehicle on a segment. Travel time is used as a key measure because travel time is also calculated on each link in VITM and used as the main criterion for assigning vehicle trips to the road network.

Two scenarios, tram operations on a one-lane link and tram operations on a two-lane link, were developed to determine the impact of tram operations on traffic. First, these scenarios are tested without trams to obtain a baseline average travel time on road links. The simulation is run with a range of input traffic volumes and tram frequencies for a one-lane link and a different set of tram frequencies for a two-lane link. These tram frequencies are representative of Melbourne's tram network on one- and two-lane links. Finally, the results of the base case scenario and the scenarios of tram operations on a one-lane link and tram operations on a two-lane link are compared to define the relationship between the percentage change in travel time and traffic volume for each tram service frequency. A set of 20 runs is undertaken for each scenario to establish a sufficient level of confidence in the results.

In VITM, the average length of links with tram operations is about 245 m, and it is assumed there are four intersections per kilometer in Melbourne's inner areas. Thus, a 250-m link with a tram route on the right lane and an intersection at the end of the link are modeled to estimate the impact of tram operations. In addition, there are approximately 2,000 curbside tram stops in Melbourne, and most of these are on-street at an average spacing of 270 m. Hence, for a simpler representation, it is assumed that a curbside tram stop is located on each 250-m road link and in front of the intersection, consistent with current Melbourne practice.

To model the impact of curbside tram stop operations, stop signs are modeled on the traffic lane behind the tram stop area. Thus, when a tram stops, vehicles behind also must stop to give way to tram passengers boarding and alighting. The average dwell time of trams at stops (13.9 s) is taken from a survey undertaken in Melbourne by Currie et al. (*17*).

Tram priority is not always provided at intersections in Melbourne. Hence, trams are sometimes delayed by traffic signals at intersections. Morton observed tram delay caused by traffic signals on a road section between Princes Street and Collins Street in Melbourne (2.7 km) (*18*). He found that the total delay time of trams at 12 intersections was 6.35 min in the morning peak, equivalent to 32 s per intersection. Thus, this figure is used to model the delay of trams at intersections in the microsimulation. The intersection is located at the end of the link so that it is consistent with links with level crossings modeled in VITM (*19*). It is assumed that this intersection is controlled by fixed traffic signals with a cycle time of 60 s. The all-red period and intergreen time are assumed to account for 6 s, so the green time for each leg is 27 s.

Many types of trams are operating in Melbourne, of which the B-class tram is the most prevalent with 129 trams in service. B-class trams composed of two sections and three bogies (a total of 23.63 m) are used in this simulation. The speed of trams ranges between 15.5 and 16.5 km/h, consistent with the average tram speed in Melbourne of about 16 km/h (*15*). Table 2 (*20*) summarizes all parameters set in the Vissim microsimulation.

To simplify the microsimulation, the following assumptions are adopted:

- The headway of trams on a road link is the same even if the link is shared by various tram routes.
- The percentage change in travel time is estimated only in a one-lane link and a two-lane link. If links with nonexclusive tram rights-of-way have more than two lanes (accounting for only 0.5% of total links with nonexclusive tram rights-of-way in Melbourne), it is assumed that the delay is similar to the delay on a two-lane link.
- The vehicle speed limit of all links with tram routes is a maximum of 60 km/h, consistent with current practice in Melbourne.

TABLE 2 Parameters Set in Vissim Microsimulation

Parameter	Value	Source
Vehicle speed limit on road link	60 km/h	
Tram speed	16 km/h	Yarra Trams 2015 (*15*)
Traffic signal cycle time	60 s	
Dwell time	13.9 s	Survey by Currie et al. (*17*)
Tram length	23.65 m	B2 Class Tram (*20*)
Acceleration, deceleration	1.3 m/s^2	B2 Class Tram (*20*)
Road link length	250 m	
Tram stop location	230 m	From beginning of link
Tram delay caused by traffic signal	32 s	Morton (*18*)

Macromodeling Approach

For modeling the positive impact of trams, VITM is first run for the with tram scenario. A tram matrix that shows the number of tram users traveling from each origin to each destination is generated from the public transport assignment. This matrix is modified by multiplying it by the mode shift to automobile obtained from the field survey to represent the increase in automobile trips in the case of tram removal. Then, the modified tram matrix is added to the existing automobile trip matrix to create an expanded automobile trip matrix. In the without tram scenario, the expanded automobile matrix is assigned to the road network to model the traffic congestion relief impact of trams.

To assign vehicle trips on Melbourne's road network in VITM, travel time is calculated for each link with Akçelik's formula (*21*). This figure is one of the major parameters for estimating the generalized cost that is used in the equilibrium assignment process. In addition, to obtain an equilibration of demand, the traffic volume on each link is changed during an iterative process, leading to a change in travel time. Equilibrium assignment techniques explicitly recognize that transport network link costs generally depend on the volume using that link. A major development in this research is to represent the travel time on a link with on-street running based on tram service frequencies and traffic volumes. The travel time on links with nonexclusive tram rights-of-way is added as a percentage change in travel time, which is estimated by microsimulation, to model the negative impact of nonexclusive tram rights-of-way. This percentage is adjusted according to the number of lanes, the volume of traffic, and the frequency of trams on each link. When iterating to obtain an equilibration, the vehicle volume is changed in each loop. Thus, the percentage change in travel time has to be changed with the updated volume. This process is carried out by coding in Cube as follows:

$$\text{travel time} = \text{travel time}_0 + p\% * \text{travel time}_0 \qquad (1)$$

where

$p\%$ = percentage change in travel time caused by nonexclusive tram rights-of-way, calculated from a function of traffic volume and tram frequency created from microsimulation;

travel time_0 = travel time on a link with nonexclusive tram rights-of-way when the impact of tram operations is not considered; and

travel time = travel time on a link with a nonexclusive tram right-of-way.

The negative impact of trams on semiexclusive tram rights-of-way is represented by considering the allocation of tram lanes on links with semiexclusive tram rights-of-way. Thus, in the "without tram" scenario, an additional lane is added to road links with semiexclusive tram rights-of-way.

The outcomes between the two scenarios, with tram and without tram, are then compared in an investigation of the changes in congestion measures on the road network. These changes are interpreted to represent the net effect of tram operations on traffic congestion. Figure 2 illustrates the process for estimating the roadway travel data in the two scenarios.

RESULTS

The results are presented in three parts. First, the mode shift to automobile from tram obtained from the primary survey is described. The effect of tram operations on travel time for a link with a nonexclusive tram right-of-way using microsimulation is then shown. The mode shift to automobile and the results from microsimulation are then incorporated into VITM (macromodeling) to estimate the net congestion relief impact associated with tram operations. These results are shown in the final part.

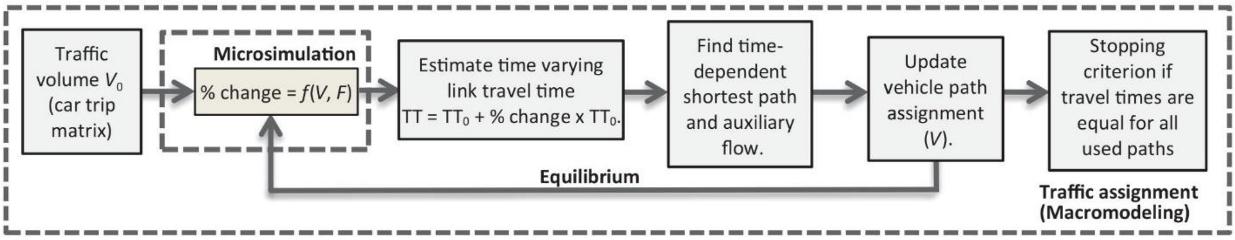
Mode Shift to Automobile

The primary data for this study were from an online travel survey of tram users in Melbourne. Figure 3 illustrates the transport mode shift of tram users in the event of tram service cancellations. About 45% of respondents stated that they would walk for their entire journey or a part of their journey. Approximately 35% and 21% of respondents would switch to train and bus, respectively. Tram users who would shift to automobile accounted for 26% of respondents, of which 19.4% would shift to automobile as the driver and 6.6% would shift to automobile as a passenger. Bicycle and motorbike were chosen as alternative transport modes by 14% and 5% of tram users, respectively.

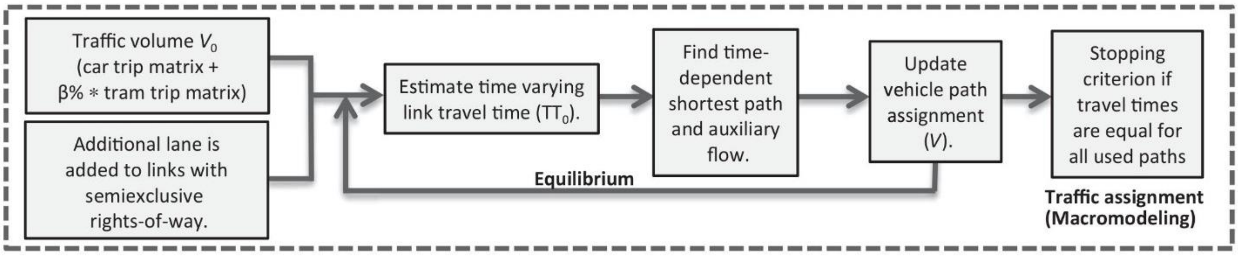
This research assumed that diversion of tram users to automobiles when tram operations cease would increase traffic congestion. The mode shift to automobile as the driver directly increases the number of automobile trips on the road network (diversion to other public transport modes, walk, or bicycle was not considered to influence congestion). However, switching to automobile as a passenger may or may not influence traffic congestion. For example, Litman argued that some automobile users can spend a significant amount of time driving children to school, family members to work, and elderly relatives on errands (chauffeuring trips) (*22*). These trips can be particularly inefficient if drivers must make empty return trips, which can contribute to congestion. Thus, for the modeling analysis, it was assumed that half of all automobile passenger trips involve chauffeuring. The mode shift to automobile contributing to traffic congestion if tram operations cease would therefore be 23% of tram users (19.4% + half of 6.6%).

Microsimulation Results

The effect of a nonexclusive tram right-of-way is explored in two scenarios: one-lane link and two-lane link with various tram service



(a)



(b)

FIGURE 2 Process of estimating travel demand with traffic assignment in two scenarios: (*a*) with tram and (*b*) without tram [V_0 = traffic volume from mode choice model; V = updated traffic volume; TT_0 = travel time in links (without tram effect); TT = travel time on links with exclusive tram rights-of-way; % change = percentage change in traffic travel time caused by tram operations; F = tram frequency; β = mode shift to private automobile from tram (%).

frequencies and traffic volumes. Figure 4 illustrates the relationship between the percentage change in travel time caused by on-street tram operations and the volume of traffic on one-lane road links and two-lane road links with various tram frequencies. The figure shows that there is a polynomial correlation between the volume of vehicles and the percentage change in travel time on links with nonexclusive tram rights-of-way. Given a similar level of traffic congestion, the effect of trams on travel time increases with an increase in tram frequency. On links with a given tram frequency, the percentage change in travel time increases when there is a rise in the vehicle volume.

These curves are used to adjust the travel time on road links with nonexclusive tram rights-of-way in VITM. This allows the impact of a nonexclusive tram right-of-way to be modeled more precisely in VITM.

Macromodeling Results

Table 3 (*23*) details the estimated net congestion relief effect of tram operations in Melbourne by contrasting congestion measures in the

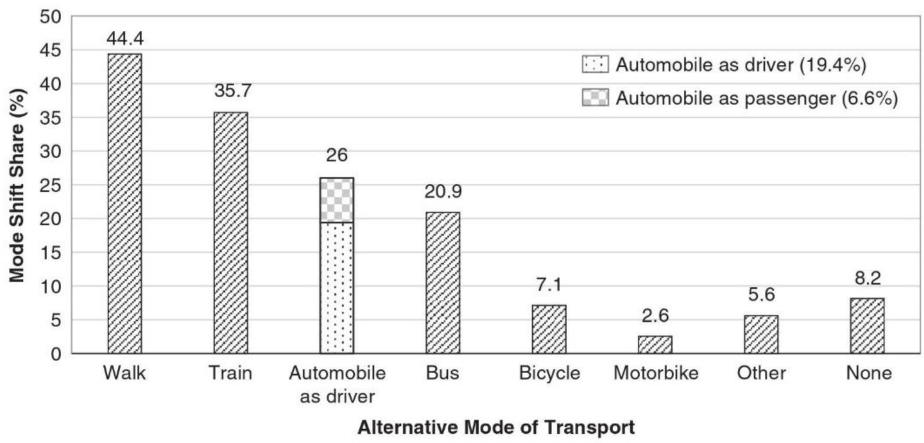


FIGURE 3 Transport mode shift from tram if tram operations cease. (Source: 2015 Public Transport Victoria survey of tram users.)

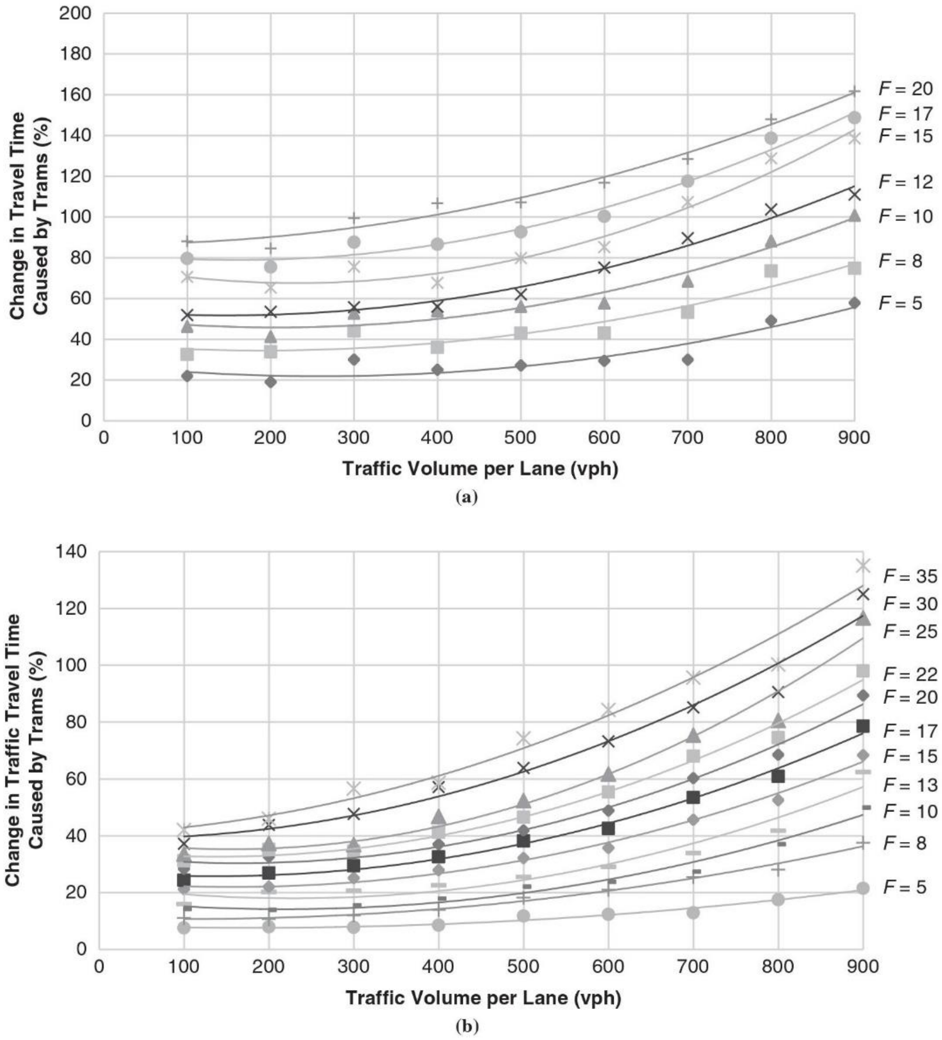


FIGURE 4 Percentage change in travel time caused by nonexclusive tram right-of-way: (*a*) one-lane link and (*b*) two-lane link [*F* = frequency of tram (trams per hour); vph = vehicles per hour].

TABLE 3 Overall Impact of Tram Operations on Melbourne Road Network

	Entire Melbourne			Inner Melbourne			Middle Melbourne		
Measure	With Tram	Without Tram	Change (%)	With Tram	Without Tram	Change (%)	With Tram	Without Tram	Change (%)
Severely congested links (V/C ≥ 0.9) (*23*)	2,125.0	2,137	0.6	458.0	438.0	–4.6	1,083.0	1,115.0	2.9
Moderately congested links (0.9 > V/C ≥ 0.8) (*23*)	1,931.0	1,997	3.3	330.0	393.0	16.0	939.0	945.0	0.6
Vehicles experiencing congestion (millions)	16.94	17.23	1.7	4.03	4.24	5.0	8.62	8.70	1.0
Vehicle distance traveled (million vehicle kilometers)	15.02	15.13	0.7	1.63	1.70	3.7	6.12	6.18	0.9
Vehicle time traveled (million vehicle hours)	0.384	0.389	1.2	0.052	0.054	3.4	0.178	0.181	1.6
Total delay on road network (million vehicle hours)	22.84	23.12	1.2	3.14	3.25	3.4	10.61	10.78	1.6
Average travel speed (km/h)	47.9	47.7	–0.5	41.9	41.6	–0.9	44.6	44.4	–0.5
Actual travel time per kilometer (min)	1.82	1.84	0.6	2.13	2.14	0.3	1.94	1.96	0.8

NOTE: V/C = volume-to-capacity ratio, that is, traffic volume divided by road capacity.

two scenarios, with tram and without tram. Results in Table 3 show the following:

- For the entire Melbourne road network,
  - More than 65 additional road links become moderately congested as a result of tram removal (3.3% increase), whereas only 12 additional road links become heavily congested;
  - An increase of 1.7% in vehicles experiencing congestion occurs when trams are removed;
  - Total network delay and vehicle time traveled increase by 1.2%; and
  - Average travel speed decreases from 47.9 to 47.7 km/h (a decrease of 0.5%);
- For inner Melbourne,
  - The number of moderately congested links increases by 16% with tram removal, and there is a decrease of 4.6% in the number of severely congested links;
  - Vehicle time traveled and total delay on the road network increase by 3.4%;
  - The average road network speed decreases from 41.9 to 41.6 km/h (a decrease of 0.9%); and
  - Travel time on average increases slightly from 2.13 to 2.14 min/km (0.3% increase); and
- For middle Melbourne,
  - Removing trams in middle Melbourne contributes to an increase of 32 severely congested links (2.9% increase) and six moderately congested links (0.6% increase);
  - Total delay on the road network increases by 170,000 vehicle hours (1.6% increase); and
  - Travel time per kilometer increases by 0.8%, and average travel speed is reduced by 0.5%.

DISCUSSION AND CONCLUSION

Almost all previous studies regarding trams and traffic congestion focused on the effects of streetcars in creating congestion on road links. This paper presented a new methodology for assessing the net impact of trams on traffic congestion, including their contribution to reducing road traffic through mode shift.

An analysis of field data found that when tram operations cease, tram users are likely to change their travel behavior. Walking was chosen as an alternative transport mode by the largest share of tram users (approximately 45%). The second most popular mode was train at more than 35%. Automobile travel resulted for about 26% of tram users (19.4% as the driver, 6.6% as a passenger). In this research, mode shift to automobile was investigated because it directly contributes to congestion on the road network.

The findings show that tram operations significantly suppress the extent of traffic congestion; however, their net effect is offset by some negative impacts on traffic flow. The analysis of congestion across metropolitan Melbourne as a whole showed that additional road links would become congested because of an increase in automobile trips when trams are removed. The total delay on the road network would be expected to rise by around 1.2%, whereas average speeds would be expected to decrease by 0.4%. The results of this research generally are consistent with those of several earlier studies. According to Lane, there was no considerable difference in traffic congestion between 13 cities with rail and 22 cities without rail in the United States (*24*). Mackett and Edwards stated that the traffic congestion relief effect of many rail-based public transport systems around the world was much lower than projections (*25*). Castelazo and Garrett argued that light rail transit alone cannot relieve traffic congestion permanently: it must be combined with other public transport modes and other types of policies such as congestion pricing (*26*).

In inner Melbourne, trams have a much greater impact for reducing congestion; vehicle time traveled and total delay on the road network decrease by 3.4% as a result of tram operations. The average road network speed rises from 41.6 to 41.9 km/h. The operation of trams in inner Melbourne reduces actual travel time on average from 2.14 to 2.13 min/km. The tram network contributes to reducing by 16% the number of moderately congested links in inner Melbourne. The number of heavily congested link increases by 4.6%. When there are tram operations, road links with semiexclusive tram rights-of-way, which are located largely in inner areas, have reduced capacity because of the allocation of tram lanes. Thus, a proportion of these links becomes more congested.

In contrast, the impact of trams on reducing traffic congestion in the middle areas of Melbourne is less significant; however this could be expected because there are fewer routes in middle Melbourne. Tram operations in these areas contribute only to a decrease of 32 severely congested links (2.9%) and six moderately congested links (0.6%). In the middle areas, trams reduce total delay on the road network by 170,000 vehicle hours (1.6%). With the operation of trams in middle areas, the actual travel time per kilometer rises by only 0.8%, while average travel speed decreases by 0.5%. A very small part of the tram network in Melbourne is located in outer areas, so the effect of trams in these areas is assumed to be negligible.

This paper has shown that Melbourne's tram–streetcar network makes an important, yet modest, contribution to reducing traffic congestion on the road network. This contribution is more pronounced in the inner area of Melbourne, playing a role in sustaining the livability of the city.

The main contributions of this paper are

- An understanding of the change in travel behavior among tram users when tram operations cease,
- The development of a new methodology for estimating the networkwide effect of tram operations on traffic congestion, and
- A preliminary understanding of the spatial variation of the impact of trams on congestion reduction.

The research assumed that diversion from tram to automobile is fixed for all areas. However, in reality, the mode shift to automobile would vary across and within each area (*27*). An understanding of this spatial distribution would lead to a more precise estimate of congestion reduction impacts. This research estimated the impact of tram operations on traffic congestion under the assumption of short-term removal of trams. If tram services are not available in the long term, the reaction of tram users could be different. Users could consider changing their work or home location to reduce their travel distance. Thus, the mode shift to automobile would have a different long-term effect and should be explored in future research.

REFERENCES

1. *Managing Urban Traffic Congestion.* European Conference of Ministers of Transport, 2007.
2. Bhattacharjee, S., and A. R. Goetz. Impact of Light Rail on Traffic Congestion in Denver. *Journal of Transport Geography,* Vol. 22, 2012, pp. 262–270. http://dx.doi.org/10.1016/j.jtrangeo.2012.01.008.

3. Vuchic, V.R. *Transportation for Livable Cities.* Rutgers Center for Urban Policy Research, New Brunswick, N.J., 1999.
4. Chandler, C., and L.A. Hoel. *Effects of Light Rail Transit on Traffic Congestion.* Center for Transportation Studies, University of Virginia, Charlottesville, Va., 2004.
5. Currie, G., and A. Shalaby. Success and Challenges in Modernizing Streetcar Systems: Experiences in Melbourne, Australia, and Toronto, Canada. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2006, 2007, pp. 31–39. http://dx.doi.org/10.3141/2006-04.
6. Currie, G., and P. Smith. Innovative Design for Safe and Accessible Light Rail or Tram Stops Suitable for Streetcar-Style Conditions. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1955, 2006, pp. 37–46. http://dx.doi.org/10.3141/1955-05.
7. Currie, G., M. Sarvi, and B. Young. A New Approach to Evaluating On-Road Public Transport Priority Projects: Balancing the Demand for Limited Road-Space. *Transportation,* Vol. 34, No. 4, 2007, pp. 413–428. http://dx.doi.org/10.1007/s11116-006-9107-3.
8. Kittelson, P., K. Quade, and K. Hunter-Zaworski. *TCRP Report 165: Transit Capacity and Quality of Service Manual.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
9. Delbosc, A., and G. Currie. Exploring Attitudes of Young Adults Toward Cars and Driver Licensing. Presented at *Australasian Transport Research Forum,* Brisbane, Australia, 2013.
10. Rymer, B., T. Urbanik II, and J.C. Cline, Jr. Delay at Light Rail Transit Grade Crossings. In *Special Report 221: Light Rail Transit: New System Successes at Affordable Prices,* TRB, National Research Council, Washington, D.C., 1989, pp. 621–634.
11. Cline, J.C., and T. Urbanik II. *Delay at Light Rail Transit Grade Crossings.* Texas Transportation Institute, College Station, 1987.
12. Vuchic, V.R. *Urban Transit Systems and Technology.* John Wiley & Sons, Inc., New York, 2007. http://dx.doi.org/10.1002/9780470168066.
13. Cairns, S., C. Hass-Klau, and P. Goodwin. *Traffic Impact of Highway Capacity Reductions: Assessment of the Evidence.* Landor Publishing, London, 1998.
14. Aftabuzzaman, M., G. Currie, and M. Sarvi. Modeling the Spatial Impacts of Public Transport on Traffic Congestion Relief in Melbourne, Australia. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2144, 2010, pp. 1–10. http://dx.doi.org/10.3141/2144-01.
15. *Facts & Figures.* Yarra Trams, Melbourne, Australia, 2015.
16. *Austroads Metropolitan Network Performance Database.* VicRoads, Melbourne, Australia, 2005.
17. Currie, G., A. Delbosc, and J. Reynolds. Modeling Dwell Time for Streetcars in Melbourne, Australia, and Toronto, Canada. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2275, 2012, pp. 22–29. http://dx.doi.org/10.3141/2275-03.
18. Morton, A.B. Observational Analysis of Tram Delays in Inner Melbourne. Presented at 30th Australasian Transport Research Forum, 2007.
19. *Guidelines for VITM Network Coding.* VITM, Melbourne, Australia, 2011.
20. *B2 Class Tram.* VICSIG, Melbourne, Australia, 2015.
21. Akçelik, R. Travel Time Functions for Transport Planning Purposes: Davidson's Function, Its Time-Dependent Form and an Alternative Travel Time Function. *Australian Road Research,* Vol. 21, No. 3, 1991, pp. 49–59.
22. Litman, T. *Rail Transit in America: A Comprehensive Evaluation of Benefits.* Victoria Transport Policy Institute, Victoria, British Columbia, Canada, 2004.
23. *Congestion Management Process.* SEMCOG, Detroit, Mich., 2011.
24. Lane, B.W. Significant Characteristics of the Urban Rail Renaissance in the United States: A Discriminant Analysis. *Transportation Research Part A: Policy and Practice,* Vol. 42, No. 2, 2008, pp. 279–295. http://dx.doi.org/10.1016/j.tra.2007.10.001.
25. Mackett, R.L., and M. Edwards. The Impact of New Urban Public Transport Systems: Will the Expectations Be Met? *Transportation Research Part A: Policy and Practice,* Vol. 32, No. 4, 1998, pp. 231–245. http://dx.doi.org/10.1016/S0965-8564(97)00041-4.
26. Castelazo, M.D., and T.A. Garrett. Light Rail: Boon or Boondoggle? *Regional Economist,* July 2004, pp. 12–13.
27. Nguyen-Phuoc, D.Q., G. Currie, and B. Young. Public Transport Congestion Relief Measurement—A New Framework and Its Impacts. Presented at 37th Australasian Transport Research Forum, Sydney, Australia, 2015.

