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Modelling the Net Traffic Congestion Impact of Street Car Networks – A Melbourne, Australia Case Study

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Abstract

Streetcars (trams) operating with other public transport modes such as train and bus has contributed to reduce urban traffic congestion in many cities around the world, particularly in inner cities. However, there has been no attempt to examine the net network-wide impacts of streetcar networks on vehicular traffic and congestion. This paper presents a new method for assessing the net traffic congestion effects associated with tram operations in Melbourne, Australia. These impacts are determined by comparing congestion measures in two scenarios: “with tram” and “without tram”. To investigate the positive impact of trams, it is assumed that there is a mode shift to car from trams when tram operations are removed. The congestion level increase caused by this mode shift is interpreted as the positive effect of trams. In contrast, the negative impacts of trams are explored by considering the curbside tram stop impact and the effect of reallocation of priority tram lanes on traffic flow. Findings show that the tram network in inner Melbourne results in a net 3.4% decrease in vehicle time travelled and total delay on the road network in these areas. It also contributes to reduce the number of moderately congested links by 16%. However, the impact of trams in the middle metropolitan areas is not significant due to the low density of tram routes in these areas. Areas for future research are suggested such as exploring the spatial distribution of the share of mode shift to car and the long-term effect of trams on traffic.

1. Introduction

Urban transport plays an important role in almost all cities around the world because it provides access for people 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 inner cities. The level of congestion in these areas is also increasing because of a rise in population, economy, urbanisation, and suburbanisation of population, housing, and jobs (ECMT, 2007). There has been some attempts to improve or create new rail-based transit systems in order to reduce traffic congestion (Bhattacharjee and Goetz, 2012). Indeed, light rail transit is considered an effective solution to deal with this problem (Vuchic, 1999). Light rail systems can be found in a variety of land use contexts, from suburbs to high-density central business district (CBD) areas, and can be operated under different right-of-way types (Chandler and Hoel, 2004). 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. A reduction of more than 3.3 million car trips was achieved following the introduction of Greater Manchester’s Metrolink light rail system in 1992. The switch from car to light rail reduced car traffic by 10% during peak hours along the Bury corridor (Knowles, 1996). The Northern Suburbs Transit System of Perth reduced car traffic by approximately 25% (Newman, 1995). However, the operation of 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 directly along public streets without any separation have to share the street with vehicle traffic and pedestrians. 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 (Currie and Smith, 2006). This results in delays to vehicle traffic and these problems become more serious when the frequency of trams and traffic volumes increase. On the other hand, trams with priority can 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 increases tram speed and reliability (Currie et al., 2007); however it also reduces the capacity of the road and increases the level of congestion (Kittelson et al., 2003).

Melbourne has the largest operating light rail system as well as the largest streetcar system in the world (Currie and Smith, 2006). It carries a total of around 177 million passenger trips each year (Yarra Trams, 2015). However, with around 180 kilometres of tram tracks located