The Public Transportation Group peer-reviewed this paper.

7.3 Discussion

Trams are the second most used form of public transport in Melbourne. The findings show that the total delay on the road network would be expected to reduce by around 1.2% whereas average speeds would be expected to increase by 0.5% with Melbourne's tram operations. The congestion effect of trams found in this research is much lower than that explored by Aftabuzzaman et al. (2010b). In fact, in this research the net congestion effect of trams is estimated by considering both the negative and positive effect of trams on traffic while Aftabuzzaman et al. (2010b) did not take into consideration the drawbacks of trams on creating congestion. The positive value of the net effect of tram operations confirms that Melbourne's tram operations have contributed to reduce traffic congestion. Currently, there have been a number of debates about whether trams stop people using their cars or whether they just congest the roads. The findings of this research provides valuable evidence that shows the relief impact of trams on traffic congestion.

In inner Melbourne, trams have a much higher impact in relieving congestion; vehicle time travelled and total delay on the road network decreases by 3.4% as a result of tram operations. The average road network speed rises from 41.6 km/h to 41.9 km/h. This is due to most trams operating in this area which serve a high proportion of public transport users. In addition, with the introduction of the Free Tram Zone in Melbourne's CBD in 2015, trams have attracted more users and there has been a large increase in patronage.

In contrast, the impact of trams on reducing traffic congestion in the middle areas of Melbourne is less significant, however this might be expected given that there is less tram coverage in middle Melbourne. Tram operations in these areas only contribute to a decrease of 32 severely congested links (2.9%) and 6 moderately congested links (0.6%). The actual travel time per kilometre rises by only 0.8%, while average travel speed decreases by 0.5% with the operation of trams.

Based on the findings, tram operations are found to contribute to significantly suppress the extent of traffic congestion however their net effect is offset by some negative impacts on traffic flow. The results of this research are generally consistent with those of several prior studies. According to Lane (2008), there was no considerable difference in traffic congestion between 13 cities with rail and 22 cities without rail in the US. Mackett and Edwards (1998) stated that the traffic congestion relief effect of many rail-based public transport systems around the world was much lower than prior projections. Castelazo and Garrett (2004) argued that light rail transit alone cannot relieve traffic congestion permanently; it has to be combined with other PT modes and other types of policies such as congestion pricing.

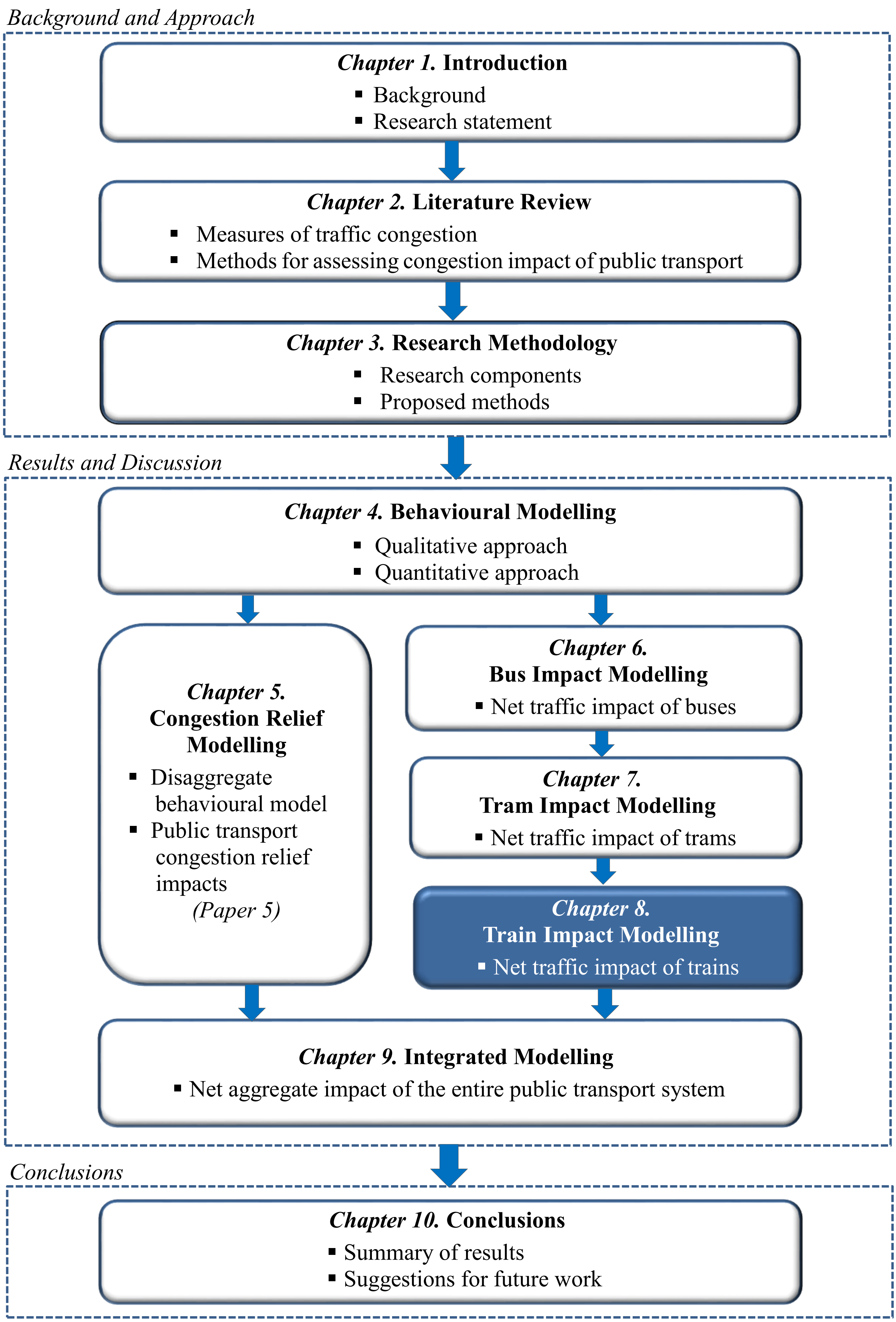
This research has assumed that diversion from tram to car is fixed for all areas. However, in reality, the mode shift to car would vary across and within each region. Understanding this spatial distribution would therefore lead to a more precise estimate of congestion reduction impacts and is covered in Chapter 5. This research has estimated the impact of tram operations on traffic congestion under the assumption of short-term removal of trams. If tram services are not available in the long-term, the reaction of tram users might be different. They might consider changing their work or home location to reduce their travel distance. Thus, the mode shift to car would be different in the long-term effect and should therefore be explored in future research.

7.4 Conclusions

This chapter presented a new methodology used to estimate the net effect of tram operations on traffic congestion. The method adopted microsimulation and a four-step transport model (VITM) to explore the negative effects of trams on generating traffic congestion. The positive effect on reducing traffic congestion was also examined using the assumption of car diversion from tram when trams are unavailable. Finally, the net impact of trams on traffic congestion was assessed by integrating both the positive and negative effects of tram operations.

Using Melbourne as a case study, this chapter explored the net short-term impact of tram operations, the largest tram network in the world, on traffic congestion. The findings show that the net congestion effect of Melbourne's trams is positive, particularly in inner areas where there is high ridership.

The next chapter uses the same methods developed in Chapters 6-7 to explore the net congestion effect associated with train operations, the most used form of public transport in Melbourne.


Background and Approach
Chapter 1. Introduction
Background
Research statement
Chapter 2. Literature Review
Measures of traffic congestion
Methods for assessing congestion impact of public transport
Chapter 3. Research Methodology
Research components
Proposed methods
Results and Discussion
Chapter 4. Behavioural Modelling
Qualitative approach
Quantitative approach
Chapter 5. Congestion Relief Modelling
Disaggregate behavioural model
Public transport congestion relief impacts
(Paper 5)
Chapter 6. Bus Impact Modelling
Net traffic impact of buses
Chapter 7. Tram Impact Modelling
Net traffic impact of trams
Chapter 8. Train Impact Modelling
Net traffic impact of trains
Chapter 9. Integrated Modelling
Net aggregate impact of the entire public transport system
Conclusions
Chapter 10. Conclusions
Summary of results
Suggestions for future work

Chapter 8
TRAIN IMPACT MODELLING

8.1 Introduction

Chapter 6 and Chapter 7 explored the net effect of bus and tram operations on traffic congestion respectively. In this chapter, the net congestion effect associated with train operations, the most used form of public transport, is examined. This chapter addresses a research gap identified in the Literature Review: No studies have explored the net network-wide impact of train operations on traffic congestion. This is in accordance with research objective 5 to develop new methods to investigate the net traffic congestion impact of train operations. The methods examining the net congestion effect balance both the positive effect and the negative effects of train operations. Table 8.1 details the research objective, research component, research gap and research opportunity associated with this chapter.

Table 8.1 Research gap, opportunity and objective associated with research component 7

Research objective	Research component	Research gap	Research opportunity
5. To develop new methods to investigate the net network-wide impact of train operations on traffic congestion	7. Train congestion effect estimation	No studies have explored the net network-wide impact of train operations on traffic congestion	Investigate the net traffic congestion effect of train operations by considering both positive and negative impacts

In line with research objective 5, the research aim of this chapter is to investigate the net traffic congestion effect of train operations. In order to achieve this aim, methods for assessing the negative effect as well as the positive effect on traffic are developed using survey data and transport network modelling.

Although urban train has a positive effect on reducing traffic congestion by encouraging mode shift from private car to train, it also has negative effects on creating congestion. For train systems, the operation of at-grade rail crossings may result in delays to road traffic movement. Traffic delays and congestion at these rail level crossings increase in scale with the frequent train services. Thus, it is necessary to assess the net effect of train operations on traffic congestion.

In this research, transport network modelling which adopted data from a field survey was used to examine these effects. Firstly, the positive effect of trains was investigated using stated mode shift data from train to private car in the event of a train withdrawal. Secondly, the negative effect of trains on traffic was explored by incorporating the results of microsimulation, which models the impact of at-grade rail crossings on specific road links, into VITM (macrosimulation). Paper 7 focuses on the method used to assess the negative effects of at-grade rail crossings on the entire road network in Melbourne. The results in this paper were selected for publication in the *Journal of Transportation Geography*. Finally, both positive and negative effects were integrated to estimate the net effect of trains on traffic congestion.

8.2 Research Context

8.2.1 Melbourne's Heavy Rail System

Melbourne's heavy rail system carries services for metropolitan commuters, regional commuters and freight. The metropolitan railway network consists of 16 regular service train lines, a central City Loop subway, and 218 stations, with a total length of 372 km of electrified lines, and in 2014, this network carried 232 million passenger trips (DOT, 2014). The train network operates from 5am to midnight. It has been constructed primarily at ground level, with 177 level crossings so the right-of-way for trains results in many impacts on vehicular traffic, such as accidents and delays at level crossings.

8.2.2 Melbourne's Level Crossings

Melbourne's railroad and road systems intersect at 177 level railway crossings where vehicles are delayed while waiting for a train to pass. To our knowledge this is the largest number of level crossings in a single city in the world. Each crossing represents a potential conflict point between trains and other road traffic including vehicles, pedestrians, trams, buses and cyclists. Hence, blockage and congestion is common when crossings are closed to allow trains to pass. While the implementation of grade separation infrastructure is often based on safety needs, in the Melbourne context, the sheer number of crossings means road congestion is also a major concern. Addressing that concern is expensive however. According to Andrews (2014), some $AUS 6 billion would be needed to eliminate the 50 level crossings that are the focus of a current policy initiative of the State Government in Victoria.

8.3 Research Methodology

Most previous studies have explored the either the positive effect of train or negative effect of train on a corridor. This research develops new methods for assessing the net network-wide effect of train operations on traffic congestion including both negative and positive impacts.

The proposed methodology involved three main parts. The share of mode shift from train to car is firstly estimated with the use of data derived from a field survey (refer to Chapter 4). This mode shift is used to investigate the positive effect of trains on traffic. In the second section, methods for exploring the negative effects of train operations are developed. Finally, the net effect of train operations is explored by integrating both negative effects and positive effect using a macrosimulation model (VITM).

8.3.1 Mode Shift from Train to Car if Train is not available

In order to estimate the positive impact of trains on reducing traffic congestion, it is necessary to investigate an expected decrease in the number of car trips due to train operations. In this study, the number of train users shifting to car in the case of a train removal are assumed to represent the number of car users attracted by train operations. A field survey was conducted from 433 train users in Melbourne (refer to section 4.3.2.6). In this survey, train users were asked to choose an alternative transport mode if train operations were not available for their last train trips in the AM peak hours (7h-9h). It was found that on average 42.7% of train users would switch to travelling by car as a driver or a passenger if trains are unavailable.

8.3.2 Negative Effects of Train Operations on Generating Traffic Congestion

The method for assessing the negative effects of train operations on traffic congestion includes two main stages. In the first stage, micro-simulation is undertaken to identify the relationship between travel time delay and traffic volume with various train frequencies. These equations were used to predict the change in travel time or traffic volume of road traffic caused by level rail crossings for different train frequencies. In the second stage, these relationships are incorporated into VITM (macro-simulation) to estimate the impact on Melbourne's road network.

The detailed approaches and findings of the research in this section are now presented in the form of a journal paper as follows:

Paper 7 *Nguyen-Phuoc, D. Q., Currie, G., De Gruyter, C. & Young, W. 2017. Local and system-wide traffic effects of urban road-rail level crossings: A new estimation technique.* ***Journal of Transport Geography****, 60(1), 89-97.*

Journal of Transport Geography 60 (2017) 89–97

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

New method to estimate local and system-wide effects of level rail crossings on network traffic flow

Duy Q. Nguyen-Phuoc [a], Graham Currie [a,*], Chris De Gruyter [a], William Young [b]

[a] Public Transport Research Group, Institute of Transport Studies, Monash University, Victoria 3800, Australia
[b] Department of Civil Engineering, Monash University, Wellington Road & Blackburn Road, Clayton, VIC 3800, Australia

ARTICLE INFO

Article history:
Received 15 February 2017
Accepted 26 February 2017
Available online 06 March 2017

Keywords:
Traffic congestion
Level crossing
Travel time
Delay

ABSTRACT

This paper makes local and aggregate estimates of the effects of 152 level crossings in the Melbourne metropolitan area, Australia on traffic congestion in the morning peak period (7 am–9 am). A new method, including micro-simulation of a range of rail crossing configurations, is used to inform a network model which makes aggregate estimates of impacts on all traffic.
Relationships between train frequency and percentage change in vehicle travel time and volume were identified. These equations can predict change in travel time/traffic flow caused by rail level crossings based on rail crossing closures and train frequency.
Overall, Melbourne's level crossings result in an average increase in travel time of 16.1% for vehicle traffic on links with a level crossing. However on average a level crossing reduces the volume of vehicles on these links by 5.9% as a result of traffic diversion. These values are higher in middle suburbs where train arrivals and crossing closure times at level crossings are more frequent.
The aggregate effect of all 152 level rail crossings on all traffic in Melbourne is a travel time change from 1.81 to 1.82 min/km (an increase of around 0.3%). The number of congested links in Melbourne increases by 0.9% while the total delay increases by 0.7%. These network wide effects are not large compared to localised effects because road links affected directly by crossings represent a very small part of the overall network. Additionally, network effects also include traffic diversion impacts which will counteract some of the immediate impacts on a localised scale. However, it is significant that the very small element of the system can have even a measurable effect on aggregate traffic congestion.

1. Introduction

Rail passenger transport can carry a significant share of urban travel and reduce car use, which may lower congestion on road networks. Hence, mass transit is seen as an important solution when dealing with urban traffic congestion (Pucher et al., 2007). However, rail systems can also generate negative impacts on road traffic movement when their alignments cross roads at level (or, at grade) crossings. Traffic delays and congestion at these rail level crossings increase in scale when the frequency of train services rises. These crossings have an impact on the lives of the surrounding communities, while also influencing system-wide road traffic. Safety at level crossings is also a big concern; rail crossings present the potential for train-vehicle and pedestrian collisions. These problems also become more serious when the frequency of trains and traffic volume increases (Hakkert and Gitelman, 1997).

Unlike other international cities, Melbourne has a very large number (177) of level railway crossings distributed throughout the metropolitan network (VicRoads, 2014). They are considered a major contributor to local congestion on Melbourne's road network and may have a system-wide effect. Due to these impacts, there has been sporadic investment in grade-separation projects; a recent government decision has ramped up this effort with work on replacement beginning in 2016 and planned to continue over the next three years (Andrews, 2014).

This paper is an exploration of both local and aggregate city wide traffic delays at level rail crossings in Melbourne. It aims to quantify the order of magnitude of impacts on traffic delay by estimating the level crossing closure time associated with the frequency of trains and for different rail service types. It does so by developing a new methodology to determine traffic delays. Micro-simulation is utilised to demonstrate vehicle travel time effects on an identified road link. Then, a conventional four step transport model (the Victorian Integrated Transport Model), which takes the result from the micro-simulation as an input, is used to forecast congestion at these railway crossings drawing upon multiple performance measures. GIS is used to illustrate the spatial impacts in the results.

* Corresponding author.
E-mail addresses: [redacted] (G. Currie), [redacted] (C. De Gruyter), [redacted] (W. Young).

http://dx.doi.org/10.1016/j.jtrangeo.2017.02.012
0966-6923/

This paper is structured as follows: the next section outlines previous approaches to measure travel delay at level crossings and provides background to the research. This is followed by a description of the study methodology. The results are then presented. The paper concludes with a summary, concluding remarks and areas for further study.

2. Background

Safety at level crossings is the major concern of published research (De Gruyter and Currie, 2016). A number of models have been created for forecasting highway-rail crossing accident frequencies and their causal factors (Austin and Carson, 2002; Hu et al., 2010; Zalinger et al., 1977; Schlossberg et al., 2006). Other researchers focussed on improved design to reduce the number of accidents. Lewiński and Bester (2010) presented a wireless warning system that can warn road users located in the area of railway crossings before the approaching train arrives. Stephens and Long (2003) evaluated supplemental pavement markings for improving safety at railroad–highway grade crossings.

There are only a few published studies investigating the impacts of level railway crossings on traffic congestion. In NCHRP Report 288, Taggart et al. (1987) explored some formulas for calculating the travel delay experienced by each vehicle at a level crossing. These equations are based on the average annual traffic, vehicular traffic and the closure time that is calculated from average train length and the average train speed at the crossing. Hakkert and Gitelman (1997) developed a simplified tool for evaluating level crossings in Israel. From the field data collected at 31 of the most problematic locations, they calculated the cost of safety problems and travel delay and used them to compare level crossing performance. Schrader and Hoffpauer (2001) created a methodology for considering the prioritization of potential highway–railway grade separation locations in Central Arkansas. In this method, the time delay at level rail crossing is one of seven factors incorporated into their analysis and is estimated by formulae developed by Taggart et al. (1987). Other research focusing on the delay at level rail crossings was undertaken by Okitsu and Lo (2010). First, they undertook a 24-hour video record at 33 level crossings in Los Angeles County's San Gabriel Valley. From the recordings, they determined several parameters such as upstream traffic signal phasing and downstream signal green-to-cycle ratios and applied them to Webster's intersection delay model. Thus, delay caused by blockages at level crossings in every individual event throughout the day could be identified.

It can be seen that almost all of these previous studies used mathematical models to focus only on the effect of level crossings on immediate road links. There are no studies investigating the network-wide effect of these level crossings. This research paper addresses that gap. We develop a new methodology to estimate aggregate travel delay and traffic volume changes on immediate (or local) links. It incorporates the effects on traffic flow of closure time as shaped by rail service frequency. In a second step, it applies the approach to the entire road network.

3. Research context

This section provides the context for the analysis undertaken. It starts by describing the heavy rail system in Melbourne. It is followed by a review of Melbourne's level crossings.

3.1. Melbourne's heavy rail system

Melbourne's heavy rail system (Fig. 1) carries services for metropolitan commuters, regional commuters and freight. The metropolitan railway network consists of 16 regular service train lines, a central City Loop subway, and 218 stations, with a total length of 372 km of electrified lines, and in 2014, this network carried 232 million passenger trips (DOT, 2014). The rail network operates from 5 am to midnight. It has been constructed primarily at ground level, with 177 level crossings so the right-of-way for trains results in many impacts on vehicular traffic, such as accidents and delays at level crossings.

3.2. Melbourne's level crossings

Melbourne's railroad and road systems intersect at 177 level railway crossings (Fig. 2) where vehicles are delayed while waiting for a train to pass. To our knowledge this is the largest number of level crossings in a single city in the world. Each crossing represents a potential conflict point between trains and other road traffic including vehicles, pedestrians, trams, buses and cyclists. Hence, blockage and congestion is common when crossings are closed to allow trains to pass. While the implementation of grade separation infrastructure is often based on safety needs, in the Melbourne context, the sheer number of crossings means road congestion is also a major concern. Addressing that concern is expensive however. According to Andrews (2014), some $AUS 6 billion would be needed to eliminate the 50 level crossings that are the focus of a current policy initiative of the State Government in Victoria.

The congestion and safety concerns vary across the network. At several level crossings, located in Melbourne's outer south eastern suburbs, low frequency (a few freight or tourist trains a day) crosses roads. This low frequency meant these crossings were not considered in this research. Putting them to one side left 152 level crossings which are the focus of the analysis that follows.

4. Study methodology

This study aims to estimate the impact of rail level crossings not only on a segment of local road but also on the entire road network as a whole. Both micro-simulation at the local level, and macro-modelling on the network, are used to create a more precise method for identifying the effect of these crossings.

4.1. Macro-modelling - the Victorian Integrated Transport Model

The Victorian Integrated Transport Model (VITM) is a conventional four-step model which estimates travel demand in Victoria, Australia. The model is implemented in a Cube software platform. In VITM, the road network is represented by a set of links (66,848 links) and nodes (28,499 nodes), divided into 2959 zones. Each zone is represented by a centroid that is a point inside the zone where people travel from and to. Nodes usually represent an intersection or a change in road characteristics. Links represent the segments of actual roads in the network, or represent centroid connectors. The links are coded with various road characteristics such as posted speed and capacity. VITM contains a number of sub-models which work together to create the required output for each link such as actual speed, volume and travel time.

The first step of modelling is trip generation which uses eight trip purposes for home-based trips, and six trip purposes for non-home based trips, in order to define the magnitude of total daily travel on the network. Trip distribution, the second step, distributes trips from a particular zone to all possible destination zones according to travel time. The third step is mode choice which splits trips into each available mode between each zone pair. A hierarchical binary logit structure is utilised to develop a choice model for each trip purpose. The last stage of VITM is trip assignment. In this stage, predicted model flows between each O-D pair are assigned to actual routes on Melbourne's road network using an equilibrium assignment process. Speed-flow curves which vary for road types are used to calculate the travel time in the assignment process.

The details it can supply on links provide the scope to explore rail crossings.

4.2. Modelling level rail crossings in VITM - limitations

In VITM, travel time on each link is calculated using the formulation of Akçelik (1991). Dowling et al. (1998) found that Akcelik's curve

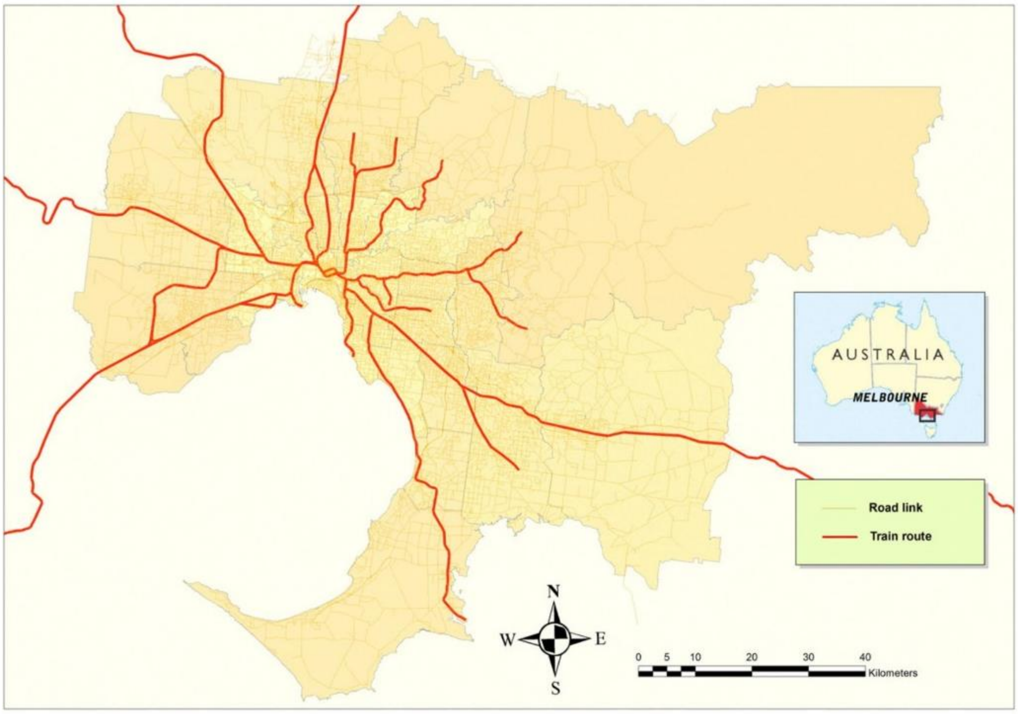


Fig. 1. Melbourne's rail network.

based on traffic queuing theory provides more accurate speed estimates over a range of demand conditions than the standard U.S. Bureau of Public Roads (1964) curve.

A set of 29 link types and 25 speed-flow curves are used in VITM to describe the performance characteristics of the road network. Link-type classifications provide information about link capacity and other

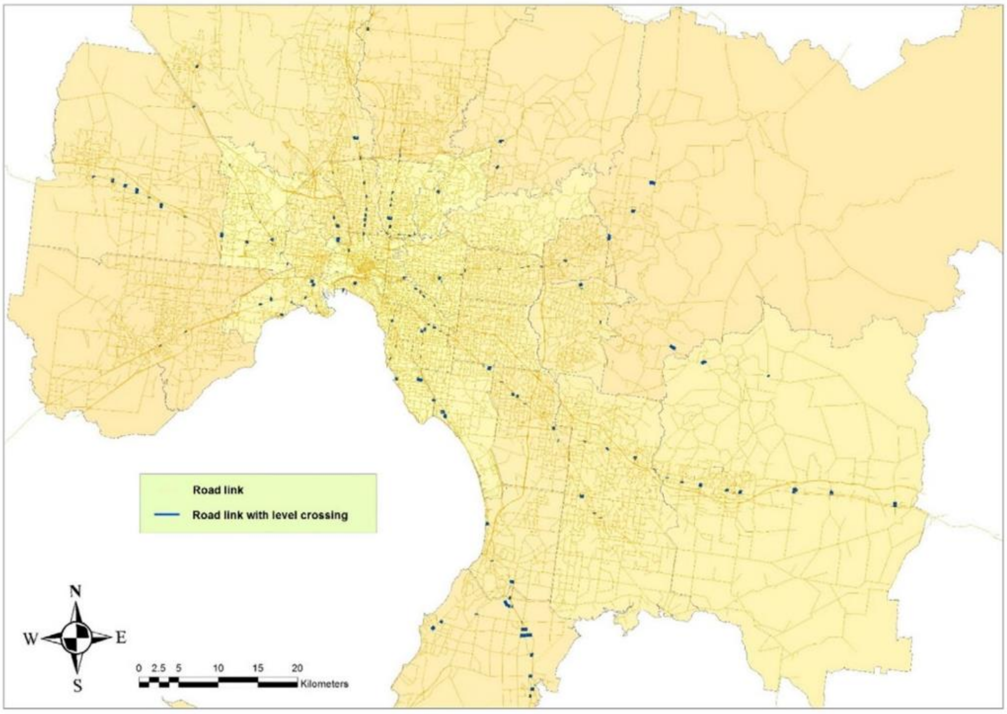


Fig. 2. Road links with level crossings in metropolitan Melbourne.

physical characteristics such as delay parameters or free flow speed, while speed-flow curves are used to establish appropriate traffic speed values on each link based on link traffic flow.

In order to model delays caused by rail level crossings in VITM, links including level crossings are set to be 500 m in length and coded with one link class for inner areas and a second for outer areas. However, it is clear that there are significant differences in the traffic characteristics of level crossing links in different locations across the metropolitan area, and a more refined classification system is needed. The critical aspects here are the train frequencies and traffic volumes along the link, which together result in the different crossing closure times and hence different levels of traffic delays. Thus, to more accurately estimate the negative impact of level crossings it is important to develop a new methodology that incorporates these dimensions. This is one of the aims of this paper.

4.3. Improved methodology – incorporating closure delay estimates

The new methodology incorporated three steps:

- Step 1: In the scenario 'without level crossing', road links with level crossings are coded with a link type which is the same as adjacent road links to represent no crossings on those links. The VITM is then run to produce a 'without level crossing' scenario.
- Step 2: In the scenario 'with level crossing', links with level crossings are coded by a specific road link. The percentage change in travel time on those links caused by level crossings is estimated by using traffic micro-simulation. The results from micro-simulation are incorporated into VITM (macro-modelling) in order to determine the impact of level crossings on the road network. In VITM, the travel time of links with level crossings is adjusted by adding normal travel time (using Akcelik's formulation) with a percentage increase in travel time caused by level crossings on each link to represent the delay generated. The VITM is run to produce a 'with level crossing' scenario.
- Step 3: Compare the outcomes between the two scenarios, 'with level crossing' and 'without level crossing', to estimate the impact of level crossings on immediate links and on the entire road network.

The modelling analysis was carried out for an average weekday morning peak (7 am–9 am).

4.4. Microsimulation approach

The aim of the microsimulation is to estimate delays associated with crossing closure times. It is expensive and difficult to collect field data from existing heavy rail operations because of the varying geometry, traffic and travel behaviour of drivers at each of the 152 level crossings.

Simulation modelling was selected as a more efficient approach in this study since this modelling can represent the effects of road condition and traffic flow on congestion. Vissim 7.0 is the software package adopted to model the operation of level crossings and identify the impact of rail service frequencies on regular traffic flow. In this study, the effect of level crossings on a link is the focus of analysis and the main measure used is the average link travel time. That is estimated by averaging the travel time of each vehicle on a segment. The reason for choosing travel time as a major measure is that travel time is calculated on each link in VITM and used as a main criterion for assigning vehicle trips to the road network.

The analysis focusses upon one particular type of crossing, the 'isolated mid-block level crossing on a one-lane link' to develop a scenario for travel time. Firstly, this scenario is built without rail crossings to obtain a baseline average travel time on links. Next, the simulation is run with a range of input traffic volumes (100, 200, 300…900 vehicles/h) and different train frequencies (5, 10, 15, 20, 25, 30, 35, 40, and 50 trains/h) which act to generate different crossing closure times. The simulation run is performed for each combination of input volume and train crossing frequency. Finally, the 'base case' and the 'isolated mid-block level crossing on a one-lane link' scenario are compared to obtain the relationship between the percentage change in travel time and traffic volume for each identified train frequency.

The model run time for the simulation is 2 h so the output can be incorporated into VITM which estimates traffic demand in the morning peak period (7 am–9 am). In order to obtain an accurate result from the simulation, the simulation is first run for a warm up period. It then continues running for 2 h and records measures of performance for that time. A set of twenty runs are undertaken for each scenario to establish a variation in measures of performance to provide the mean and level of confidence in the result.

In the micro-simulation model, traffic travels from the west to east while rail runs south-north. A 500 m link with an intersection at the end and a railway crossing in the middle is modeled to estimate the impact of a level crossing on the link (Fig. 3). This distance is long enough to be able to capture vehicle delay caused by rail crossings.

The actual delays at level crossings are determined by train movement detectors positioned prior to rail crossings in each direction. The signal located on the road link at the crossing is activated when the detectors are activated. The signal is programmed so that the signal controlling the street is red for a minimum of 25 s before a train is permitted to cross. An intersection is located at the end of the link in order to be consistent with links with level crossings modeled in VITM (DOT, 2011). It is assumed that this intersection is controlled by fixed

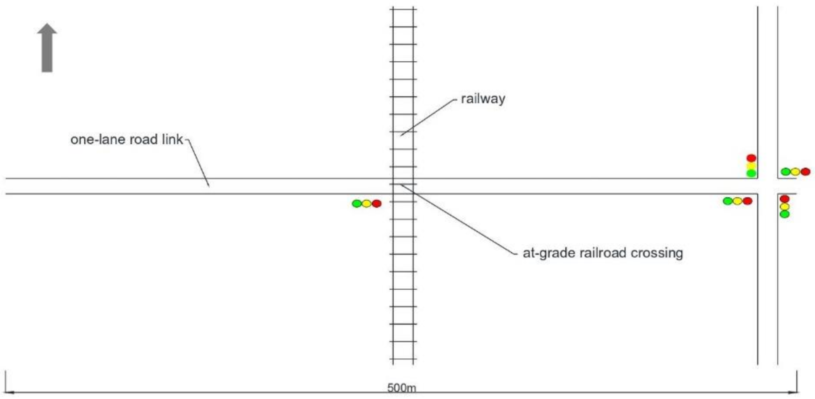


Fig. 3. A modelled one-lane road link with a level crossing.

Table 1
Parameters set in Vissim.

No	Parameter	Value	Standard
1	Speed limit on road link	60 km/h	
2	Distance between stop line on road link and rail road	3.5 m	(TED-M-011, 1996)
3	Distance between outer rails of tracks at crossing	4 m	(TED-M-011, 1996)
4	Closure time at level rail crossing	57 s	Field survey
5	Road link length	500 m	

traffic signals with a cycle time of 60 s. The all red period and the intergreen time account for 6 s so green time for each leg is 27 s.

Rail services modelled in this simulation are composed of six 24.1 m train cars with a total length of 144.6 m commensurate with typical commuter rail services in Melbourne. The speed is set to range between 90 and 115 km/h. The arrival frequency of rail vehicles is specified in Vissim by adopting a deterministic 'service frequency' for the train lines in each direction.

To model the impact of signals at level rail crossings, the average closure time of a single train is based on a series of level crossing field surveys. From results in the peak, the average closure time for a single train is 57 s. This value is set into the micro-simulation to model the crossing closure time (Table 1).

In order to simplify the micro-simulation, the following assumptions are made.

- Two trains on each direction do not run through a crossing at the same time. Thus, the number of closures at crossings equals the total frequency of trains on two directions. This assumption implies that estimated traffic delays are high or maximum values.
- The travel delay is estimated in a one-lane link in this simulation. If links include more than one lane, it is assumed that the delay is similar on every lane.
- The speed limit of all links including level rail crossings is 60 km/h which is consistent with current general practice on Melbourne roads at rail crossings.

4.5. Macro-modelling approach

As noted earlier VITM assigns vehicle trips on Melbourne's road network using travel time calculated for each link using Akcelik's speed-flow formula. This figure is one of the major parameters for estimating travel cost which is used in the equilibrium assignment process. In addition, to obtain an equilibration of demand, traffic volume on each link is changed after an iterative process leading to changes in travel time. Equilibrium assignment techniques explicitly recognize that transport network link costs generally depend on the volume of traffic using that link.

A major development in this research is to more accurately represent the travel time on a link with level rail level crossings to the crossing closure times as influenced by the frequency of rail traffic, using the simulation outlined above. That is, in this research the travel time on the links including level crossings is adjusted by the percentage change in travel time that is estimated by micro-simulation. This percentage can be adjusted based on the volume of traffic on the road link and frequency of trains at each location. When iterating to get an equilibrium value the volume is changed in each loop. So the percentage change in travel time changes with the updated volume. This process is carried out by coding in CUBE as follows:

$$Travel\ time = Travel\ time_0 + p\% * Travel\ time_0 \quad (1)$$

where:

p%: is the percentage change in travel time caused by level rail crossings which is calculated using the results from micro-simulation.
Travel time$_0$: Travel time of link including level rail crossing when impact of rail level crossing is not considered.
Travel time: Travel time of link with level rail crossing when impact of rail level crossing is considered.

Fig. 4 illustrates the process for estimating the effect of level rail crossings on traffic congestion.

Finally, VITM is run with a 'with level crossing' scenario which is compared to the outcome of a 'without level crossing' scenario to estimate the changes in congestion on the road network as a whole. These changes are considered to represent the congestion effect of all level rail crossings.

5. Results

The results are presented in two parts. Firstly, the effect of level crossings on vehicle traffic flow on a particular link is shown (micro-simulation). The results are then incorporated into VITM (macro-modelling) to determine the local effects as well as aggregate effect of level crossings on network traffic flow.

5.1. Micro-simulation results

In this section, based on train frequency and traffic volume, the impact of a level rail crossing on an identified link is shown. Fig. 5 illustrates the relationship between the percentage change in travel time caused by level crossings and the volume of traffic on road links with various train frequencies (5, 10…50 trains/h). As can be seen from the graph, there is a polynomial relationship between the volume of vehicles on a road approach and the percentage increase in travel time at level crossings. For those with high train frequencies (F = 35, 40, 50 trains/h), the impact on travel time increases gradually with low traffic volumes. However, this effect increases rapidly when the traffic volume begins to approach the capacity of the link. This outcome is sensitive to train frequency. So for example, at level crossings with

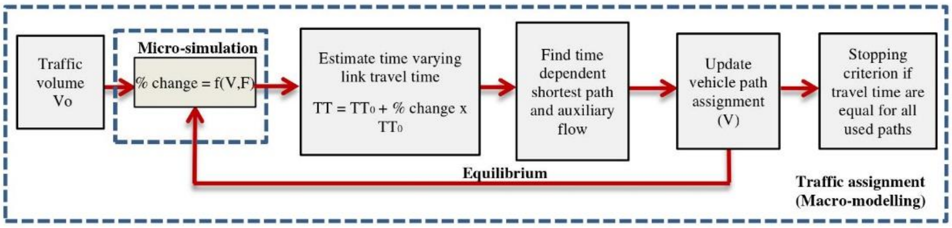


Fig. 4. The process of estimating the effect of level rail crossings in contributing to traffic congestion. where: V_0: traffic volume from mode choice model. V: updated traffic volume. TT0: travel time on links (without level crossing effect). TT: travel time on links (with level crossing effect). % change: Percentage change in traffic travel time caused by an level rail crossing. F: train frequency.

94 D.Q. Nguyen-Phuoc et al. / Journal of Transport Geography 60 (2017) 89–97

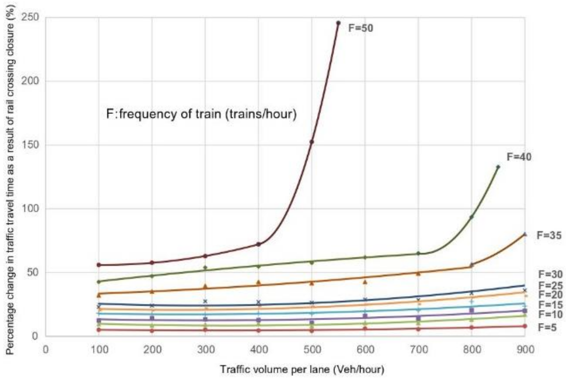


Fig. 5. Percentage change in travel time caused by level crossings.

only five trains crossing per hour, travel time only increases slightly even with a large increase in traffic volume.

Table 2 shows the polynomial function of the relationship between vehicle volume and percentage change in travel time, and the value of R^2 significance for various train frequency levels. These equations are utilised to adjust the travel time on road links with level crossings in VITM. The impact of level crossings can be then modelled precisely under alternative traffic movement volumes.

5.2. Macro-modelling results

In this section, the effect of level crossings on local links with a rail crossing, as well as upon the wider road network, is shown. The relationship between train frequency/traffic volume and increase in vehicle travel time caused by crossings is also described.

In this research, 304 road links (152 level crossings) with level crossings are analysed. Table 3 presents the average percentage change in travel time and volume of vehicular traffic on road links with different train frequencies. Overall, Melbourne's level crossings result in an average increase in travel time of 16.1% on immediate road links. On average a level crossing reduces the volume of vehicles on road links by 5.9% as a result of traffic diversion. For a few selected rail crossings impacts are much larger than this average effect. Six crossings are identified in the middle suburbs where the average impact on travel time is 56.8% whilst traffic diversion acts to reduce traffic volumes by 15.4%. These crossing all have very high train frequencies (50 trains an hour). Table 3 illustrates that level rail crossings with low train frequencies result in small effects on travel time and traffic volume on approaches. When the train frequency increases, traffic congestion increases, leading to a higher change in travel time and volume.

Table 2
The relationship between traffic volume and the percentage change in travel time as a result of level crossings.

Frequency of train in 1 h	Function	R^2
50	$y = 0.0002x^2 - 0.0406x + 58.188$ (V < 400)	1.00
	$y = 0.0071x^2 - 5.5661x + 1166.3$ (V ≥ 400)	1.00
40	$y = 0.00002x^2 + 0.0498x + 38.287$ (V < 700)	0.98
	$y = 0.0033x^2 - 4.7226x + 1734.9$ (V ≥ 700)	1.00
35	$y = 0.00002x^2 + 0.0105x + 32.255$ (V < 800)	0.92
	$y = 0.0011x^2 - 1.5702x + 631.59$ (V ≥ 800)	1.00
30	$y = 0.00004x^2 - 0.0239x + 27.552$	0.88
25	$y = 0.00003x^2 - 0.0165x + 22.809$	0.92
20	$y = 0.00002x^2 - 0.0109x + 18.62$	0.87
15	$y = 0.00002x^2 - 0.0127x + 14.412$	0.82
10	$y = 0.00002x^2 - 0.0169x + 11.292$	0.94
5	$y = 0.00001x^2 - 0.0065x + 5.6295$	0.93

Table 3
Average percentage of change in travel time and traffic volume on links with various frequencies.

Area	Train frequency[a] (trains/h)	Number of level rail crossings	Average percentage change in travel time on link (%)	Average percentage change in traffic volume on link (%)
Entire Melbourne	0	0	0	0
	5	22	4.7	−2.9
	10	31	8.1	−2.2
	15	23	12.3	−2.6
	20	21	16.6	−6.0
	25	23	20.3	−8.9
	30	23	22.6	−9.4
	40	3	42.8	−20.1
	50	6	56.8	−15.4
	Average	152	**16.1**	**−5.9**
Inner Melbourne	5	6	4.5	−1.4
	10	1	6.8	−2.3
	15	0	0	0
	20	0	0	0
	25	2	18.3	−9.9
	30	0	0	0
	40	0	0	0
	50	0	0	0
	Average	9	**7.8**	**−3.4**
Middle Melbourne	5	0	0	0
	10	14	7.5	−4.0
	15	10	11.5	−4.3
	20	4	16.7	−1.9
	25	20	20.3	−13.6
	30	16	22.2	−9.1
	40	3	42.8	−24.4
	50	6	56.8	−15.4
	Average	73	**20.8**	**−9.4**
Outer Melbourne	5	16	4.7	−1.5
	10	16	8.6	−0.5
	15	13	12.8	−1.3
	20	17	16.6	−7.0
	25	1	18.5	−8.1
	30	7	23.6	−10.2
	40	0	0	0
	50	0	0	0
	Average	70	**12.1**	**−3.5**

[a] Include trains in both directions.

Table 3 also shows the spatial distribution of level rail crossings and their impacts on their road links. Approximately 50% of level rail crossings in Melbourne are located in middle suburbs where rail services have high frequencies, ranging from 10 trains/h to 50 trains/h. The average increase in travel time on road links in these areas is over 20% while the volume of vehicles on these links reduces by 9.4% on average due to traffic diversion. These figures are lower in outer areas where level crossings have lower frequency services.

From the data in Table 3, the relationship between train frequency, traffic travel time and volume change caused by level rail crossings are explored (Fig. 6a, b).

Fig. 6a describes the polynomial and linear relationship and between train frequency and travel time change on road traffic. The polynomial equation is $y = 0.0135x^2 + 0.4347x + 1.463$ with a high R^2 value (0.99). When the frequency is around 5 trains/h, the travel time of road traffic increases by approximately 5%. As shown earlier, there is a significant increase in the vehicle travel time when the number of trains going through a level crossing increases. In contrast, Fig. 6b illustrates the negative linear relationship between train frequency and the change in vehicle volume on approaches. Increased train frequency results in a reduction in vehicle volume. The linear equation is $y = -0.3779x + 0.6977$ with a high value of R^2 (0.86).

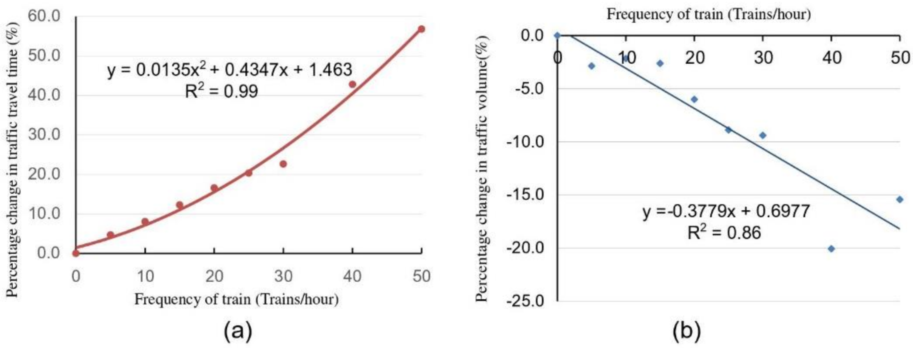


Fig. 6. Percentage change in travel time (a) and traffic volume (b) caused by level rail crossings with various train frequencies.

Fig. 7 illustrates the frequency of trains at Melbourne's level crossings and the percentage increase in travel time caused by these level crossings. The increase shown in this figure is the average value of the percentage increase for both directions.

This illustrates that:

- Level railway crossings in Melbourne's middle suburbs, usually with a relatively high frequency of trains, which leads to high travel delay for vehicles on roads.
- The frequency of trains reduces gradually at locations further away from the CBD. Thus, the effect of level rail crossings declines in these locations.
- It can be seen that there is no level rail crossings in inner areas of Melbourne.

Table 4 summarizes the estimated congestion impacts of level rail crossings in Melbourne by contrasting congestion measures (number of congested links, total delay on road network, average travel speed, actual travel time per km) in the two scenarios: 'without level crossing' and 'with level crossing'. Results in Table 4 show that:

For the entire Melbourne road network:

- The number of congested links in Melbourne increases by 0.9%.
- Total delay on the overall road network increases by 0.3%.
- Travel time on average increases slightly from 1.81 min/km to 1.82 min/km (an increase of around 0.3%) for all traffic in Melbourne.

For middle Melbourne:

- The existence of level rail crossings in middle Melbourne contributes to an increase of 1% in the number of congested links.
- The average road network speed decreases from 44.9 km/h to 44.8 km/h (a decrease of 0.3%).
- Total network delay increases by 0.5%.

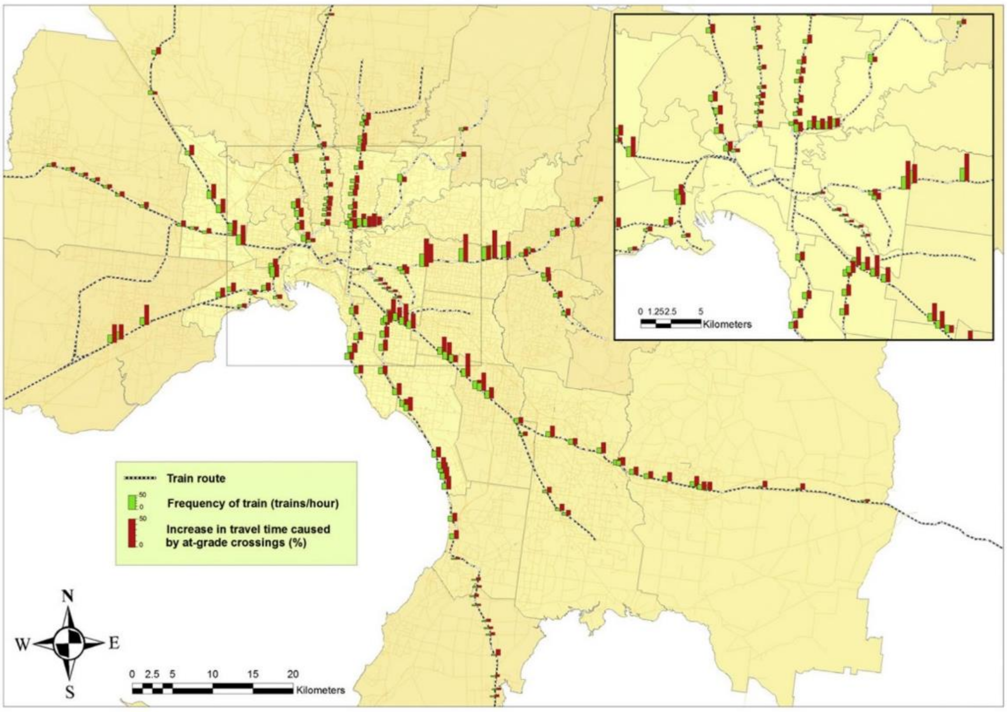


Fig. 7. Distribution of level crossings in Melbourne with various train frequencies.

Table 4
Overall impact of level rail crossings on Melbourne's road network weekday (7 am–9 am).

Congestion measure	Entire Melbourne			Middle Melbourne			Outer Melbourne		
	Without level crossing	With level crossing	Change (%)	Without level crossing	With level crossing	Change (%)	Without level crossing	With level crossing	Change (%)
Number of congested links (V/C ≥ 0.8)	4136	4173	0.9	2070	2090	1.0	1179	1187	0.7
Total delay on road network (million veh-h)	22.62	22.68	0.3	10.51	10.56	0.5	8.91	8.93	0.2
Average travel speed (km/h)	48.1	48.0	−0.1	44.9	44.8	−0.3	55.0	55.0	−0.1
Actual travel time per km (min)	1.81	1.82	0.3	1.93	1.94	0.5	1.51	1.52	0.2

Notes: Congested links are road links which have a volume to capacity ratio (V/C) equal to or >0.8 (Semcog, 2011).

For outer Melbourne:

- An increase of 0.7% in the number of congested links occurs when having level rail crossing operations in outer Melbourne.
- Total delay on the road network increases by 0.2%.
- Actual travel time increase by 0.2%.

Fig. 8 shows the percentage of additional vehicles impacted by level crossings in relation to travel time. It can be seen from the graph that more vehicles experience delay than the number of vehicles experiencing a reduction in travel time. This illustrates that:

- Level rail crossings cause a significant increase (>5%) in travel time for over 3% vehicles on Melbourne's road network.
- In contrast, <2% of Melbourne's vehicle traffic experience a considerable decrease (<5%) in travel time due to level crossings.

There is some corroboration of the effects at a localised scale within existing before/after studies of the removal of level crossings in Melbourne. VicRoads (2010), a state road authority, conducted travel time surveys before and after a rail-road crossing was grade-separated in Melbourne. Results show travel times generally decreased following the grade separation (by 2–9% in the AM peak). However, traffic often increased over crossings as traffic from adjacent roads was re-routed onto the quicker major road.

6. Discussion and conclusions

This paper explored the local and aggregate effects of level crossings on traffic congestion in Melbourne. It firstly reviewed previous studies related to the effect of railroad level crossings on congestion and found almost all of these studies used mathematical models to show the effect only on immediate road links. There was no attempt to explore the local as well as the network-wide impacts incorporating levels of traffic movement and also rail service frequencies. This paper responded to that lack of analysis and developed a new methodology. It involves two main stages. In the first stage, micro-simulation is undertaken to identify the relationship between travel time delay and traffic volume with various train frequencies. In the second stage, these relationships are incorporated into VITM (macro-simulation) to estimate impacts on Melbourne's road network.

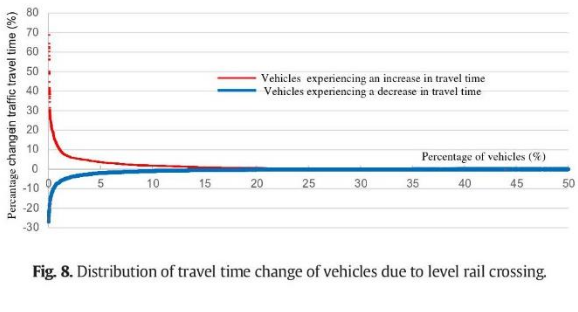


Fig. 8. Distribution of travel time change of vehicles due to level rail crossing.

Micro-simulation results have established relationships between the change in travel time and traffic volume for various train frequencies. The analysis of Melbourne's 152 level crossings established a relationship between train frequency and the percentage change in travel time and traffic volume. These equations were used to predict the change in travel time or traffic volume of road traffic caused by level rail crossings for different train frequencies.

The results show that the operation of level crossings causes an increase in travel time for vehicle traffic on immediate road links and is also associated traffic volume reduction since links with level crossings become less attractive compared to other links available for through traffic. Overall, Melbourne's level crossings cause an average increase in travel time of 16.1% on their immediate road links and reduces the volume of vehicles by 5.9%. These figures are higher in middle suburban sites where train lines often have higher train frequencies.

The aggregate effect of all 152 level crossings on all Melbourne's traffic is an increase in the average travel time from 1.81 to 1.82 min/km (an increase of around 0.3%) and an increase of 0.9% in the number of congested links. These network-wide effects are very small when compared to the local effects as the 304 road links studied here represent a very small part of the overall network (66,848 road links), and also in many cases there is the option of diversion to avoid the crossings. It is significant that this very small element of the system (0.005% of links) can have even a measurable effect on traffic congestion.

These results are based on a simple assumption where one train crosses at a time. However, it is possible two trains in different directions can cross at the same time, or with a small gap between one another, while there can also be small gaps between trains traveling in the same direction (especially in the peak period). These more complex (and realistic) situations could act to substantially increase the closure time of the crossings and so magnify the delays caused. Site surveys at different level crossings could also be used to identify a more precise closure time per train, incorporating information on train types, level crossing design and nearby road network configuration. These features can be incorporated into refinements of the simulations used here to further improve the methods in this field.

The research is part of a wider project exploring how to evaluate the impact of public transport on traffic congestion. This agenda has called for improved methodological approaches. The new method described in this paper is one response to that agenda. Elements of the approach will be applied to other public transport modes and also to congestion issues in other parts of the metropolitan area in the authors future research.

References

Akçelik, R., 1991. Travel time functions for transport planning purposes: Davidson's function, its time-dependent form and an alternative travel time function. Aust. Road Res. 21 (3), 49–59.
Andrews, D., 2014. Project 10,000. Victorian Labor Party, Victoria.
Austin, R.D., Carson, J.L., 2002. An alternative accident prediction model for highway-rail interfaces. Accid. Anal. Prev. 34, 31–42.
De Gruyter, C., Currie, G., 2016. Rail-road crossing impacts: an international synthesis. Transp. Rev. 1–23.
DOT, 2011. Guidelines for VITM Network Coding. Department of transport, modelling and analysis group, Melbourne.
DOT, 2014. 2013–14 Annual Report. Department of transport, planning and local infrastructure, Melbourne, Australia.

Dowling, R., Singh, R., Cheng, W., 1998. Accuracy and performance of improved speed-flow curves. Transp. Res. Rec. J. Transp. Res. Board 1646, 9–17.

Hakkert, A.S., Gitelman, V., 1997. Development of evaluation tools for road-rail crossing consideration for grade separation. Transp. Res. Rec. 1605 (1), 96–105.

Hu, S.-R., Li, C.-S., Lee, C.-K., 2010. Investigation of key factors for accident severity at rail-road grade crossings by using a logit model. Saf. Sci. 48 (2), 186–194.

Lewiński, A., Bester, L., 2010. Application of wireless transmission systems for improving safety at railway crossings. Konferencja Transport XXI wieku.

Okitsu, W., Lo, K., 2010. Simulation-free railroad grade crossing delay calculations. Western ITE Annual Meeting. San Francisco.

Pucher, J., Peng, Z., Mittal, N., Zhu, Y., Korattyswaroopam, N., 2007. Urban transport trends and policies in China and India: impacts of rapid economic growth. Transp. Rev. 27 (4), 379–410.

Schlossberg, M., Greene, J., Phillips, P.P., Johnson, B., Parker, B., 2006. School trips: effects of urban form and distance on travel mode. J. Am. Plan. Assoc. 72 (3), 337–346.

Schrader, M.H., Hoffpauer, J.R., 2001. Methodology for evaluating highway–Railway grade separations. Transp. Res. Rec. J. Transp. Res. Board 1754, 77–80.

SEMCOG, 2011. Congestion Management Process (CMP). Michigan Southeast Michigan Council of Governments.

Stephens, B.W., Long, G., 2003. Supplemental pavement markings for improving safety at railroad-highway grade crossings. Transp. Res. Rec. 1844, 18–24.

Taggart, R.C., Lauria, P., Groat, G., Rees, C., Brick-Turin, A., 1987. NCHRP Report 288: Evaluating Grade-Separated Rail and Highway Crossing Alternatives. Transportation Research Board, NRC, Washington, D.C.

Ted-M-011, 1996. Manual For Determining Required Sight Distance to Train at Level Crossing. Public Transport Corporation Infrastructure Division.

U.S. Bureau of Public Roads, 1964. Traffic Assignment Manual (Washington, DC).

VicRoads, 2010. Nunawading Springvale Road Rail Separation Impact Study (Victoria, Australia).

VicRoads, 2014. Strategic Framework for the Prioritisation of Level Crossings in Metropolitan Melbourne.

Zalinger, D.A., Johri, H.P., Rogers, B.A., 1977. Calculation of hazard indices for highway-railway crossings in Canada. Accid. Anal. Prev. 9 (4), 257–273.

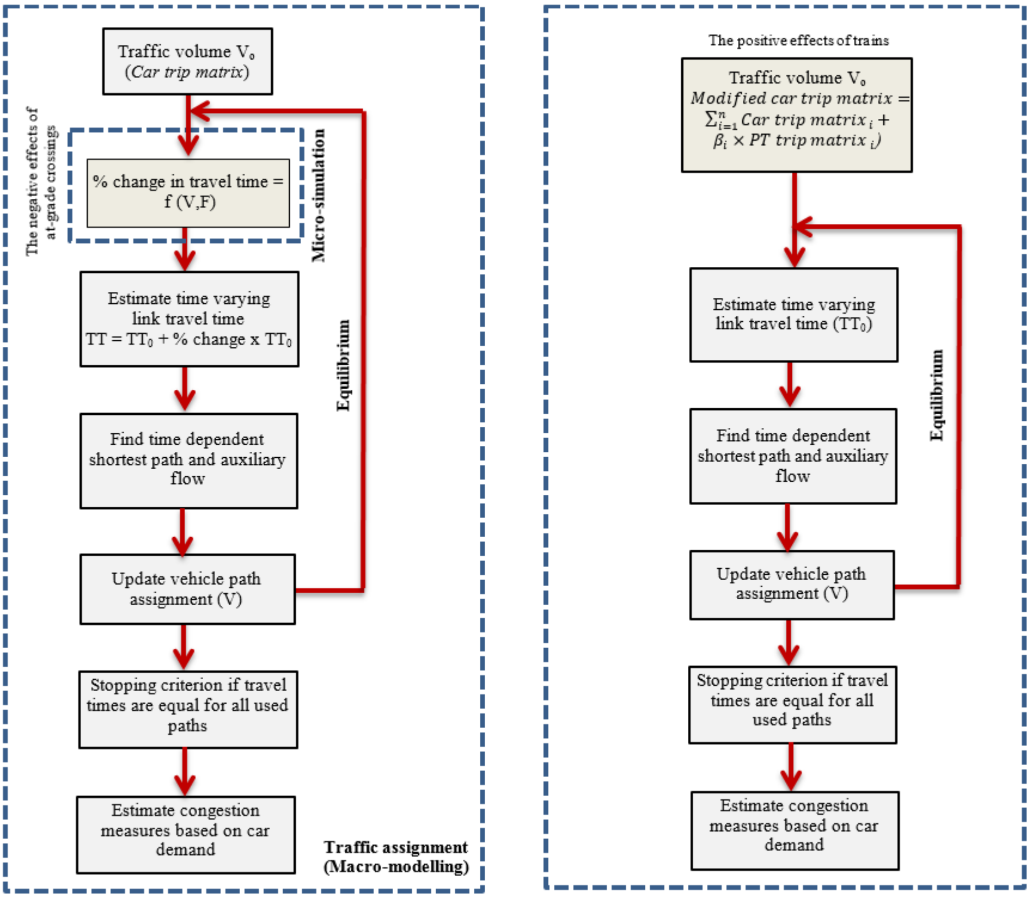
8.3.3 Net Traffic Congestion Effect of Train Operations

A modelling procedure is adopted which incorporates an assumption regarding train user diversion to private car, the negative effects of train operations on road links (the effect of at-grade rail crossings) and a transport network model to assess the net impact of trains on traffic congestion. The modelling analysis was carried out for weekday morning peak (7am-9am) as the highest level of congestion is expected to occur during this period. Hence, the highest congestion impact of trains can be quantified.

The modelling procedure comprises three major steps:

- In the scenario 'with train', the impacts of train on creating traffic congestion (impacts caused by at-grade rail crossings) are modelled by incorporating the results of microsimulation models into VITM. The vehicle travel time on links with at-grade rail crossings is added with an increase in travel time obtained from the microsimulations. The level of congestion on the entire road network is then predicted.
- In the scenario 'without train', the congestion relief impact is modelled by adding the current car trip matrix with a modified train trip matrix (train trip matrix is multiplied with mode shift to car which varies for LGAs) to obtain a modified car trip matrix. This matrix is then assigned into the road network to explore the level of congestion in the case of a train withdrawal with the use of VITM.
- The level of congestion in two scenarios 'with train' and 'without train' are contrasted to assess the net congestion effect of a train system on the road network.

Figure 8.1 illustrates the modelling procedure for assessing the level of congestion in two scenarios: 'with train' and 'without train'.



(a) With train **(b) Without train**

Figure 8.1 Process of estimating the travel demand with traffic assignment in two scenarios

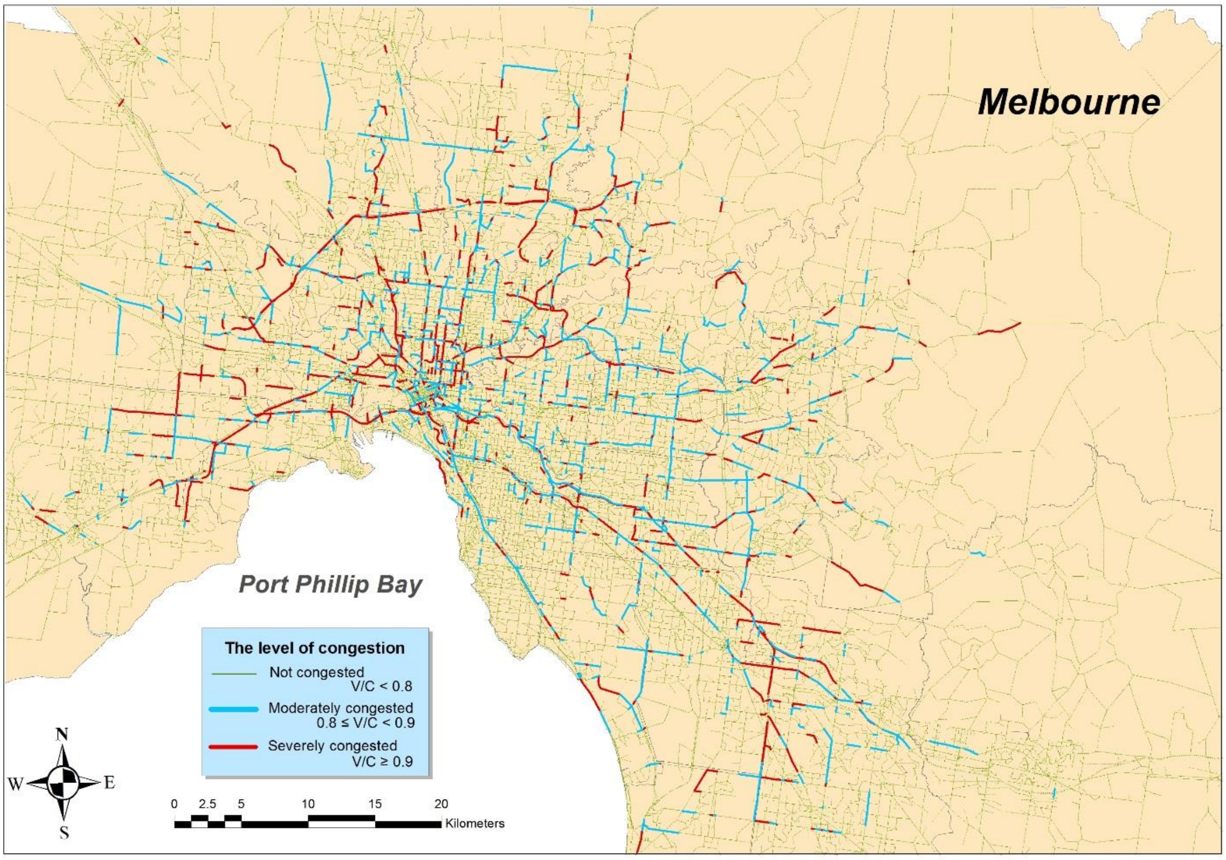
Where

V_0: traffic volume
V: updated traffic volume
F: frequency of trains
TT_0: travel time without train effects
TT: travel time with train effects
β : mode shift to private car (%). β is different for inner, middle and outer areas

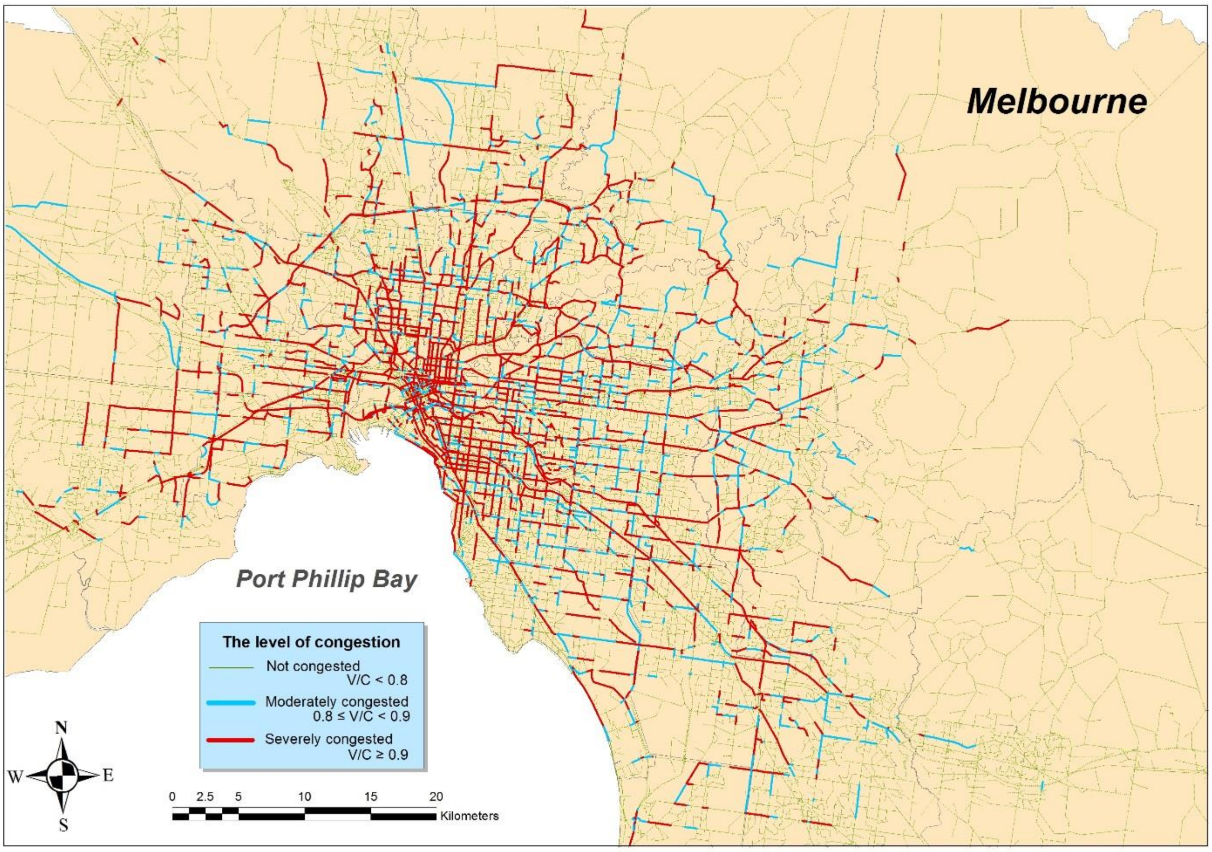
8.4 Results

Table 8.2 presents the net congestion effect associated with the entire Melbourne train system on the road network. The results in Table 6.2 indicate that:

- The operation of trains contributes to reduce the number of severely congested links and moderately congested links by around 56% and 7% respectively (as shown in Figure 8.2).
- Vehicle time travelled and total delay on the road network reduce by around 46%.
- Average travel speed increases from 38.5 km/h to 48.0 km/h (an increase of 24.5%) whilst actual travel time per km reduces by approximately 42%.



a) Base case



b) Train withdrawal

Figure 8.2 Distribution of congested road links in Melbourne

Table 8.2 Net congestion impact of trains on Melbourne's road network in AM peak hours (7h-9h)

Measure	With train	Without train	Absolute change	Change (%)
Number of severely congested links	2,155.0	4,938.00	2783	**56.4**
Number of moderately congested links	2,018.0	2,167.00	149	**6.9**
Vehicle distance travelled (million veh-km)	14.99	17.02	2.03	**11.9**
Vehicle time travelled (million veh-hr)	0.38	0.71	0.33	**46.5**
Total delay on road network (million veh-hr)	22.68	42.7	20.02	**46.9**
Average travel speed (km/h)	48.0	38.5	-9.5	**-24.5**
Actual travel time per km (min)	1.82	3.15	1.33	**42.2**

Notes: Severely congested links are road links which have a volume to capacity (V/C) ratio equal to or greater than 0.9. Moderately congested links are road links which have a V/C ratio equal to or greater than 0.8 and lower than 0.9 (SEMCOG, 2011).

8.5 Discussion

The data from the survey conducted in Melbourne indicates that if trains were not available, on average 42.7% of train users would switch to private car. Other users would shift to other public transport modes (tram and bus), walk, cycle or even cancel their trip. A high proportion of train users would switch to driving a car because the majority of train users have long distance trips which cannot be taken by non-motorised modes such as cycling or walking. Shifting to other public transport modes is not always an appropriate alternative, particularly for users living in outer areas where public transport services are limited. The mode shift explored in this research is much higher than the figure explored by Aftabuzzaman et al. (2010a) (around 32%). Thus, the congestion relief impact of train operations is expected to be higher than that estimated in the previous research.

The findings also show that the operation of at-grade rail crossings causes an increase in travel time for vehicle traffic on immediate road links and is also associated with a traffic volume reduction since links with level crossings become less attractive compared to other links available for through traffic. Overall, Melbourne's level crossings cause an average increase in travel time of 16.1% on their immediate road links and reduce the volume of vehicles by 5.9%. These figures are higher in middle suburban sites where train lines often have higher train frequencies. However, the aggregate effect of all 152 level crossings on all Melbourne's traffic is an increase in the average travel time from 1.81 to 1.82 minutes/km (an increase of around 0.3%) and an increase of 0.9% in the number of congested links. These network-wide effects are very small when compared to the local effects as the 304 road links studied here represent a very small part of the overall network (66,848 road links), and also in many cases there is the option of diversion to avoid the crossings. It is significant that this very small element of the system (0.005%) can have even a measurable effect on traffic congestion.

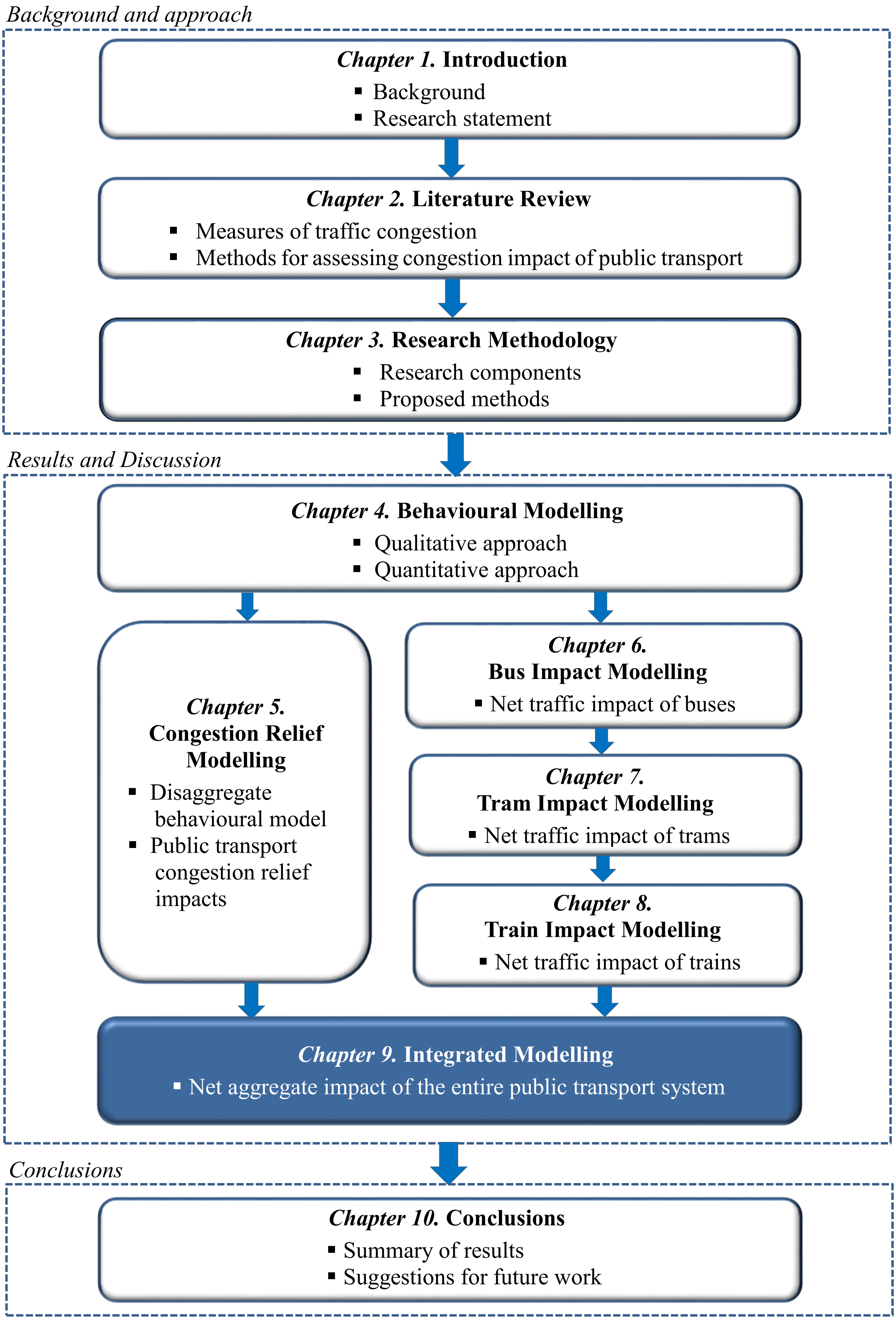
The net impact of train operations on reducing traffic congestion is found to be significant. The operation of Melbourne's train system contributes to reduce the number of severely congested links by around 56%. It also reduces vehicle time travelled and total delay on the road network by approximately 46%. The congestion relief effect of trains is much higher than that of buses as well as trams since Melbourne's train network carried more than 230 million passenger trips per year (the highest ridership) (DOT, 2014) and the mode shift to private car when trains are unavailable is expected to be more than 40% (compared to around 34% for bus and 17% for tram). Another reason is that Melbourne's rail network is highly radial to the centre of the city and the spatial spread of its network covers the entire city. In fact, the train network has a high value in reducing traffic congestion as it is concentrated in major corridors accessing into the centre of the city. When the train system is suspended, a high proportion of train users would switch to private car and access the CBD on these major corridors which have been already congested. This mode shift would contribute significantly to the increase in the level of congestion on these corridors. In contrast, the tram network covers only a part of the city (mostly in CBD) while the bus network is spread out across the road network. Hence, the congestion relief impact of buses and trams is not as high as that of trains

8.6 Conclusions

This chapter explored the net effect of train operations on traffic congestion. The positive effect of trains on reducing traffic congestion was investigated by adopting a simple assumption on car diversion from train in the event of a train withdrawal. The research also adopted microsimulation and a four-step transport model (VITM) to explore the negative effects of trains on generating traffic congestion. Finally, the net traffic congestion impact associated with tram operations can be assessed by integrating both positive and negative effects.

The findings show that trains have a much higher congestion relief effect than buses and trams because of the high ridership, the concentration in major corridors and the spatial spread on the entire city. Thus, it can be concluded that train operations have a highest value in reducing traffic congestion. However, in order to have an efficient train network in terms of congestion relief, it is necessary to be well integrated with other public transport modes such as bus and tram to increase the use of a public transport system.

The next chapter will integrate both positive effect and negative effects of all public transport modes to examine the net traffic congestion effect of the entire public transport system.


Background and approach
Chapter 1. Introduction
Background
Research statement
Chapter 2. Literature Review
Measures of traffic congestion
Methods for assessing congestion impact of public transport
Chapter 3. Research Methodology
Research components
Proposed methods
Results and Discussion
Chapter 4. Behavioural Modelling
Qualitative approach
Quantitative approach
Chapter 5. Congestion Relief Modelling
Disaggregate behavioural model
Public transport congestion relief impacts
Chapter 6. Bus Impact Modelling
Net traffic impact of buses
Chapter 7. Tram Impact Modelling
Net traffic impact of trams
Chapter 8. Train Impact Modelling
Net traffic impact of trains
Chapter 9. Integrated Modelling
Net aggregate impact of the entire public transport system
Conclusions
Chapter 10. Conclusions
Summary of results
Suggestions for future work

Chapter 9
INTEGRATED MODELLING

9.1 Introduction

Chapter 9 takes the findings from Chapter 4-8 to develop enhanced methods for assessing the net congestion effect of the entire public transport system. This chapter addresses a research gap identified in the Literature Review: No research has been undertaken to assess the net congestion effect of the entire public transport system. This is in accordance with research objective 6 to develop methods to investigate the net traffic congestion impact of public transport. The methods examining the net congestion effect balance both the positive effect and the negative effects of the entire public transport system. Table 9.1 details the research objective, research component, research gap and research opportunity associated with this chapter.

Table 9.1 Research gap, opportunity and objective associated with research component 8

Research objective	Research component	Research gap	Research opportunity
6. To understand the net impact of entire public transport on traffic congestion	8. Net public transport congestion effect estimation	No research has been undertaken to assess the net congestion effect of entire public transport systems	Explore the net network-wide effect of entire public transport systems

In line with research objective 6, the research aim of this chapter is to develop enhanced methods for assessing the net congestion effect of the entire public transport system. In order to achieve this aim, both the positive and the negative effects of public transport on traffic congestion are taken into account in this research. The positive impact of public transport on reducing congestion is estimated by adopting mode shift from public transport to car in the event of a public transport withdrawal. In contrast, the negative impacts of public transport on generating congestion are investigated by considering the impacts which public transport itself can have on congestion at places like at-grade rail crossings or on roads where the frequent stopping of buses and trams might slow traffic. The effect of public transport priority lanes on reducing road capacity is also taken as a negative impact of public transport.

A journal paper was conducted based on the methodology and the findings presented in this chapter as follows:

Paper 8 *Nguyen-Phuoc, D.Q., Currie, G., De Gruyter, C. & Young, W., 2017, 'Quantifying the net traffic congestion effect of urban public transport – Including both negative and positive effects',* ***Public Transport (under review).***

This chapter begins by outlining the research methods used for assessing the net congestion effect associated with the entire public transport system. This is followed by the results and a discussion.

9.2 Research Methodology

The methodology involved three major parts. The share of mode shift from public transport to car for each LGA is firstly estimated with the use of data from a field survey as well as secondary data. In the second part, microsimulation is used to model the impact of public transport operations in generating congestion. Finally, the mode shift and results from microsimulation models are incorporated into a macrosimulation model (VITM) to estimate the net congestion impact associated with public transport.

9.2.1 Prediction of the Share of Mode Shift from Public Transport to Car

In order to estimate the positive impact of public transport on reducing traffic congestion, a decrease in the number of car trips due to public transport operations needs to be explored. However, it is impossible to estimate this decrease so in this research, the number of public transport users shifting to car in the case of public transport removal are assumed to represent the number of car users attracted by public transport operations. Chapter 5 developed methods to estimate mode shift to car for difference regions when public transport ceases. Firstly, a field survey was conducted from 648 public transport users in Melbourne. In this survey, public transport users were asked to choose an alternative transport mode if public transport was not available for their last public transport trips in the AM peak hours (7h-9h). The survey also collected information about the traffic characteristics of public transport users. A linear regression equation showing the relationship between the share of mode shift and traffic characteristics of public transport users was then developed. Finally, the equation was applied for the Victorian Integrated Survey of Travel and Activity (VISTA) database, which comprises the detailed travel information and individual information of Melbourne's travelers using public transport in the AM peak hours, to predict mode shift to car and explore its spatial distribution for LGAs in Melbourne.

9.2.2 Modelling of the Impact of Public Transport Operations on Generating Traffic Congestion – Microsimulation Approach

In this research, the impact of at-grade rail crossings, the impact of bus stop operations and the impact of tram stop operations on traffic congestion are considered to be the negative impacts of public transport operations. VISSIM, a microscopic multi-modal traffic flow simulation software package, was used to simulate the operation of public transport and identify the impact of individual public transport modes (train, tram and bus) on general traffic flow (refer to Chapter 6-8). For each public transport mode, two scenarios 'with public transport' and 'without public transport' were developed and run to obtain the average travel time on a road link. The simulations were run with a range of inputs such as traffic volumes and public transport frequencies. Finally, the travel time between two scenarios, 'with public transport' and 'without public transport', are compared to define the relationship between the percentage change in travel time and a range of traffic characteristics (Equation 9.1).

$$\text{Increase in travel time} = f\,(\text{Traffic characteristics}) \qquad (9.1)$$

9.2.3 Modelling of the Net Traffic Congestion Impact associated with Public Transport – Macrosimulation Approach

A modelling procedure adopts assumptions regarding public transport user diversion to private car, the negative effects of public transport on road links (from microsimuation) and a transport network model to assess the net impact of public transport on traffic congestion. The modelling analysis was carried out for an average weekday morning peak (7am-9am) as the highest level of congestion is expected in this period. Hence, the highest congestion impact of public transport can be quantified.

The modelling procedure comprises three major steps:

1. In the scenario 'with public transport', the impacts of public transport on creating traffic congestion (impacts caused by frequent stopping of public transport) are modelled by incorporating the results of the microsimulation models into VITM. The vehicle travel time on links with at-grade rail crossings, non-exclusive tram rights-of way and bus operations is added with an increase in travel time obtained from the microsimulations. The level of congestion on the entire road network is then predicted.
2. In the scenario 'without public transport', the congestion relief impact is modelled by adding the current car trip matrix with a modified public transport trip matrix (public transport trip matrix is multiplied with mode shift to car which varies for LGAs) to obtain

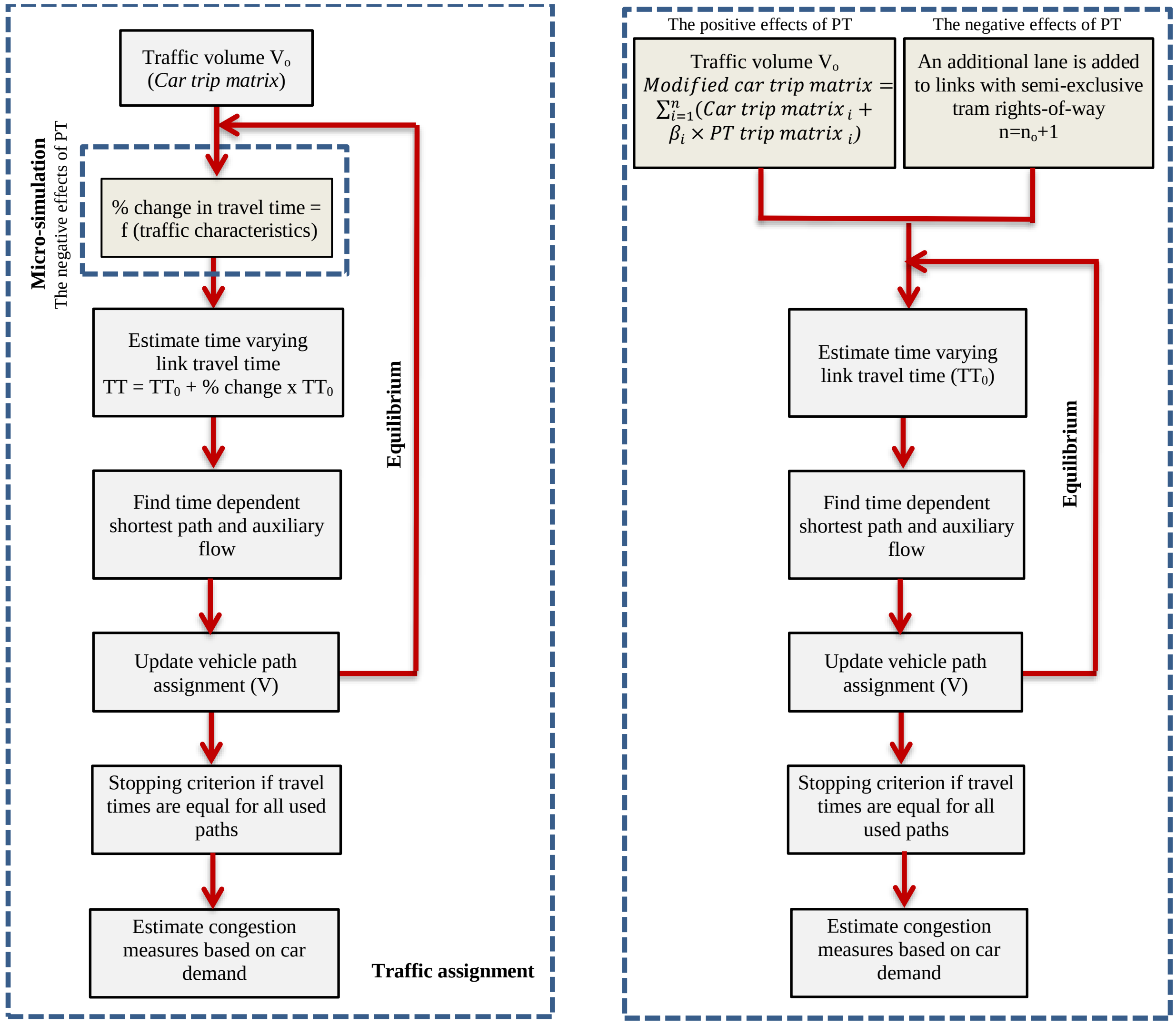
a modified car trip matrix. This matrix is then assigned into the road network to explore the level of congestion in the case of public transport withdrawal with the use of VITM. In this step, the capacity of road links with priority public transport lanes (such as semi-exclusive tram rights-of-way) is increased as these lanes can be transferred to traffic lanes. One more traffic lane is added to model the effect of the occupation of priority public transport lanes which reduce the capacity of roads.

3. The level of congestion in two scenarios 'with public transport' and 'without public transport' are contrasted to investigate the net congestion effect of the entire public transport system on the road network.

To simplify the simulation, the following assumptions are adopted:

- For a road link with both tram and bus operations, it is assumed that only tram operations have negative impacts on traffic congestion on that link. The number of road links which include both tram and bus operations account for a small proportion of the road network.
- Due to the small proportion of priority bus lanes in Melbourne's bus network (approximately 0.7%), it is assumed that this type of lane has no impact on traffic congestion of the entire road network. When considering the negative impact of priority public transport lanes, only priority tram lanes are focused on in this study.

Figure 9.1 illustrates the modelling procedure for assessing the level of congestion in two scenarios: 'with public transport' and 'without public transport'.



(a) With public transport (b) Without public transport

Figure 9.1 Process of estimating the travel demand with traffic assignment in two scenarios

Where

V_0: traffic volume
V: updated traffic volume
TT_0: travel time without public transport effects
TT: travel time with public transport effects
β : mode shift to private car (%)
n_o: number of traffic lanes on link with semi-exclusive tram rights-of-way
n: number of traffic lanes on link with semi-exclusive tram rights when tram is removed

9.3 Results

The results are presented in three major subsections. The first subsection presents the spatial distribution of mode shift to car when public transport is unavailable. In the second subsection, the impact of individual public transport modes on generating congestion on a road link is shown. The third subsection reports the results of the net congestion impact associated with public transport.

9.3.1 Mode Shift from Public Transport to Car

After undertaking regression analysis for primary data obtained from the field survey, four parameters were found to be significant (P value < 0.05) including share of public transport users with a driver's license (P1), share of public transport users with more than one car in their household (P2), share of public transport users with long public transport trip distance (more than 5 km) (P3) and share of public transport users with trip destinations in the CBD (P4). Equation 9.2 shows the relationship between the share of mode shift to car and these four traffic characteristics P1, P2, P3 and P4 . It can be seen that a public transport user with a driver's license and more than one car in their household, and who has a long distance trip and to the CBD is more likely to shift to car.

$$\text{Share of mode shift to car (\%)} = -42.834 + 0.377*P1 + 0.501*P2 + 0.382*P3 + 0.285*P4 \quad (9.2)$$

Table 9.2 Distribution share of car mode shift for Melbourne's LGAs

	LGA	Share of mode shift to car (%)	Average (%)
Inner	Melbourne	38.2	48.0
	Port Phillip	46.4	
	Stonnington	60.9	
	Yarra	46.6	
Middle	Banyule	68.3	63.2
	Bayside	69.2	
	Boroondara	58.1	
	Brimbank	68.9	
	Darebin	55.5	
	Glen Eira	65.6	
	Hobsons Bay	58.1	
	Kingston	66.4	
	Manningham	75.8	
	Maribyrnong	55.0	
	Monash	67.8	
	Moonee Valley	64.1	
	Moreland	52.1	
	Whitehorse	59.9	
Outer	Cardinia	76.2	66.9
	Casey	65.9	
	Frankston	72.3	
	Greater Dandenong	49.5	
	Hume	64.1	
	Knox	72.8	
	Maroondah	64.8	
	Melton	74.7	
	Mornington Peninsula	61.2	
	Nillumbik	68.5	
	Whittlesea	64.7	
	Wyndham	69.2	
	Yarra Ranges	66.3	

Applying secondary data (VISTA database) for Equation 9.2, mode shift from public transport to car for each Local Government Area (LGA) can be estimated (as shown in Table 9.2). These figures will be adopted into VITM to represent the positive effects of public transport on traffic congestion.

Figure 9.2 illustrates the spatial distribution of the share of mode shift to car for LGAs in Melbourne. It can be seen that in inner Melbourne, the share of mode shift to car of public transport users is lowest (48%). This figure is higher in middle and outer Melbourne with 63.2% and 66.9% respectively.

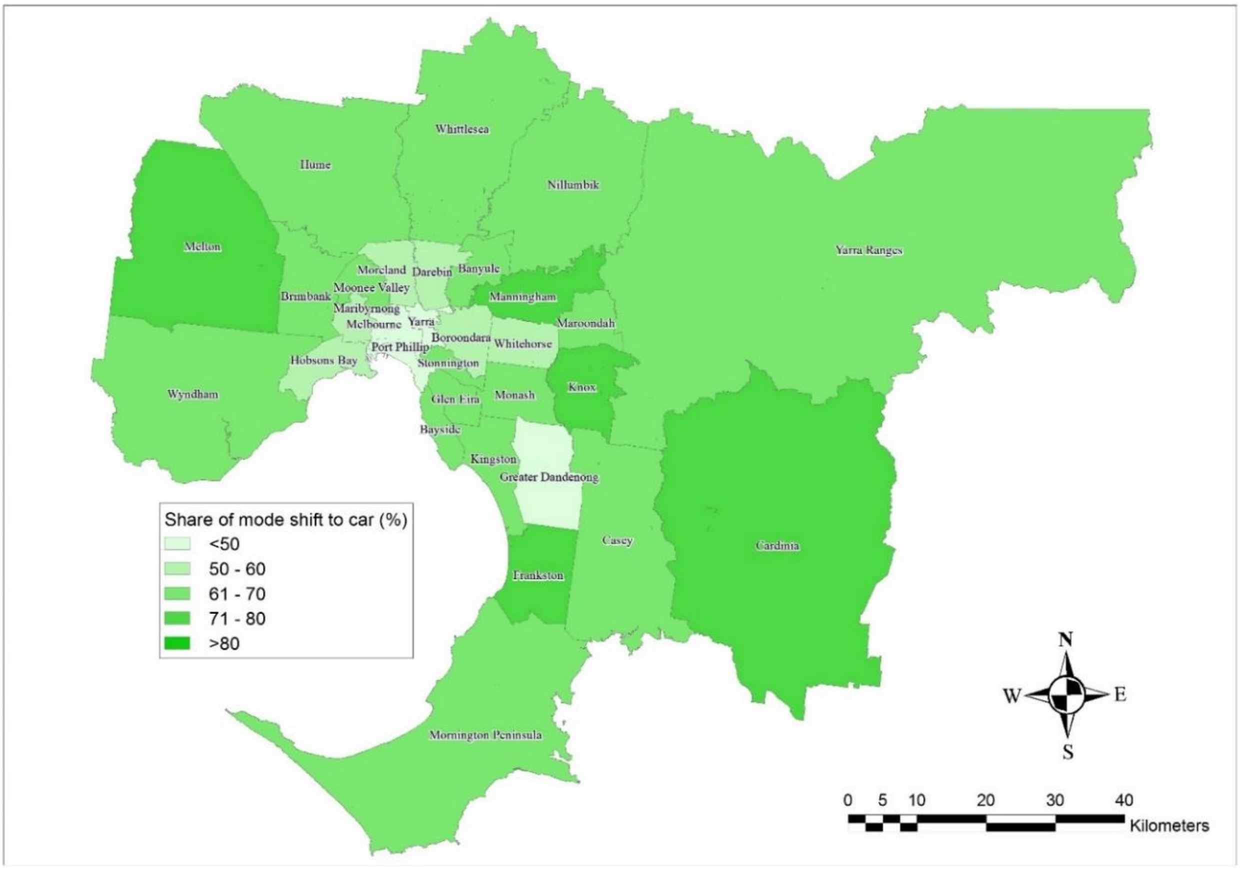


Figure 9.2 Spatial distribution of the share of mode shift to car for LGAs in Melbourne

9.3.2 Negative Impact of Public Transport Operations on Traffic Congestion

Impact of Bus Operations on Creating Congestion

From the results of microsimulation models, six non-linear regression models are developed to predict the percentage change in travel time resulting from bus operations for different road link types (as shown in Table 9.3). Four parameters including traffic volume (V), dwell time (D), speed limit (S) and bus arrival frequency (F) have a significant impact on the increase in travel time in these regression models (refer to section 6.4.2).

Table 9.3 Functions for estimating travel time increases caused by bus stop operations

Type of road link		Regression functions	R^2
Curbside bus stop	One-lane road link	$y = e^{0.000003*V^2-0.0029*V+0.0256*D+0.0160*S+0.0751*F+0.3337}$	0.80
	Two-lane road link	$y = e^{0.000005*V^2-0.0048*V-0.0109*D+0.0197*S+0.0705*F-0.2124}$	0.82
	Three-lane road link	$y = e^{0.000005*V^2-0.0050*V-0.01118*D+0.0183*S+0.0680*F-0.4102}$	0.82
Bus bay	One-lane road link	$y = e^{0.000005*V^2-0.0055*V-0.0149*D+0.0026*S+0.0687*F+1.8971}$	0.82
	Two-lane road link	$y = e^{0.000005*V^2-0.0055*V-0.0160*D+0.0089*S+0.0699*F+0.7111}$	0.82
	Three-lane road link	$y = e^{0.000005*V^2-0.0055*V-0.0131*D+0.0106*S+0.0687*F+0.1618}$	0.83

Where:
y: Increase in travel time (%)
V: Traffic volume (vehicles/lane/hour)
D: Dwell time (second)
S: Speed limit (km/h)
F: Bus arrival frequency (buses/hour)

Impact of Tram Operations on Creating Congestion

Table 9.4 shows the polynomial functions of the relationship between vehicle volume and the percentage change in travel time for various tram service frequencies on a one-lane and two-lane road link respectively (refer to section 7.2). These equations are used to adjust the travel time on road links with non-exclusive tram rights-of-way in VITM. This allows the impact of a non-exclusive tram right-of-way to be modelled more precisely in VITM.

Table 9.4 The relationship between traffic volume and the percentage change in travel time on a road link with a non-exclusive tram right-of-way

Frequency (trams/hour)	Type of road link	Function	R^2
35	Two-lane road link	$y = 0.00009x^2 + 0.0147x + 40.569$	0.97
30	Two-lane road link	$y = 0.0001x^2 - 0.0032x + 39.098$	0.97
25	Two-lane road link	$y = 0.0001x^2 - 0.0419x + 38.544$	0.97
22	Two-lane road link	$y = 0.0001x^2 - 0.0297x + 34.688$	0.99
20	One-lane road link	$y = 0.00009x^2 - 0.0005x + 86.605$	0.98
	Two-lane road link	$y = 0.0001x^2 - 0.0339x + 33.162$	0.99
17	One-lane road link	$y = 0.0001x^2 - 0.0421x + 82.277$	0.98
	Two-lane road link	$y = 0.00009x^2 - 0.023x + 27.3$	0.99
15	One-lane road link	$y = 0.0002x^2 - 0.078x + 76.639$	0.97
	Two-lane road link	$y = 0.00008x^2 - 0.0251x + 23.964$	0.99
13	One-lane road link	$y = 0.0001x^2 - 0.0323x + 54.084$	0.98
	Two-lane road link	$y = 0.00009x^2 - 0.0397x + 22.531$	0.95
10	One-lane road link	$y = 0.0001x^2 - 0.0463x + 50.636$	0.96
	Two-lane road link	$y = 0.00007x^2 - 0.031x + 17.543$	0.98
8	One-lane road link	$y = 0.00008x^2 - 0.0317x + 37.519$	0.91
	Two-lane road link	$y = 0.00004x^2 - 0.0085x + 11.183$	0.99
5	One-lane road link	$y = 0.00008x^2 - 0.0428x + 27.479$	0.89
	Two-lane road link	$y = 0.00003x^2 - 0.0093x + 8.4764$	0.97

Where: y: Increase in travel time (%)
x: Traffic volume (vehicle/lane/hour)

Impact of Train Operations on Creating Congestion

Table 9.5 shows the polynomial function of the relationship between vehicle volume and percentage change in travel time for various train frequency levels (refer to section 8.3.2). These equations are used to adjust the travel time on road links with at-grade rail crossings in VITM. The impact of at-grade rail crossings can be then modelled precisely under alternative traffic movement volumes.

Table 9.5 The relationship between traffic volume and the percentage change in travel time as a result of at-grade rail crossings

Frequency (trains/hour)	Function	R^2
50	$y = 0.0002x^2 - 0.0406x + 58.188$ (V<400) $y = 0.0071x^2 - 5.5661x + 1166.3$ (V>=400)	1.00 1.00
40	$y = 0.00002x^2 + 0.0498x + 38.287$ (V<700) $y = 0.0033x^2 - 4.7226x + 1734.9$ (V>=700)	0.98 1.00
35	$y = 0.00002x^2 + 0.0105x + 32.255$ (V<800) $y = 0.0011x^2 - 1.5702x + 631.59$ (V>=800)	0.92 1.00
30	$y = 0.00004x^2 - 0.0239x + 27.552$	0.88
25	$y = 0.00003x^2 - 0.0165x + 22.809$	0.92
20	$y = 0.00002x^2 - 0.0109x + 18.62$	0.87
15	$y = 0.00002x^2 - 0.0127x + 14.412$	0.82
10	$y = 0.00002x^2 - 0.0169x + 11.292$	0.94
5	$y = 0.00001x^2 - 0.0065x + 5.6295$	0.93

Where:
y: Increase in travel time (%)
x: Traffic volume (vehicle/lane/hour)

9.3.3 Net Impact of Public Transport on Traffic Congestion

Table 9.6 presents the net congestion effect associated with the entire Melbourne public transport system on the road network. Although public transport can be a cause of congestion through the provision of priority lanes, slow public transport vehicles or at-grade rail crossings, the net impact of removing public transport on congestion is highly negative. Overall, the positive effects of public transport in reducing traffic from roads outweigh negative impacts. The results in Table 9.6 indicate that:

- The operation of public transport contributes to reduce the number of severely congested links and moderately congested links by more than 60% and 7% respectively.
- Vehicle time travelled and total delay on the road network reduce by around 48%.
- Average travel speed increases from 37.22 km/h to 47.53 km/h (an increase of 27.7%) whilst actual travel time per km reduces by approximately 43%.

Table 9.6 Net congestion impact of public transport on Melbourne's road network in AM peak hours (7h-9h)

Measure	With public transport	Without public transport	Absolute change	Change (%)
Number of severely congested links	2,198	5,591	3,393	60.7
Number of moderately congested links	1,983	2,142	159	7.4
Vehicle distance travelled (million veh-km)	15.06	17.58	2.52	14.4
Vehicle time travelled (million veh-hr)	0.41	0.80	0.39	48.5
Total delay on road network (million veh-hr)	24.62	48.00	23.38	48.7
Average travel speed (km/h)	47.53	37.22	-10.31	-27.7
Actual travel time per km (min)	1.98	3.49	1.50	43.1

Notes: Severely congested links are road links which have a volume to capacity (V/C) ratio equal to or greater than 0.9. Moderately congested links are road links which have a V/C ratio equal to or greater than 0.8 and lower than 0.9 (SEMCOG, 2011).

In Chapter 5, the congestion relief impact associated with public transport was estimated by considering only the positive impacts of public transport on reducing congestion through mode shift from public transport to car. In this chapter, the net congestion impact of public transport is investigated by taking into consideration both the positive and negative impacts. Table 9.7 gives information about the differences between the net congestion impact of public transport and the positive impact of public transport on congestion. It is clear that the net impact is lower than the only positive impacts. The difference is considered to be the negative impact of public transport which are:

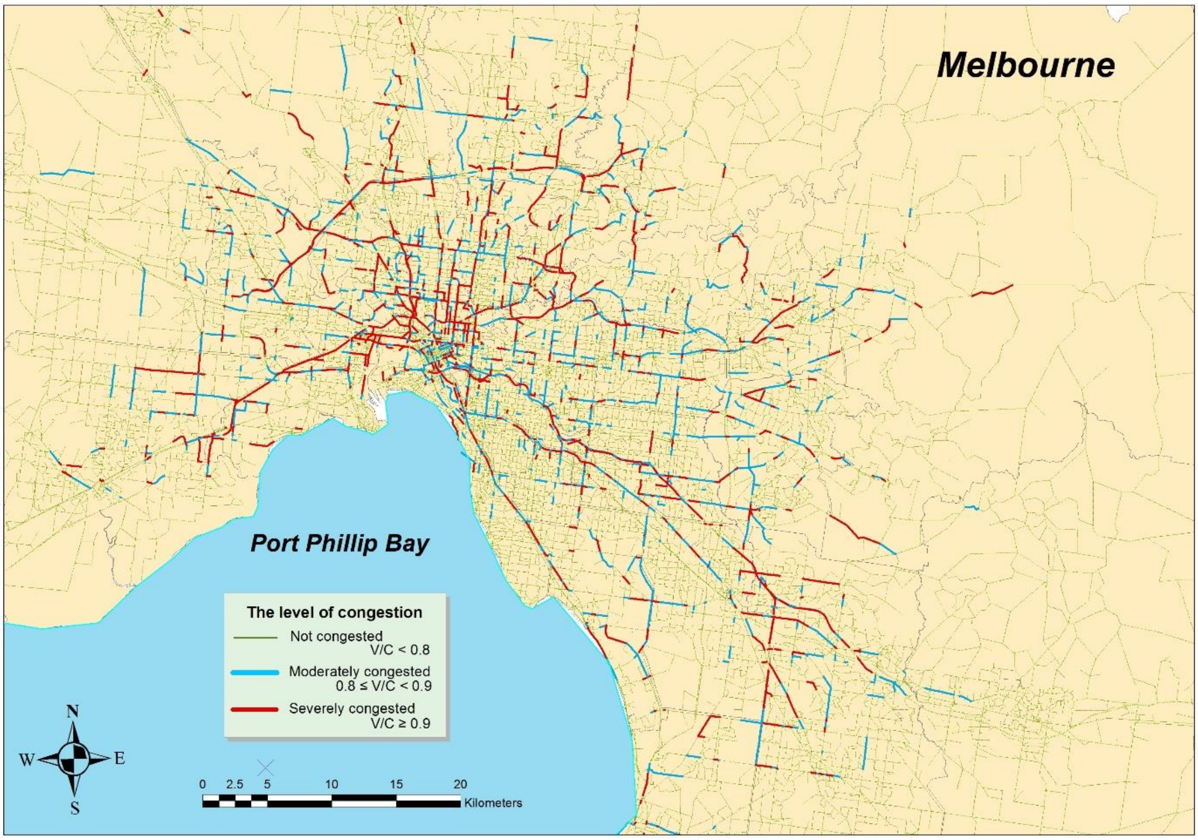
- Public transport contributes to increase vehicle time travelled and total delay on road network by 7.3%
- Average travel speed reduces by 3.9 because of the operation of public transport

Table 9.7 Compare net impact and relief impact of public transport on traffic congestion

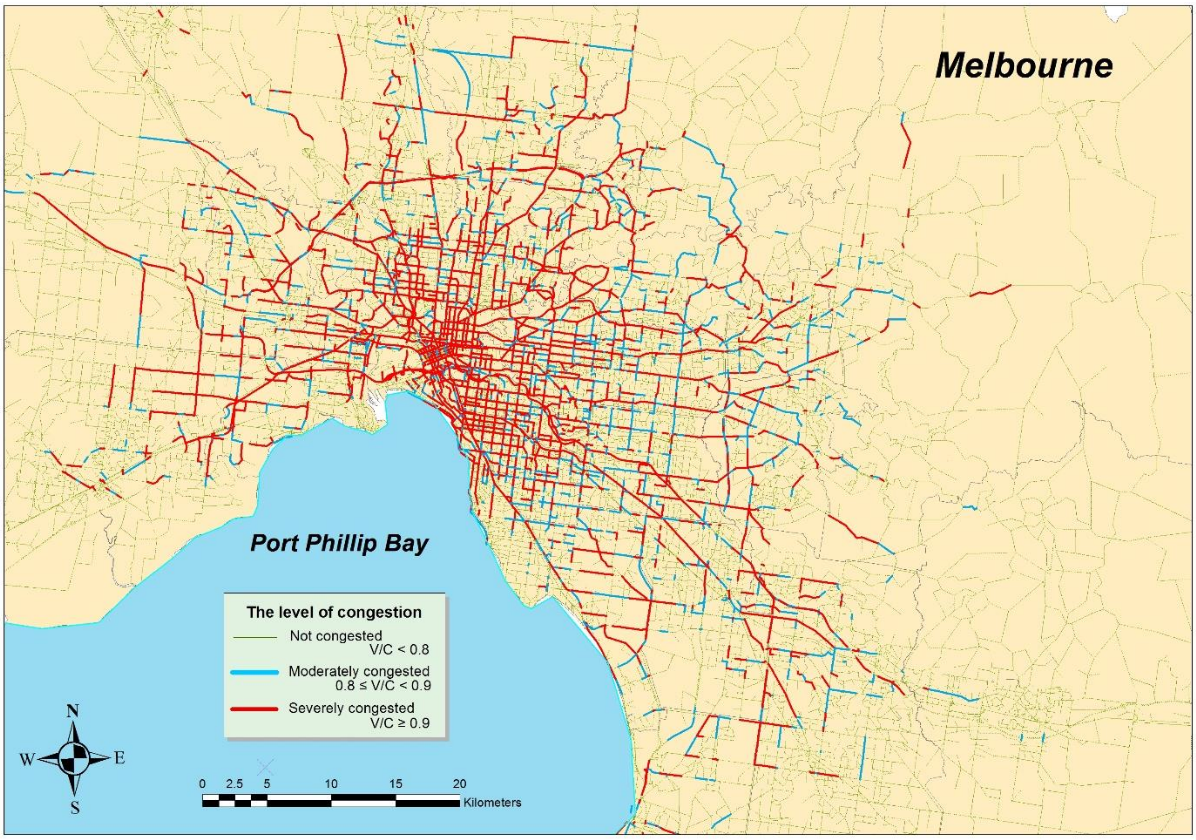
Measure	Positive impact (%)*	Net congestion impact (%)	Negative impact (%)
Number of severely congested links	63.7	60.7	-3.0
Number of moderately congested links	5.9	7.4	1.5
Vehicle distance travelled (million veh-km)	15.0	14.4	-0.6
Vehicle time travelled (million veh-hr)	55.8	48.5	-7.3
Total delay on road network (million veh-hr)	56.0	48.7	-7.3
Average travel speed (km/h)	-31.6	-27.7	3.9
Actual travel time per km (min)	52.1	43.1	-9.0

* Congestion relief impact (positive impact) of public transport was estimated in Chapter 5 with the consideration of mode shift from public transport to car. The congestion creation impact was not taken into account.

In terms of spatial impact, Figure 9.3 shows that when there is no public transport, the level of congestion in inner and out areas increases significantly. Thus, it can be said that public transport contributed to reduce considerably the congestion level in these areas where there has been a heavy reliance on public transport. In contrast, the level of congestion in outer areas increases slightly when public transport is removed.



(a)



(b)

Figure 9.3 Spatial distribution of congested links in two scenarios: (a) with public transport and (b) without public transport

The comparison of public transport congestion impact on the road network in different parts of Melbourne is detailed in Table 9.8. The results show that Melbourne's public transport system has the highest congestion relief impact in inner areas and the lowest impact in outer areas. Table 9.8 shows that:

For inner Melbourne:

- Public transport operations contribute to reduce the number of severely congested links by 68.5% and the number of moderately congested links by 22.8%.
- Vehicle time travelled and total delay on the road network decrease by approximately 65%.
- Average travel speed increases from 24.90 km/h to 42.43 km/h (an increase of 70.4%).

For middle Melbourne:

- The number of heavily congested links decreases by approximately 60% with public transport operations while the number of moderately congested road links decreases by around 14%.
- Total network delay and vehicle time travelled reduce by over 50%.
- Average travel speed increases by nearly 31%.

For outer Melbourne:

- The operation of public transport results in a reduction in the number of severely congested links of more than 54% and in the number of moderately congested links of around 11%.
- There is a decrease in vehicle time travelled and total delay on the road network of more than 25%.
- Travel time on average decreases from 1.87 minutes/km to 1.54 minutes/km (a decrease of 17.6%).

Table 9.8 Net congestion impact of the entire public transport system on Melbourne's road network in inner, middle and outer areas

Measure	Inner			Middle			Outer		
	With public transport	Without public transport	Change (%)	With public transport	Without public transport	Change (%)	With public transport	Without public transport	Change (%)
Number of severely congested links	464	1473	**68.5**	1,175	2,901	**59.5**	559	1,217	**54.1**
Number of moderately congested links	268	347	**22.8**	973	1,132	**14.0**	663	742	**10.6**
Vehicle distance travelled (million veh-km)	1.61	2.17	**25.8**	6.17	7.37	**16.3**	7.27	8.04	**9.6**
Vehicle time travelled (million veh-hr)	0.07	0.20	**65.0**	0.19	0.40	**52.5**	0.15	0.21	**28.6**
Total delay on road network (million veh-hr)	3.89	11.94	**67.4**	11.53	23.71	**51.4**	9.20	12.35	**25.5**
Average travel speed (km/h)	42.43	24.90	**-70.4**	43.68	33.25	**-31.4**	54.56	49.49	**-10.2**
Actual travel time per km (min)	2.51	5.95	**57.8**	2.14	3.64	**41.2**	1.54	1.87	**17.6**

9.4 Discussion

Melbourne's public transport operations were found to contribute to reduce the number of severely congested links and moderately congested links by more than 60% and 7% respectively. Vehicle time travelled and total delay on the road network also reduces by around 48%. The net congestion effect of public transport is assessed in the AM peak hours (7h-9h) when the level of traffic congestion on the road network is expected to be highest. Hence, the findings show that public transport operations significantly contribute to alleviate vehicle traffic congestion. These congestion effects estimated in this study are much higher than the findings of Aftabuzzaman et al. (2010b) even when the negative effects of public transport are subtracted (which was not considered in the Aftabuzzaman et al. research). The main reason is that this research adopts a higher estimate of mode shift to car derived from real-world primary data (38.2%-76.2% compared to 32.4%).

In terms of spatial impact, the net congestion impact of public transport is highest in inner areas and lowest in outer areas. In inner areas, the operation of public transport contributes to reduce the total network delay and vehicle time travelled of the entire road network by over 65%. However, these figures decrease by approximately 51% in middle areas and around 26% in outer areas. The level of traffic congestion in inner areas, particularly in the peak hour, is much higher in comparison to that in middle and outer areas. Hence, although the average mode shift from public transport to car in inner areas is the lowest (48%), public transport operations have the highest effect on reducing congestion in these areas. In contrast, the impact of public transport in outer areas is much lower even though mode shift to car is higher (66.9%). This is because of the low level of congestion in these areas and also because the ratio of the number of public transport users to total road network length is low.

The results suggest that the net effect of public transport is significant and positive. However, reported results in this research may be overestimated because, in practice, the savings from public transport withdrawal could be reinvested in the road network to reduce the level of congestion. Although overall public transport is found to be highly beneficial, this is not to ensure that incremental public transport investments will be equally beneficial. Public transport modes which operate on shared road with other vehicles such as tram or bus can be delayed due to traffic jams or collisions. Thus, there may be limits to the effectiveness of public transport on reducing traffic congestion in these conditions.

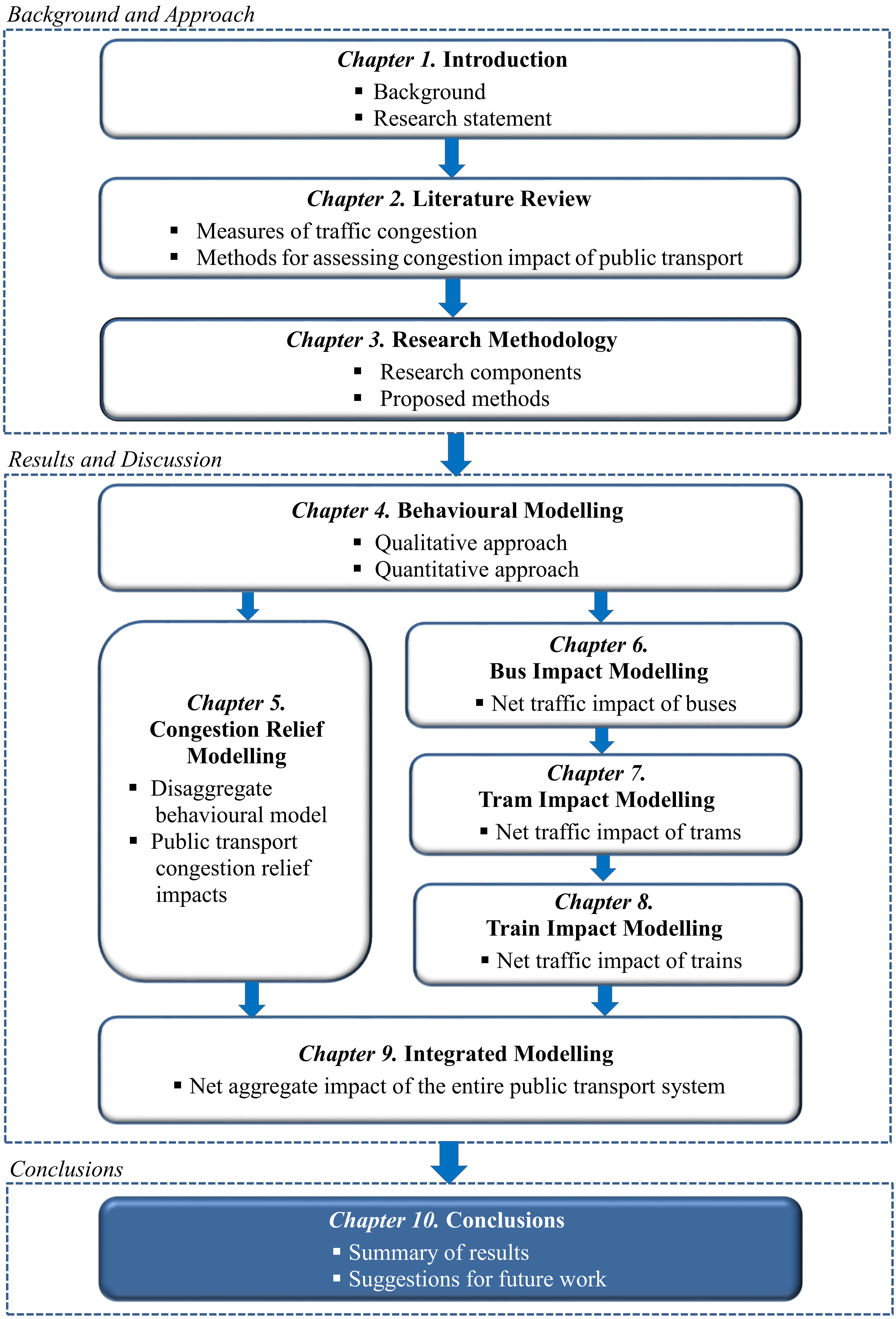
The developed model can be applied for other cities to assess the congestion effects of public transport. The model adopted a four-step transport model and the mode shift from public transport to car. Transport network models have been developed and used in most major cities to predict the flow of vehicles on the road network. Additionally, it is possible for other cities to conduct a field survey in an actually public transport withdrawal or using a hypothetical situation (if public transport withdrawal does not appear often) in order to determine mode shift to private car. There have been a number of studies exploring the effect of PT strikes which assume a one hundred percent of public transport users shift to using a car (Schrank et al., 2012, Moylan et al., 2016). This research suggests this is unrealistic as users can shift to other transport modes. The model developed in this study takes into consideration both positive and negative effect of public transport. Thus, it is considered to improve greatly the accuracy of the estimations undertaken in previous research.

Overall the method described in this thesis is considered to be an improvement to methodological approaches for assessing one of public transport's most significant impacts on Australian cities; acting to reduce urban traffic congestion. It is clear these impacts are growing as the Australian urban population rises. This method can be applied to estimate the net congestion effect of public transport for other cities. The future research would be to explore the long term effects of public transport on traffic congestion. The absence of public transport in a long term is expected to influence land-use which leads to the change in travel patterns. Hence, the long term congestion relief impact of public transport could be different due to the difference in trip distribution.

9.5 Conclusions

The aim of this chapter was to propose methods for exploring the net network-wide congestion effect of the entire public transport system in the short term. The approach employs a transport network model (VITM) to examine both the positive and negative effects of public transport on traffic congestion. The net congestion impact of public transport is taken to be the difference between the level of congestion in two scenarios ‘with public transport’ and ‘without public transport’. The positive impact of public transport on reducing congestion are assessed by estimating an adopting mode shift from public transport to car in the event of a public transport withdrawal. In contrast, the negative impacts of public transport on generating congestion are investigated by considering the impact which public transport itself can have in increasing congestion at places like at-grade rail crossings or on roads where the frequent stopping of buses and trams might slow traffic. The effect of public transport priority lanes on reducing road capacity is also taken as a negative impact of public transport on traffic congestion.

The developed methods can be applied for other cities to identify the effectiveness of a public transport system in terms of congestion relief. However, there are some possible limitations to transferability of findings such as the lack of consideration the effect of priority bus lanes in the method. These limitations could be explored in further research in order to aid wider applicability. The next and final chapter concludes this thesis with a summary of key findings and highlights directions for future research.


Background and Approach
Chapter 1. Introduction
Background
Research statement
Chapter 2. Literature Review
Measures of traffic congestion
Methods for assessing congestion impact of public transport
Chapter 3. Research Methodology
Research components
Proposed methods
Results and Discussion
Chapter 4. Behavioural Modelling
Qualitative approach
Quantitative approach
Chapter 5. Congestion Relief Modelling
Disaggregate behavioural model
Public transport congestion relief impacts
Chapter 6. Bus Impact Modelling
Net traffic impact of buses
Chapter 7. Tram Impact Modelling
Net traffic impact of trams
Chapter 8. Train Impact Modelling
Net traffic impact of trains
Chapter 9. Integrated Modelling
Net aggregate impact of the entire public transport system
Conclusions
Chapter 10. Conclusions
Summary of results
Suggestions for future work

Chapter 10
CONCLUSIONS

10.1 Introduction

This thesis focuses on understanding the congestion effects associated with public transport. Although several research efforts have investigated the relationship between public transport and traffic congestion, this research creates new knowledge in this area as has been presented in previous chapters (see Chapter 4-9). The research framework includes four main components: (1) modelling the behavioural reaction of public transport users in the event of a public transport withdrawal, (2) modelling the congestion relief impact of the entire public transport system, (3) modelling the net traffic congestion impact of individual public transport modes and (4) integrating models to estimate the net congestion effect of the entire public transport system. This chapter concludes this thesis with contributions to new knowledge (Section 10.2), a summary of key findings that have emerged from the research (Section 10.3), implications of the research findings (Section 10.4), opportunities to improve the research (Section 10.5), directions for future research (Section 10.6) and final conclusions (Section 10.7).

10.2 Contributions to New Knowledge

This research has made contributions in four major areas relevant to the road traffic congestion effects associated with public transport. These are listed as follows:

- ***Modelling of the behavioural response of public transport users when public transport is not available (Chapter 4)*** – Although the share of mode shift from public transport to using a car is considered to be a key parameter for estimating the traffic congestion relief impact associated with public transport, limited research has been conducted in this area. This research provides an in-depth understanding of the mode shift of public transport users when public transport is unavailable. A number of factors influencing mode shift from public transport to private car use were explored. They can be classified into three main themes with several subcategories: individual-specific factors, context-specific factors and journey-specific factors. A formal questionnaire survey involving 648 public transport users was then conducted to statistically validate the findings from the qualitative research. Thus, factors which have more significant impact than others can be determined.

- ***Development of an enhanced method to assess the congestion relief effect of public transport (Chapter 5)*** – Only one earlier study was found to assess the network-wide congestion relief effect of urban public transport using transport network modelling (Aftabuzzaman et al., 2010b). This study adopted a fixed mode shift from public transport to car. The current research developed a new method for estimating the share of public transport users shifting to car for different regions using both primary data and secondary data. Thus, the estimation of the congestion relief effect of public transport is considered to be more accurate as mode shift to using a car, which depends on a series of factors related to public transport users' characteristics, varies for different spatial regions.
- ***Development of methods to estimate the traffic impacts of individual public transport modes (Chapter 6-8)*** – While there have been several attempts to explore the congestion impacts of individual public transport modes (train, tram and bus) on a road link or a corridor, little is known about the network-wide impacts of public transport modes on traffic. Indeed, the operation of public transport not only affects adjacent links but also results in traffic volume changes in surrounding areas due to traffic diversion and reassignment. To date, only one study has examined the network-wide effect of individual public transport modes on reducing traffic congestion (Aftabuzzaman et al., 2010b). In this study, only the positive effects of public transport modes were estimated; negative effects such as traffic delay caused by bus/tram stop operations or rail level crossings were not considered. This research is the first to provide a methodology for examining the negative impacts of individual public transport mode operations on generating traffic congestion. Based on this, the net congestion effect of individual public transport modes can be assessed.
- **Modelling of the net congestion effect associated with the entire public transport system (Chapter 9)** – No previous studies have investigated the net network-wide impact of the entire public transport system on traffic congestion. This research makes a contribution to this area by integrating both positive effects and negative effects of public transport on vehicle traffic. The spatial distribution of the congestion effects is also explored. The findings show that Melbourne's public transport system contributes to reduce vehicle time travelled and total delay on the road network by around 48%. The public transport system also reduces the number of severely congested links by more than 60%. The congestion impacts of public transport vary spatially across regions. The highest effects in relieving traffic congestion are in inner areas (traditionally the most congested parts of the city).

10.3 Summary of Key Findings

This section highlights the key findings of the research which aims to improve the methods for estimating the impacts of public transport on traffic congestion. A number of previous studies have investigated the traffic congestion impacts associated with urban public transport using various approaches. However, no systematic methods have been proposed to estimate these impacts since previous approaches have used simplistic assumptions and constructs. This current study for assessing the net traffic congestion impact of public transport involves four major stages: (1) behavioural modelling, (2) congestion relief modelling, (3) public transport impact modelling and (4) integrated modelling. The key results of each stage are summarized as follows:

Behavioural Modelling

- The findings from the qualitative survey, which explores factors influencing the mode shift of public transport users when public transport is removed in the short term, provides a basis for developing a conceptual model that attempts to structure the public transport user's mode shift process. The conceptual model that consists of multi-dimensional factors provides a tentative explanation of how public transport users switch to travelling by car.
- If public transport is unavailable in the short term, there are a number of factors influencing mode shift from public transport to private car use. They can be classified into three main themes with several subcategories: individual-specific factors, context-specific factors and journey-specific factors. However, in the long term, only context-specific factors were found to affect public transport users' mode shift. The removal of public transport in the short term may act only to increase traffic congestion due to mode shift to car. However, in the long term, removing public transport may also affect travel patterns and land use.
- The results from the quantitative survey conducted in Melbourne show that in the event of a major public transport withdrawal, 52% of users would switch to travelling in a car as a driver and 11% would shift to travelling in a car as a passenger. Mode shift to car as a driver is higher than other figures (5-50%) found by previous studies around the world (Exel and Rietveld, 2001) and nearly double the figure estimated by Aftabbuzzaman et al. in the Melbourne context (Aftabuzzaman et al., 2010a).
- The multinominal logit analysis shows that there are a number of factors significantly influencing mode shift to car among public transport users. These include driver's license ownership, car ownership, health concerns, the number of vehicles in a household, trip destination (in the CBD or not) and station accessibility.

Congestion Relief Modelling

- The analysis of data derived from the field survey conducted with public transport users in Melbourne shows that there is a linear relationship between the share of mode shift to car for a specific area and a set of factors including the share of public transport users with: a driver's license, more than one car in their household, with long distance trips and with a trip destination in the CBD. The developed regression model can be used to predict mode shift to travelling by car for other areas. In this research, the characteristics of public transport users obtained from the VISTA database are used to predict mode shift to car for Melbourne's LGAs. The results demonstrate that mode shift from public transport to car is lowest in inner areas (48%). This mode shift is higher for regions located further from the CBD (ranging from 49.5% to 76.2%).
- The findings of transport network modelling show that Melbourne's public transport operations contribute to reduce the number of severely congested links and moderately congested links by 63.7% and 5.9% respectively. Vehicle time travelled and total delay on the road network is expected to reduce by around 56%.

Public Transport Impact Modelling

- The results show that the operation of level crossings causes an increase in travel time for vehicle traffic on immediate road links but is also associated with traffic volume reductions since links with level crossings become less attractive compared to other links available for through traffic. Overall, Melbourne's level crossings are found to cause an average increase in travel time of 16.1% on their immediate road links and reduce the volume of vehicles by 5.9%.
- The aggregate effect of all 152 level crossings on all Melbourne's traffic is an increase in average travel time from 1.81 to 1.82 minutes/km (an increase of around 0.3%) and an increase of 0.9% in the number of congested links.
- Tram operations contribute to significantly suppress the extent of traffic congestion however their net effect is offset by some negative impacts on traffic flow. Total delay on the road network increases by around 1.2% whereas average speeds decrease by 0.4% as a result of Melbourne's tram operations.
- In inner Melbourne, trams have a much higher impact in reducing congestion; vehicle time travelled and total delay on the road network decreases by 3.4% as a result of tram operations. The average road network speed rises from 41.6 km/h to 41.9 km/h. The operation of trams in inner Melbourne reduces actual travel time on average from 2.14

minutes/km to 2.13 minutes/km. The tram network contributes to reduce 16% of the number of moderately congested links in inner Melbourne.

- The findings show that although there are some negative effects, the net congestion impact of bus operations on the entire road network, including both roads with and without bus operations, is significant and positive. The operation of buses on Melbourne's entire road network acts to reduce the number of severely congested links and moderately congested links by approximately 10% and 6% respectively. There is a reduction of nearly 3% in vehicle time travelled and total delay on the road network.
- Melbourne's bus services have the largest congestion effect on the road network in inner areas. Vehicle time travelled and total delay on the road network decreases by 7% due to bus operations. The operation of buses in inner areas also contributes to reduce the number of heavily congested links by 16% and the number of moderately congested links by 6%. Bus operations in outer Melbourne reduces vehicle time travelled and total delay on the road network by only 2%. This is despite a reduction in the number of heavily congested links of more than 15%, compared to only 6% in middle areas.

Integrated Modelling

- The results show that the net congestion effect of Melbourne's entire public transport system is significant and positive. Melbourne's public transport operations were found to contribute to reduce the number of severely congested links and moderately congested links by more than 60% and 7% respectively. Vehicle time travelled and total delay on the road network also reduces by around 48%.
- In terms of spatial impact, the net congestion impact of public transport is highest in inner areas and lowest in outer areas. In inner areas, the operation of public transport contributes to reduce total network delay and vehicle time travelled on the entire road network by over 65%. However, these figures decrease to approximately 51% in middle areas and around 26% in outer areas. The impact of public transport in outer areas is much lower even though mode shift to using a car is higher (66.9%).

10.4 Implications

This section presents the implications of the findings for practice.

- Firstly, factors influencing mode shift from public transport in the event of a public transport disruption would be of interest to transport planners and decision makers. Based on the understanding of factors affecting participants' choice of alternative transport modes, policies can be designed to reduce potential mode shift to using a car in an event of a public transport strike.

- Secondly, the results of this thesis can help authorities and policy makers to estimate the effect of individual public transport mode withdrawals on traffic congestion. From this, a measure or a number of measures can be better targeted to deal with these issues. For instance, the frequency of alternative public transport modes can be increased in areas experiencing high levels of traffic congestion during public transport strikes. Other policies could be proposed such as allowing vehicles to travel or park in priority bus lanes or tram lanes if these public transport modes cease, thereby increasing road capacity during strikes. In cities which have bike-sharing systems, they could be free in the event of a public transport strike as this can encourage mode shift from car users and reduce the level of congestion. Increasing the number of real time passenger information systems is another possible measure. Different types of information pre-journey, en-route and post-journey, which can be provided by using appropriate channels before and during a journey, is extremely valuable for road users (Papangelis et al., 2016, Beecroft and Pangbourne, 2015).
- Thirdly, understanding the congestion relief impacts of entire public transport systems can provide guidance both from an operational and a strategic point of view. From the operational perspective, routes and corridors facing congestion can be targeted for attention to seek a desired level of congestion relief. From a strategic perspective, appropriate public transport policies can be developed to encourage desired development in designated locations and again seek desired levels of congestion relief.
- Finally, the findings on public transport congestion relief impacts help public transport agencies and operators to demonstrate the ‘value’ of a public transport network in reducing traffic congestion. Public transport congestion relief impacts can be different for cities based on the size, the quality or the level of integration of public transport networks. Determining how much congestion is reduced by public transport provides evidence about the benefits of public transport for city officials. Thus, they have a much stronger argument for using taxpayer money to improve public transportation services.

10.5 Critique

While the thesis has provided a number of original contributions to knowledge, there are opportunities to improve it. Some specific improvements could be:

- In considering the qualitative survey in Chapter 5, it is noted that the interviews were conducted from August to October when the temperature was relatively cold and there were many rainy days. Thus, participants may have been more likely to identify the influence of this weather on their mode selection than they normally would in other seasons. The interviews ideally would be carried out in different seasons so that the effect of weather on public transport users' choice can be understood more clearly. In addition, interview participants were mainly staff and students of a university. It is expected that university students' mode shift from public transport to private cars may be different from other public transport users. Thus, the findings cannot be generalised to all public transport users.
- Regarding the quantitative survey in Chapter 5, while best efforts were made to attract participants from different age groups, people under 18 years old were under represented due to ethics requirements. A proportion of people in this age group use public transport to travel to school and they may switch to private car as a passenger in the event of a public transport disruption. Thus, mode shift from public transport to car would be overestimated as the survey addresses only adults who have a higher chance of switching to car. This leads to an overestimation in the findings of the traffic congestion impact of public transport. In further research, this bias needs to be addressed to increase the accuracy of the developed methods.
- In the framework used to estimate the congestion generation impact of at-grade rail crossings in Chapter 8, a simple assumption where one train crosses at a time was used in this research. However, it is possible that two trains in different directions can cross at the same time, or with a small gap between each other, while there can also be small gaps between trains traveling in the same direction (especially in the peak period). These more complex (and realistic) situations could substantially increase the closure time of the crossings and so magnify the delays caused. Therefore, there is a need to consider these situations in the modelling which is likely to increase the accuracy of the method.
- This research only focuses on the short-term impacts of public transport on traffic congestion. If public transport is not available in a long-term, the behavioural response of public transport users might be different as they may change their workplace, find a new job closer to their home or buy a car for travelling. In addition, the change in land use, level of congestion or socio-economic status of users would affect the congestion impacts associated with public transport. Further research which distinguishes between the short-

term and long-term impacts of public transport is there for needed.

10.6 Future Research Directions

There are a range of areas where future research can be undertaken to advance existing knowledge on the traffic congestion effects associated with public transport. Opportunities for future research are listed as follows:

- There is clear scope for future research to develop a more comprehensive model to assess the negative effects of public transport on generating traffic congestion. For instance, when modelling the effects of at-grade rail crossings on traffic, site surveys at different at-grade rail crossings could be used to identify the precise closure time per train. Information on train types, level crossing design and nearby road network configurations could also be incorporated into refinements of the simulations used.
- To gain a better understanding of mode shift to car when public transport ceases, the sample for the qualitative survey should be expanded on the basis of their socio-demographics so that the findings are more representative all public transport users.
- Future research could focus on the mode shift of public transport users when public transport is not available in the long-term. From this, the long-term effects of public transport on urban traffic congestion can be assessed and compare to the short-term impacts of public transport.
- In further research, person-based congestion measures (such as person delay per hour and person delay per kilometre) could be used to investigate the traffic congestion impacts associated with public transport. Using person-based measures is considered to be more accurate than vehicle-based measures given that the vehicle occupancy of public transport differs to that of private cars. However, person-based measures require more detailed data on many factors such as travel demand and the number of passengers using public transport means or public transport travel conditions.

10.7 Final Conclusions

The traffic congestion effects associated with urban public transport have been examined through qualitative, quantitative, microsimulation and macrosimulation modelling approaches in this research. Results from the analyses indicate that the net effect of Melbourne’s entire public transport system on traffic congestion is significant and positive. Train operations are found to have the highest impact on reducing congestion, followed by buses and trams. The spatial impact of system-wide effects of public transport was also investigated in this research. Based on these findings, policies to influence travel patterns or improvement projects related to public transport (such as removing level crossings or providing new bus routes) can be proposed to seek a desired level of congestion relief thereby providing benefits to the entire community.

In summary, it is worth highlighting two main points that have a bearing on an understanding of the congestion effects of public transport. Firstly, the research has been undertaken in the context of Melbourne. However, the methods developed in this research can be used to explore the congestion effects of public transport in other cities where a transport network model is available. Secondly, while the methods adopted in this research are considered to be robust, it is acknowledged that they come with their own limitations. Further research can address these limitations to build on the knowledge gained from this research.

APPENDIX

TRAVEL SURVEY

Screening questions:

1. Are you a resident of metropolitan Melbourne?

a. Yes
b. No

2. What means of travel did you use in the last month from Monday to Friday? (*In this question you can choose more than one option*)

a. Private car
b. Train
c. Tram
d. Bus
e. Motorcycle
f. Walking
g. Cycling
h. Other

3. Did you use public transport last month for travelling to your destination between 7am to 9am?

a. Yes

b. No

4. Which Council/Local Government Area do you live in?

Inner Melbourne	Middle Melbourne	Outer Melbourne
a) City of Melbourne	e) City of Banyule	a) City of Cardinia
b) City of Port Phillip	f) City of Bayside	b) City of Casey
c) City of Stonnington	g) City of Boroondara	c) City of Frankston
d) City of Yarra	h) City of Brimbank	d) City of Greater Dandenong
	i) City of Darebin	e) City of Hume
	j) City of Glen Eira	f) City of Knox
	k) City of Hobsons Bay	g) City of Maroondah
	l) City of Kingston	h) City of Melton
	m) City of Manningham	i) City of Mornington Peninsula
	n) City of Maribyrnong	j) City of Nillumbik
	o) City of Monash	k) City of Whittlesea
	p) City of Moonee Valley	l) City of Wyndham
	q) City of Moreland	m) City of Yarra Ranges
	r) City of Whitehorse	

For those responding a. for Q1, b, c or d. for Q2 and a. for Q3 above: The panellists are eligible to take part in a short survey about public transport.

5. What is your age?

a. 18 – 29
b. 30 – 39
c. 40 – 49
d. 50 – 59
e. 60 and over

6. Gender:

a. Male
b. Female

You are eligible to participate in a short survey about public transport in your city. This survey is hosted and administered by Monash University (Melbourne, Australia). The survey will take about 20 minutes to complete and is completely anonymous. If you are interested in completing this survey, please [click here] to exit this screener and begin the survey.

EXPLANATORY STATEMENT
Public Transport User Opinion Survey

You are invited to take part in this study. Please read this Explanatory Statement in full before deciding whether or not to participate in this research.
The main purpose of this survey is to investigate the travel behaviour of public transport users in Melbourne and the flexibility which they have to change that behaviour. The survey will ask you some questions related to your perceptions, experiences and attitudes towards public transport. The data collected from this survey will be used for research purposes only to define the extent to which the public transport system can reduce traffic congestion. We would be grateful if you could spare about 20 minutes of your time to participate in this survey.
Your responses are completely anonymous and you can stop taking the survey at any time. However if you stop the survey we cannot remove questions you have already answered. Data will be stored in accordance with Monash University regulations, on a password-protected computer, for five years. If you are interested in the results of the study or have any further questions regarding any aspect of this project, please contact Professor Graham Currie via the phone number or email address listed below.
We do not anticipate that the survey will cause any distress to you. Should you have any concerns or complaints about the conduct of the project, you are welcome to contact the Monash University Human Research Ethics Committee (MUHREC):
Executive Officer
Monash University Human Research Ethics Committee (MUHREC)
Room 111, Building 3e
Research Office
Monash University VIC 3800
[redacted]

Thank you,

Professor Graham Currie
Department of Civil Engineering
[redacted]

GENERAL INFORMATION

1. Do you have a full driver's license?

a. Yes
b. No

2. Do you currently own a private car?

a. Yes
b. No

3. Do you have any health concerns that prevent you from driving a car?

a. Yes
b. No

4. How many adults in your household including yourself have a full driver's license?

a. One
b. Two
c. Three
d. More than three
Please specify.....
e. No one

5. How many cars are there in your household?

a. No car
b. One
c. Two
d. Three
e. More than three
Please specify.....

6. How many bicycles are there in your household?

a. No bicycle
b. One
c. Two
d. Three
e. More than three
Please specify.....

PRE ON ITS OWN SCREEN: Thinking about your last weekday public transport trip that started from your home between 7am and 9am

7a. What types of public transport did you use for that trip? *(Multiple Response)*

a. Train
b. Tram
c. Bus

7. How often did you take this trip by public transport?

a. 4 times per week or more
b. 1-3 times per week
c. 1-3 times per month
d. Less than once per month

8. What were the weather conditions during that trip?

a. Hot, scorching
b. Rainy, wet, miserable, damp
c. Windy, dull, grey
d. Cold, chilly

e. Warm, mild, fine, dry

9. What was the suburb or postcode of your place of residence where you started your trip?
Suburb………………………………
Postcode…………………………..

10. What is the specific address or nearest intersection from your home? (*e.g. 123 Collins St or Collins St & Elizabeth St*)
………………………………………………………………..

11. What was the suburb or postcode of your destination?
Suburb………………………………
Postcode…………………………..

12. What is the specific address or nearest intersection from your destination? (*e.g. 123 Collins St or Collins St & Elizabeth St*)
…………………………………………………………………………

13. What was the main purpose of that trip?

a. Accompany some one
b. Buy something
c. Pick up/deliver something
d. Education
e. Work related
f. Personal business
g. Social
h. Other
Please specify ………………………….

14. Did you use a car to access public transport?

a. Yes - Go to Q14c
   14c**. How did you access public transport?**
   a. Drove a car
   b. Got a lift (travelling as a passenger in a car)
b. No - Go to Q15

INFORMATION RELATED TO YOUR CHOICE WHEN PUBLIC TRANSPORT IS REMOVED

15. We would like you to imagine that <u>entire</u> public transport was <u>no longer available</u> for the day of your last public transport trip. How would you travel to your destination for that trip (choose only one major transport mode)?

a. Drive a car - Go to Q16,Q17, Q30 -> Q39, Q40 -> Q48
b. Get a lift (car passenger) - Go to Q18, Q19, Q28, Q29, Q32 -> Q39, Q40 -> Q48
c. Use a taxi/uber - Go to Q20, Q21, Q28 -> Q31, Q34 -> Q39, Q40 -> Q48
d. Cycle - Go to Q22, Q23, Q28 -> Q33, Q36 -> Q39, Q40 -> Q48
e. Walk - Go to Q24, Q25, Q28-> Q35, Q38, Q39, Q40 -> Q48
f. Cancel the trip - Go to Q26, Q27, Q28 -> Q37, Q40 -> Q48
g. Other
Please specify …………………………. - Go to Q28 -> Q48

16. What factors would make you choose to <u>drive a car</u> if public transport was not available?
....

17. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide to <u>drive a car</u>?

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. I have an available car	5	4	3	2	1

b. I can find a parking spot easily at my destination	5	4	3	2	1
c. I have a driver's license	5	4	3	2	1
d. I feel a car is flexible because I can travel anytime	5	4	3	2	1
e. I have to travel a long distance	5	4	3	2	1
f. I need a car to pick up someone	5	4	3	2	1
g. I like to drive	5	4	3	2	1
h. I can avoid bad weather outside when travelling by car	5	4	3	2	1
i. I am able to cover the cost of driving (petrol cost, parking cost…)	5	4	3	2	1
j. I need to carry items/equipment	5	4	3	2	1
k. It is the quickest way to get my destination	5	4	3	2	1
l. I have no other alternative	5	4	3	2	1
Other					
m. …………………………………	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide to drive a car: 1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

18. What factors would make you choose to get a lift if public transport was not available?

……

19. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide to get a lift?

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. My relatives/friends have cars and they can take me	5	4	3	2	1
b. I want to save money	5	4	3	2	1
c. My relatives/friends and I have the same route	5	4	3	2	1
d. I feel comfortable and safe when travelling with people I know	5	4	3	2	1
e. I do not want to focus on driving a car	5	4	3	2	1
f. I can do something when getting a lift	5	4	3	2	1
g. I have no other alternative	5	4	3	2	1
h. It is the quickest way to get my destination	5	4	3	2	1
i. I can avoid bad weather outside when travelling by car	5	4	3	2	1
Other					
j. …………………………………………	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide to travel as a car passenger: 1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

20. What factors would make you choose to travel by taxi/uber if public transport was not available?

……

21. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide to travel <u>by taxi/uber</u>?

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. I feel safe when travelling by taxi	5	4	3	2	1
b. I can do something when travelling such as checking email or reading a book	5	4	3	2	1
c. I cannot travel by myself because of health concerns	5	4	3	2	1
d. I can reduce the risk of getting lost	5	4	3	2	1
e. I feel comfortable	5	4	3	2	1
f. I can avoid bad weather outside when travelling by car	5	4	3	2	1
g. I am able to cover the cost of the taxi/uber fare	5	4	3	2	1
n. It is the quickest way to get my destination	5	4	3	2	1
h. I have no other alternative	5	4	3	2	1
Other					
i. …………………………………….	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide to travel <u>by taxi/uber</u>: 1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

22. What factors would make you choose to <u>cycle</u> if public transport was not available?

………

23. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide to <u>cycle</u>?

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. The distance to my destination is not far	5	4	3	2	1
b. I want to do exercise and improve my health	5	4	3	2	1
c. I own a bike	5	4	3	2	1
d. There are facilities for cyclists at my destination	5	4	3	2	1
e. I feel safe when travelling by bicycle	5	4	3	2	1
f. I can save money	5	4	3	2	1
g. I can avoid traffic congestion	5	4	3	2	1
h. Travelling by bicycle is environmentally friendly	5	4	3	2	1
i. I enjoy cycling	5	4	3	2	1
j. I have no other alternative	5	4	3	2	1
Other					
k.……………………………………….	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide to <u>cycle:</u>
1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

24. What factors would make you choose to <u>walk</u> if public transport was not available?

………

25. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide to <u>walk?</u>

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. The distance to my destination is not far	5	4	3	2	1
b. I want to do exercise and improve my health	5	4	3	2	1
c. Facilities for walking to my destination are convenient (footpaths, crossings)	5	4	3	2	1
d. I can save money	5	4	3	2	1
e. I can avoid traffic congestion	5	4	3	2	1
f. I feel relaxed when walking	5	4	3	2	1
g. Travelling on foot is environmentally friendly	5	4	3	2	1
h. I have no other alternative	5	4	3	2	1
Other i. ………………………………………	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide to <u>walk:</u>

1.☐ **2.**☐ **3.**☐

Please write the letter (a, b, c ….) for each factor in the box.

26. What factors would make you choose to <u>cancel the trip</u> if public transport was not available?

....

27. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide to <u>cancel the trip?</u>

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. The trip is not too important	5	4	3	2	1
b. The trip distance is too long	5	4	3	2	1
c. I am not able to cover the travel cost	5	4	3	2	1
d. I have no alternative travel mode	5	4	3	2	1
e. I cannot navigate my way to get the destination	5	4	3	2	1
f. I can reschedule my trip to another day	5	4	3	2	1
Other g.……………………………………	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide to <u>cancel the trip</u>: 1.☐ **2.**☐ **3.**☐

Please write the letter (a, b, c ….) for each factor in the box.

28. What factors would make you <u>not</u> choose to <u>drive a car</u> if public transport was not available?

....

29. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide <u>not</u> to <u>drive a car?</u>

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. A car is not available	5	4	3	2	1
b. I do not have a driver’s license	5	4	3	2	1
c. I cannot drive because of health concerns	5	4	3	2	1

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
d. I only need to travel a short distance	5	4	3	2	1
e. The cost of parking at my destination is too high	5	4	3	2	1
f. It is difficult to find a car park	5	4	3	2	1
g. I am not able to cover the cost of travelling by car	5	4	3	2	1
h. I feel stressed when driving a car	5	4	3	2	1
i. Traffic congestion on my route is high	5	4	3	2	1
j. I want to reduce air pollution	5	4	3	2	1
k. I cannot use my time productively when driving a car (e.g. reading)	5	4	3	2	1
Other					
l. ……………………………………….	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide not to drive a car: 1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

30. What factors would make you not choose to travel by getting a lift if public transport was not available?

....

31. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide not to travel by getting a lift?

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. I am living alone	5	4	3	2	1
b. My relatives/friends do not have any free time	5	4	3	2	1
c. I cannot find anyone who has the same route as me	5	4	3	2	1
d. I only need to travel a short distance	5	4	3	2	1
e. Traffic congestion on my route is high	5	4	3	2	1
f. I do not want to depend on other people	5	4	3	2	1
g. I do not want to bother my relatives/friends	5	4	3	2	1
Other					
h.…………………………………….	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide not to travel by taking a lift: 1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

32. What factors would make you not choose to travel by taxi/uber if public transport was not available?

....

33. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide not to travel by taxi/uber?

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. I have to spend time waiting for a taxi	5	4	3	2	1
b. I am not able to cover the cost of a taxi	5	4	3	2	1
c. I feel unsafe when travelling by taxi	5	4	3	2	1

d. Traffic congestion on my route is high	5	4	3	2	1
e. I do not feel comfortable when travelling by taxi	5	4	3	2	1
f. Taxi drivers often choose a longer journey so I have to pay more money	5	4	3	2	1
g. I do not want to travel with a stranger (taxi driver)	5	4	3	2	1
Other h.……………………………………….	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide not to travel by taxi/uber: 1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

34. What factors would make you not choose to cycle if public transport was not available?

……

35. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide not to cycle?

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. Travelling by bicycle is exhausting	5	4	3	2	1
b. Travelling by bicycle is time-consuming	5	4	3	2	1
c. Travelling by bicycle is dependent on weather conditions	5	4	3	2	1
d. Travelling by bicycle is dangerous	5	4	3	2	1
e. Facilities for cycling to my destination are inadequate (e.g. no bicycle lane)	5	4	3	2	1
f. I cannot find a parking spot for my bicycle	5	4	3	2	1
g. I cannot pick up someone	5	4	3	2	1
h. I have to travel a long distance	5	4	3	2	1
i. I have to carry items/equipment	5	4	3	2	1
Other j. …………………………………….	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide not to cycle: 1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

36. What factors would make you not choose to walk if public transport was not available?

……

37. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide not to walk?

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. Travelling by walking is exhausting	5	4	3	2	1
b. Travelling by walking is time-consuming	5	4	3	2	1
c. Travelling by walking is dependent on weather conditions	5	4	3	2	1
d. Travelling by walking is dangerous	5	4	3	2	1
e. Facilities for walking to my destination are inadequate (e.g. no footpath)	5	4	3	2	1
f. I have to carry something heavy	5	4	3	2	1

g. I have to travel a long distance	5	4	3	2	1
Other h.……………………………………….	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide <u>not</u> to <u>walk</u>: 1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

38. What factors would make you <u>not</u> choose to <u>cancel the trip</u> if public transport was not available?

………

39. On a scale of 1 to 5 how IMPORTANT are the following factors in making you decide <u>not</u> to <u>cancel the trip</u>?

	Extremely Important	Very Important	Important	Not Very Important	Not Important at All
a. The trip is too important	5	4	3	2	1
b. I want a change of scenery	5	4	3	2	1
c. I need to have a face-to-face interaction	5	4	3	2	1
d. I have options available which I prefer to use	5	4	3	2	1
Other e. ……………………………………	5	4	3	2	1

Of those factors, which do you think are the TOP 3 which best explain why you would decide <u>not</u> to <u>cancel the trip</u>: 1.☐ 2.☐ 3.☐

Please write the letter (a, b, c ….) for each factor in the box.

40. If <u>only the train system</u> was no longer available for the day of your last public transport trip. How would you travel to your destination for that trip (choose only one major transport mode)?

a. I did not use train for the last public transport trip
b. Take a bus
c. Take a tram
d. Drive a car
e. Get a lift (car passenger)
f. Use a taxi/uber
g. Cycle
h. Walk
i. Cancel the trip
j. Other
Please specify …………………………

41. If <u>only the tram system</u> was no longer available for the day of your last public transport trip. How would you travel to your destination for that trip (choose only one major transport mode)?

a. I did not use tram for the last public transport trip
b. Take a train
c. Take a bus
d. Drive a car
e. Get a lift (car passenger)
f. Use a taxi/uber
g. Cycle
h. Walk
i. Cancel the trip

j. Other
Please specify ………………………….

42. If <u>only the bus system</u> was no longer available for the day of your last public transport trip. How would you travel to your destination for that trip (choose only one major transport mode)?

a. I did not use bus for the last public transport trip
b. Take a train
c. Take a tram
d. Drive a car
e. Get a lift (car passenger)
f. Use a taxi/uber
g. Cycle
h. Walk
i. Cancel the trip
j. Other
Please specify ………………………….

43. If the <u>entire public transport</u> was <u>no longer</u> available for the <u>next ten years,</u> how would you have travelled for your last trip (choose only one option)?

a. Drive a car
b. Car passenger
c. Get a taxi/uber
d. Carpool
e. Cycle
f. Walk
g. Cancel the trip
h. Change job location
i. Change place of residence
j. Work at home
k. Other
Please specify ………………………….

PERSONAL INFORMATION

44. Can you please indicate which of the following best describes your current employment status?

a. Full-time Work
b. Part-time Work
c. Casual Work
d. Study (TAFE/Uni)
e. Other Education
f. Keeping House
g. Unemployed
h. Retired
i. Other

45. Which of the following best describes your personal income before tax (including wages/salaries, government benefits, pensions, allowances and other income)?

a. $2,000 or more per week ($104,000 or more per year)
b. $1,600 - $1,999 per week ($83,200 - $103,999 per year)
c. $1,300 - $1599 per week ($67,600 - $83,199 per year)
d. $1,000 - $1,299 per week ($52,000 - $67,599 per year)

e. $600 - $999 per week ($31,200 - $51,999 per year)
f. $250 - $599 per week ($13,000 - $31,199 per year)
g. $1- $249 per week ($1 - $12,999 per year)
h. Nil income

46. Do you have any comments about public transport system in your area?

……
……
……………………………………………………………………………………………

Thank you for your time on the survey!

REFERENCES

Abkowitz, M. D. 1981. An analysis of the commuter departure time decision. *Transportation,* 10(3), 283-297.
ABS 2016. *Regional Population Growth, Australia, 2014-15*. Australian Bureau of Statistics, Australia.
Adler, M. & Van Ommeren, J. N. 2015. Does public transit reduce car travel externalities? *Tinbergen Institute Discussion Paper 15-011/VIII.*
Aftabuzzaman, M., Currie, G. & Sarvi, M. 2010a. Evaluating the congestion relief impacts of public transport in monetary terms. *Journal of Public Transportation,* 13(1), 1-23.
Aftabuzzaman, M., Currie, G. & Sarvi, M. 2010b. Modeling the spatial impacts of public transport on traffic congestion relief in Melbourne, Australia. *Transportation Research Record: Journal of the Transportation Research Board,* 2144(1), 1-10.
Akçelik, R. 1991. Travel Time Functions for Transport Planning Purposes: Davidson's Function, its Time-Dependent Form and an Alternative Travel Time Function. *Australian Road Research,* 21(3), 49-59.
Anderson, M. L. 2013. *Subways, strikes, and slowdowns: The impacts of public transit on traffic congestion*. University of California, Berkeley, United States.
Andrews, D. 2014. *Project 10,000*. Victorian Labor Government, Australia.
APTA 2007. *Public transportation: Benefits for the 21st century*. American Public Transportation Association, United States.
ATC 2006. *National guidelines for transport system management in Australia*. Australian Transport Council (ATC), Canberra, Australia.
Bailey, L., Mokhtarian, P. L. & Little, A. 2008. *The broader connection between public transportation, energy conservation and greenhouse gas reduction*. ICF International Fairfax, VA, United States.
Barker, W. & Polzin, S. 2004. Synergies of bus rapid transit and high-occupancy toll lanes: Simulation of bus rapid transit in congested corridor with roadway value pricing. *Transportation Research Record: Journal of the Transportation Research Board,* 1884, 3-9.
Beecroft, M. & Pangbourne, K. 2015. Personal security in travel by public transport: the role of traveller information and associated technologies. *IET intelligent transport systems,* 9(2), 167-174.
Beimborn, E., Horowitz, A., Schuetz, J. & Zejun, G. 1993. *Measurement of transit benefits*. University of Wisconsin, Milwaukee, United States.
Beirao, G. & Cabral, J. A. S. 2007. Understanding attitudes towards public transport and private car: A qualitative study. *Transport Policy,* 14(6), 478-489.
Ben-Edigbe, J. & Mashros, N. 2011. Determining impact of bus-stops on roadway capacity. *Proceedings of the Irish Transport Research Network, Aug*, 1-7.
Bergström, A. & Magnusson, R. 2003. Potential of transferring car trips to bicycle during winter. *Transportation Research Part A,* 37(1), 649–666.
Black, A. 1995. *Urban mass transportation planning,* McGraw-Hill, Incorporated, United States.
Cabinet Office Strategy Unit 2009. *The wider costs of transport in English urban areas in 2009*. Cabinet Office, London, UK.
Cairns, S., Hass-Klau, C. & Goodwin, P. 1998. *Traffic impact of highway capacity reductions: assessment of the evidence,* London, UK.
Calderdale Council 2015. *Tackling traffic congestion and pollution*. Calderdale Council, UK.
Carse, A., Goodman, A., Mackett, R. L., Panter, J. & Ogilvie, D. 2013. The factors influencing car use in a cycle‐friendly city: the case of Cambridge. *Journal of Transport Geography,* 28(1),67-74.

Castelazo, M. D. & Garrett, T. A. 2004. Light rail: boon or boondoggle? *The Regional Economist,* Jul, 12-13.

Cervero, R. 1991. Conjestion Relief: The Land Use Alternative. *Journal of Planning Education and Research,* 10(2), 119-129.

Cervero, R. 1998. *The transit metropolis: a global inquiry,* Islandpress, United States.

Cervero, R. 2002. Built environments and mode choice: toward a normative framework. *Transportation Research Part D: Transport and Environment,* 7(4), 265-284.

Chand, S., Chandra, S. & Dhamaniya, A. 2014. Capacity drop of urban arterial due to a curbside bus stop. *International Conference on Sustainable Civil Infrastructure.* Civil Engineering Department IIT Hyderabad, India.

Chandler, C. & Hoel, L. A. 2004. *Effects of light rail transit on traffic congestion*. Center for Transportation Studies, University of Virginia, United States.

Chen, X., Yu, L., Zhu, L., Guo, J. & Sun, M. 2010. Microscopic traffic simulation approach to the capacity impact analysis of weaving sections for the exclusive bus lanes on an urban expressway. *Journal of Transportation Engineering,* 136(10), 895-902.

Cherry, C., Tang, E., Deakin, E. & Skabardonis, A. 2005. High-occupancy vehicle systems: Analysis of freeway improvements for express bus service. *Transportation Research Record: Journal of the Transportation Research Board,* 1925(1), 256-264.

Cosgrove, D. & Gargett, D. 2007. *Estimating urban traffic and congestion cost trends for Australian cities,* Bureau of Transport and Regional Economics, Australia.

Crain, J. L. & Flynn, S. D. 1975a. *Southern California rapid transit district 1974 strike impact study*. California Department of Transportation, United States.

Crain, J. L. & Flynn, S. D. 1975b. *Southern California rapid transit district 1974 strike impact study*, United States.

Currie, G. 2006. Bus rapid transit in Australasia: Performance, lessons learned and futures. *Journal of Public Transportation,* 9(3), 1-22.

Currie, G. & Burke, M. 2013. Light Rail in Australia – Performance and Prospects. *Australasian Transport Research Forum*, Brisbane, Australia.

Currie, G. & Loader, C. 2010. Bus network planning for transfers and the network effect in Melbourne, Australia. *Transportation Research Record: Journal of the Transportation Research Board,* 2145(2), 8-17.

Currie, G., Sarvi, M. & Young, B. 2007. A new approach to evaluating on-road public transport priority projects: balancing the demand for limited road-space. *Transportation,* 34(4), 413-428.

Currie, G. & Shalaby, A. S. 2007. Success and Challenges in Modernizing Streetcar Systems: Experiences in Melbourne, Australia, and Toronto, Canada. *Journal of the Transportation Research Board,* 2006(4), 31-39.

Currie, G. & Smith, P. 2006. Innovative Design for Safe and Accessible Light Rail or Tram Stops Suitable for Streetcar-Style Conditions. *Transportation Research Record,* 2219(1), 20-29.

Dargay, J. M. 2001. The effect of income on car ownership: evidence of asymmetry. *Transportation Research Part A: Policy and Practice,* 35(9), 807-821.

Delbosc, A. & Currie, G. 2013. Exploring Attitudes of Young Adults toward Cars and Driver Licensing. *Australasian Transport Research Forum.* Brisbane, Australia.

Deng, T. & Nelson, J. D. 2011. Recent developments in bus rapid transit: a review of the literature. *Transport Reviews,* 31(1), 69-96.

Department of Transport 2011. *Guidelines for VITM network coding*. Department of Transport, Transport Information, Modelling and Analysis group, Melbourne.

DOT 2014. *2013-14 Annual Report*. Department Of Transport, Planning And Local Infrastructure., Melbourne, Australia.

Douglas, N. 1993. Travel demand, economic growth and transport infrastructure in rapidly growing economies. *The Australian Transport Research Forum (ATRF)*, Queensland, Australia.

Dowling, R., Singh, R. & Cheng, W. 1998. Accuracy and performance of improved speed-flow curves. *Transportation Research Record: Journal of the Transportation Research Board,* 1646(2), 9-17.

Downs, A. 1992. *Stuck in traffic: Coping with peak-hour traffic congestion,* Brookings Institution, WD, United States.

Downs, A. 2004. Still stuck in traffic: coping with peak-hour congestion. *The Brookings Institution, Washington, DC*, United States.

Downs, A. 2005. *Still stuck in traffic: coping with peak-hour traffic congestion,* Brookings Institution, United States.

ECMT 2007. *Managing urban traffic congestion*. European conference of ministers of transport, OECD Publishing, Paris, France.

Ewing, R., Schroeer, W. & Greene, W. 2004. School Location and Student Travel: Analysis of Factors Affecting Mode Choice. *Transportation Research Record: Journal of the Transportation Research Board,* 1895(1),55-63.

Exel, N. J. A. v. & Rietveld, P. 2001. Public transport strikes and traveller behaviour. *Transport Policy,* 8(4), 237-246.

Exel, N. J. A. V. & Rietveld, P. 2009a. Could you also have made this trip by another mode? An investigation of perceived travel possibilities of car and train travellers on the main travel corridors to the city of Amsterdam, The Netherlands. *Transportation Research Part A,* 43(1),374–385.

Exel, N. J. A. v. & Rietveld, P. 2009b. When strike comes to town… anticipated and actual behavioural reactions to a one-day, pre-announced, complete rail strike in the Netherlands. *Transportation Research Part A: Policy and Practice,* 43(5), 526–535.

Exel, N. J. A. v. & Rietveld, P. 2009c. When strike comes to town… anticipated and actual behavioural reactions to a one-day, pre-announced, complete rail strike in the Netherlands. *Transportation Research Part A: Policy and Practice,* 43(5), 526–535.

Falcocchio, J. C. & Levinson, H. S. 2015. *Road traffic congestion: A concise guide,* Roger P. Roess, New York University Polytechnic School of Engineering, New York, United States.

FHWA 2002. *Conditions and Performance Report,*. U.S. Department of Transportation, Federal Highway Administration (FHWA), United States.

Fitzpatrick, K., Hall, K., Perkinson, D., Nowlin, L. & Koppa, R. 1996. *TCRP Report 19: Guidelines for the location and design of bus stops*. Transportation Research Board of the National Academies, Washington, DC, United States.

Fitzpatrick, K. & Nowlin, R. 1997. Effects of bus stop design on suburban arterial operations. *Transportation Research Record: Journal of the Transportation Research Board,* 1571(5), 31-41.

Frank, L., Bradley, M., Kavage, S., Chapman, J. & Lawton, T. K. 2008. Urban form, travel time, and cost relationships with tour complexity and mode choice. *Transportation,* 35(1), 37-54.

FTA 2000. *Transit Benefits Working Papers: A Public Choice Policy Analysis*. Federal Transit Administration, Washington, D.C., United States.

Gardner, B. & Abraham, C. 2007. What drives car use? A grounded theory analysis of commuters' reasons for driving. *Transportation Research Part F: Traffic Psychology and Behaviour,* 10(3), 187-200.

Garnaut, R. 2012. Transforming Transport. *The Garnaut climate change review.* Australia.

Gillen, D. W. 1977. Estimation and specification of the effects of parking costs on urban transport mode choice. *Journal of Urban Economics,* 4(2), 186-199.

Glaser, B. & Strauss, A. 1967. *The discovery of grounded theory,* Aldine Transaction, UK.

Golob, T. F. 1990. The dynamics of household travel time expenditures and car ownership decisions. *Transportation Research Part A: General,* 24(6), 443-463.

Gray, G. E. 1992. Perceptions of public transportation. *In:* 2nd (ed.) *Public transportation.* Prentice Hall, Englewood Cliffs, New Jersey, United States.

Gu, W., Cassidy, M. J., Gayah, V. V. & Ouyang, Y. 2013. Mitigating negative impacts of near-side bus stops on cars. *Transportation Research Part B: Methodological,* 47(1), 42-56.

Guiver, J. W. 2007. Modal talk: discourse analysis of how people talk about bus and car travel. *Transportation Research Part A: Policy and Practice,* 41(3), 233-248.

Hagman, O. 2003. Mobilizing meanings of mobility: car users' constructions of the goods and bads of car use. *Transportation Research Part D: Transport and Environment,* 8(1), 1-9.

Hakkert, A. S. & Gitelman, V. 1997. Development of evaluation tools for road-rail crossing consideration for grade separation. *Transportation Research Record,* 1605(1), 96-105.

Hall, R. & Vyas, N. 2000. Buses as a traffic probe: Demonstration project. *Transportation Research Record: Journal of the Transportation Research Board,* 1731(12), 96-103.

Hensher, D. A. & Reyes, A. J. 2000. Trip chaining as a barrier to the propensity to use public transport. *Transportation,* 27(4), 341-361.

Hess, D. 2001. Effect of free parking on commuter mode choice: Evidence from travel diary data. *Transportation Research Record: Journal of the Transportation Research Board,* 1753), 35-42.

Homburger, W. S., Hall, J. W., Loutzenheiser, R. C. & Reilly, W. R. 1996. *Fundamentals of traffic engineering*. University of California, Berkeley, United States.

Johansson, M. V., Heldt, T. & Johansson, P. 2006. between trafssThe effects of attitudes and personality traits on mode choice. *Transportation Research Part A: Policy and Practice,* 40(6), 507-525.

Johnson, R. B., Onwuegbuzie, A. J. & Turner, L. A. 2007. Toward a definition of mixed methods research. *Journal of mixed methods research,* 1(2), 112-133.

Kim, S. & Ulfarsson, G. 2004. Travel mode choice of the elderly: effects of personal, household, neighborhood, and trip characteristics. *Transportation Research Record: Journal of the Transportation Research Board,* 1894), 117-126.

Kittelson 2003. *TCRP Report 100: Transit Capacity and Quality of Service Manual*. National Research Council, Washington, D.C, United States.

Kockelman, K. M. & Kalmanje, S. 2005. Credit-based congestion pricing: a policy proposal and the public's response. *Transportation Research Part A: Policy and Practice,* 39(7), 671-690.

Koshy, R. Z. & Arasan, V. T. 2005. Influence of Bus stops on flow characteristics of Mixed traffic. *Journal of Transportation Engineering,* 13(8), 640-643.

Kothari, C. R. 2004. *Research methodology: Methods and techniques,* New Age International.

Kwami, A. V., Kuan, Y. X. & Zhi, X. 2009. Effect of Bus Bays on Capacity of Curb Lanes. *Journal of American Science,* 5(2), 107-118.

Lane, B. W. 2008. Significant characteristics of the urban rail renaissance in the United States: A discriminant analysis. *Transportation Research Part A: Policy and Practice,* 42(2), 279-295.

Larwin, T. F. 1999. Urban transit. *In:* 2nd (ed.) *Transportation planning handbook.* Institute of Transportation Engineers, Washington, D.C, United States.

Lee, Y. J. & Vuchic, V. R. 2005. Transit network design with variable demand. *Journal of Transportation Engineering,* 131(1), 1-10.

Levinson, H. S. & Lomax, T. J. 1996. Developing a travel time congestion index. *Transportation Research Record: Journal of the Transportation Research Board,* 1564(1), 1-10.

Lewis, D. & Williams, F. L. 1999. *Policy and planning as public choice: Mass transit in the United States,* Citeseer, United States.

Limtanakool, N., Dijst, M. & Schwanen, T. 2006. The influence of socioeconomic characteristics, land use and travel time considerations on mode choice for medium-and longer-distance trips. *Journal of Transport Geography,* 14(5), 327-341.

Lindley, J. A. 1987. Urban freeway congestion: quantification of the problem and effectiveness of potential solutions. *ITE journal,* 57(1), 27-32.

Litman, T. 2000. Transportation market reforms for sustainability. *Transportation Research Record: Journal of the Transportation Research Board,* 1702(1), 11-20.

Litman, T. 2003. *Transportation cost and benefit analysis guidebook—Congestion costs*. Victoria Transport Policy Institute, Victoria, Bristish Columbia, Canada

Litman, T. 2004a. *Evaluating rail transit criticism,* Victoria Transport Policy Institute, Victoria, British Columbia, Canada.

Litman, T. 2004b. *Rail transit in America: a comprehensive evaluation of benefits*. Victoria Transport Policy Institute, Victoria, British Columbia, Canada. .

Litman, T. 2007. Evaluating rail transit benefits: A comment. *Transport Policy,* 14(1), 94-97.

Litman, T. 2015. *Evaluating public transit benefits and costs*. Victoria Transport Policy Institute, Victoria, British Columbia, Canada. .

Lo, S. C. & Hall, R. W. 2006. Effects of the Los Angeles transit strike on highway congestion. *Transportation Research Part A,* 40(10), 903–917.

Lomax, T., Schrank, D. & Eisele, W. 1999. *The keys to estimating mobility in urban areas, applying definitions and measures that everyone understands*. Texas Transportation Institute, The Texas A&M University System, College Station, Texas, United States.

Lomax, T., Turner, S., Shunk, G., Levinson, H., Pratt, R., Bay, P. & Douglas, G. 1997. *NCHRP Report 398: Quantifying congestion. Volume 1: Final report*. National Research Council, Washington DC, United States.

Lomax, T. J. 1997. *Quantifying congestion,* Transportation Research Board, Washington DC, United States.

Lomax, T. J. & Schrank, D. L. 2005. *The 2005 urban mobility report*. Texas Transportation Institute, Texas, United States.

Mackett, R. L. & Edwards, M. 1998. The impact of new urban public transport systems: will the expectations be met? *Transportation Research Part A: Policy and Practice,* 32(4), 231-245.

Maitra, B., Sikdar, P. K. & Dhingra, S. L. 1999. Modeling congestion on urban roads and assessing level of service. *Journal of transportation engineering,* 125(1), 508-514.

Mann, E. & Abraham, C. 2006. The role of affect in UK commuters' travel mode choices: An interpretative phenomenological analysis. *British Journal of Psychology,* 97(2), 155-176.

McCollom, B. E. & Pratt, R. H. 2004. *Traveler Response to Transportation System Changes. Chapter 12-Transit Pricing and Fares,* Transportation Research Board, Washington, DC, United States

McConville, Megan, Rodríguez, A., D., Clifton, J, K., Cho, Gihyoug & Sheila, F. 2011. Disaggregate Land Uses and Walking. *American Journal of Preventive Medicine,* 40(1), 25-32.

McFadden, D. 1976. *Properties of the multinomial logit (MNL) model,* Urban Travel Demand Forecasting Project, Institute of Transportation Studies, United States.

McFadden, D. 1980. Econometric models for probabilistic choice among products. *Journal of Business,* 53(3), 13-29.

McFadden, D. & Reid, F. 1975. Aggregate travel demand forecasting from disaggregated behavioral models. *Transportation Research Record,* 534(1), 24-37.

Meyer, M. D. 1997. *A toolbox for alleviating traffic congestion and enhancing mobility,* Institute of Transportation Engineers, Washington D.C, United States.

Mogridge, M. J. 1990. Travel in towns. Palgrave Macmillan, United States.

Moylan, E., Foti, F. & Skabardonis, A. 2016. Observed and simulated traffic impacts from the 2013 Bay Area Rapid Transit strike. *Transportation Planning and Technology,* 39(2), 162-179.

Müller, S., Tscharaktschiew, S. & Haase, K. 2008. Travel-to-school mode choice modelling and patterns of school choice in urban areas. *Journal of Transport Geography,* 16(5), 342-357.

Mulley, C., Nelson, J. D. & Anderson, J. 2008. No car lanes or bus lanes: which gives public transport the better priority? An evaluation of priority lanes in Tyne and Wear. *40th UTSG Annual Conference*.

Naudé, C. & Tsolakis, D. 2005. *Defining transport congestion*. Melbourne, Victoria, Australia.

Nelson, J., Brookes, D. W. & Bell, M. G. 1993. Approaches to the provision of priority for public transport at traffic signals: a European perspective. *Traffic engineering & control,* 34(9).

Nelson, P., Baglino, A., Harrington, W., Safirova, E. & Lipman, A. 2007. Transit in Washington, DC: Current benefits and optimal level of provision. *Journal of urban Economics,* 62(2), 231-251.

New York City Transit Authority 1967. *The Effect of the 1966 New York City Transit Strike on the Travel Behavior of Regular Transit Users*. Department of Housing and Urban Development, New York, United States.

Nielsen, G., Nelson, J., Mulley, C., Tegner, G., Lind, G. & Lange, T. 2005. Public transport–planning the networks. HiTrans, Hestholms Trykkeri AS, Skytta, Norway.

Okitsu, W. & Lo, K. 2010. Simulation-free railroad grade crossing delay calculations. *Western ITE Annual Meeting.* San Francisco, United States.

Papangelis, K., Velaga, N. R., Ashmore, F., Sripada, S., Nelson, J. D. & Beecroft, M. 2016. Exploring the rural passenger experience, information needs and decision making during public transport disruption. *Research in Transportation Business & Management,* 18(57-69.

Parkany, E. 1999. Can high-occupancy/toll lanes encourage carpooling? Case study of carpooling behavior on the 91 express lanes. *Transportation Research Record: Journal of the Transportation Research Board,* 1682(6), 46-54.

Parry, I. W. H. 2002. Comparing the efficiency of alternative policies for reducing traffic congestion. *Journal of public economics,* 85(3), 333-362.

Parry, I. W. H. & Small, K. A. 2009. Should urban transit subsidies be reduced? *American Economic Review,* 3(1), 700–724.

Patankar, V. M., Kumar, R. & Tiwari, G. 2007. Impacts of bus rapid transit lanes on traffic and commuter mobility. *Journal of urban planning and development,* 133(2), 99-106.

Pnevmatikou, A. M., Karlaftis, M. G. & Kepaptsoglou, K. 2015. Metro service disruptions: how do people choose to travel? *Transportation,* 42(6), 933-949.

Polzin, S. E. & Baltes, M. R. 2002. Bus rapid transit: A viable alternative? *Journal of public Transportation,* 5(2), 3.

Polzin, S. E., Chu, X. & Raman, V. S. 2008. *Exploration of a shift in household transportation spending from vehicles to public transportation*.

Powell, J. L. 1982. Effects of rail-highway grade crossings on highway users. *61st Annual Meeting of the Transportation Research Board* Washington DC, United States.

PTV 2015. *PTV VISSIM 8 user manual*. Karlsruhe, Germany.

Public Transport Victoria 2015a. Benefits of public transport. Public Transport Victoria, Melbourne, Australia.

Public Transport Victoria 2015b. Facts & Figures. Public Transport Victoria, Melbourne, Australia.

Public Transport Victoria 2016. *Annual Report 2015-16*. Public Transport Victoria, Melbourne, Australia.

Pucher, J., Altshuler, A. & Womack, J. 1979. The urban transportation system: politics and policy innovation. Cambridge MA MIT Press, UK.

Pushkarev, B. & Zupan, J. M. 1977. *Public transportation and land use policy,* Indiana University Press, United States.

Quiroga, C. A. 2000. Performance measures and data requirements for congestion management systems. *Transportation Research Part C: Emerging Technologies,* 8(1), 287-306.

Rajbhandari, R., Chien, S. & Daniel, J. 2003. Estimation of bus dwell times with automatic passenger counter information. *Transportation Research Record: Journal of the Transportation Research Board,* 1841(13), 120-127.

Reed, G. F., Lynn, F. & Meade, B. D. 2002. Use of coefficient of variation in assessing variability of quantitative assays. *Clinical and diagnostic laboratory immunology,* 9(6), 1235-1239.

Rosenbloom, S. 1978. Peak-period traffic congestion: A state-of-the-art analysis and evaluation of effective solutions. *Transportation,* 7(2), 167-191.

Rothenberg, M. J. 1985. *Urban Congestion in the United States: What Does the Future Hold?* Institute of Transportation Engineers, Washington DC, United States.

Rubin, T. A. & Mansour, F. 2013. *Transit utilization and traffic congestion: Is there a connection?* Reason Foundation, Los Angeles, United States.

Rymer, B., Urbanik II, T. & Cline Jr, J. C. 1989. Delay at light rail transit grade crossings. *Transportation Research Board,* 221(1), 621-634.

Sabir, M., Koetse, M. J. & Rietveld, P. 2008. The impact of weather conditions on mode choice: empirical evidence for the Netherlands. *Department of Spatial Economics, VU University, Amsterdam, Netherlands*.

Sandelowski, M. 2001. Real qualitative researchers do not count: The use of numbers in qualitative research. *Research in Nursing & Health,* 24(3), 230-240.

Saneinejad, S., Roorda, M. J. & Kennedy, C. 2012. Modelling the impact of weather conditions on active transportation travel behaviour. *Transportation Research Part D: Transport and Environment,* 17(2), 129-137.

Schrader, M. H. & Hoffpauer, J. R. 2001. Methodology for evaluating highway–Railway grade separations. *Transportation Research Record: Journal of the Transport Research Board* 1754(9), 77-80.

Schrank, D., Eisele, B. & Lomax, T. 2012. *TTI's 2012 Urban mobility report*. Texas A&M Transportation Institute, United States.

Schrank, D. & Lomax, T. 2009. *The 2009 urban mobility report*. Texas Transportation Institute, The Texas A&M University, United States.

Schuman, R. 2011. *INRIX national traffic scorecard: 2010 annual report*. Technical report, INRIX, Kirkland, WA, United States.

SEMCOG 2011. Congestion Management Process (CMP) Plan for Southeast Michigan. Southeast Michigan Council of Governments, Michigan, United States.

Shalaby, A. S. 1999. Simulating performance impacts of bus lanes and supporting measures. *Journal of transportation engineering,* 125(5), 390-397.

Simons, D., Clarys, P., De Bourdeaudhuij, I., de Geus, B., Vandelanotte, C. & Deforche, B. 2013. Factors influencing mode of transport in older adolescents: a qualitative study. *BMC Public Health,* 13(1), 323.

Sun, Z. 2011. Simulation of vehicle traffic flow on the block with the impact of buses' stopping. *Seventh international conference on natural computation*. IEEE, 2256-2259.

Systematics, C. 2008. *NCHRP report 168: Cost-effective performance measures for travel time delay, variations, and reliability*. Dowling associates, System Metrics Group, and Texas Transportation Institute, United States.

Taggart, R. C., P. Lauria, G. Groat, C. Rees & Brick-Turin, A. 1987a. NCHRP Report 288: Evaluating grade-separated rail and highway crossing alternatives. Transportation Research Board, NRC, Washington D.C, United States.

Taggart, R. C., P. Lauria, G. Groat, C. Rees & Brick-Turin, A. 1987b. NCHRP Report 288:

Evaluating Grade-Separated Rail and Highway Crossing Alternatives. . Transportation Research Board, NRC, Washington, D.C., United States.

Tang, T. Q., Li, Y. & Huang, H. J. 2009. The effects of bus stop on traffic flow. *International Journal of Modern Physics C,* 20(06), 941-952.

Tettamanti, T. & Horváth, M. T. 2015. A practical manual for Vissim COM programming in Matlab. Dept. for Control of Transportation and Vehicle Systems, Budapest University of Technology and Economics.

Thomson, J. 1968. The value of traffic management. *Journal of Transport Economics and Policy*, 3-32.

Tortore, M. 2011. *Sustainable Systems and Energy Management at the Regional Level: Comparative Approaches,* Information Science Reference, United States.

Transport Research Center 2007. Managing Urban Traffic Congestion. Paris, France.

TTF 2010. *The Benefits of Public Transport*. Tourism & Transport Forum (TTF), United States.

Vaziri, M. 2002. Development of highway congestion index with fuzzy set models. *Transportation Research Record: Journal of the Transportation Research Board,* 1802(3), 16-22.

Verhoef, E. T. 2000. The implementation of marginal external cost pricing in road transport. *Papers in Regional Science,* 79(3), 307-332.

VicRoads 2005. Austroads Metropolitan Network Performance Database. Melbourne, Australia.

VicRoads 2010. *Nunawading Stringvale road rail separation impact study*. VicRoads, Melbourne, Australia.

VicRoads 2014. *Strategic Framework For The Prioritisation Of Level Crossings In Metropolitan Melbourne*. Melbourne, Australia.

Victorian Government 2013. *Victorian Integrated Survey of Travel and Activity 2012-13*. State Government of Victoria, Melbourne, Australia.

Voith, R. 1998. Parking, transit, and employment in a central business district. *Journal of Urban Economics,* 44(1), 43-58.

Vuchic, V., Lee, Y. J. & Shin, Y. 1998. Travel costs and intermodal distribution in urban transportation. *Transportation Research Record: Journal of the Transportation Research Board,* 1649(1), 105-112.

Vuchic, V. R. 1999. *Transportation for Livable Cities,* Rutgers Center for Urban Policy Research, New Brunswick, N.J, United States.

Vuchic, V. R. 2005. *Urban transit: operations, planning, and economics,* John Wiley & Sons, Hoboken, New Jersey, United States.

Vuchic, V. R. 2007. *Urban transit systems and technology,* John Wiley & Sons, Hoboken, New Jersey, United States.

WDOT 2003. *The socio-economic benefits of transist in Wisconsin*. Wisconsin Department of Transportation Research, Development & Technology Transfer, United States.

Weisbrod, G., Vary, D. & Treyz, G. 2001. *Economic implications of congestion*. Transportation Research Board — National Research Council, Washington D.C, United States.

Weisbrod, G., Vary, D. & Treyz, G. 2003. Measuring economic costs of urban traffic congestion to business. *Transportation Research Record: Journal of the Transportation Research Board,* 1839(1), 98-106.

Wilson, R. W. 1992. Estimating the travel and parking demand effects of employer-paid parking. *Regional Science and Urban Economics,* 22(1), 133-145.

WSDT 2011. *The 2011 Congestion Report*. Washington State Department of Transportation.

Xia, Y. X. & Xue, Y. 2010. Analysis of the Effect of Bay-bus-stop on Traffic Flow in One-direction Two Road by the Continuum Model. *Artificial Intelligence and Computational Intelligence (AICI), 2010 International Conference on*. IEEE, 19-22.

Yang, X., Gao, Z., Si, B. & Gao, L. 2011. Car capacity near bus stops with mixed traffic derived by additive-conflict-flows procedure. *Science China Technological Sciences,* 54(3), 733-

740.
Yarra Trams 2015. Facts & figures. Melbourne, Australia.
Yong-Sheng, Q., Pei-Ji, S., Qiong, Z., Chang-Xi, M., Fang, L., Peng, S. & Hai-Long, W. 2010. A study on the effects of the transit parking time on traffic flow based on cellular automata theory. *Chinese Physics B,* 19(4), 048201.
Yuan, Y. M., Jiang, R., Wu, Q. S. & Wang, R. 2007. Traffic behavior in a two-lane system consisting of a mixture of buses and cars. *International Journal of Modern Physics C,* 18(12), 1925-1938.
Zhao, X. M., Gao, Z. Y. & Jia, B. 2007. The capacity drop caused by the combined effect of the intersection and the bus stop in a CA model. *Physica A: Statistical mechanics and its applications,* 385(2), 645-658.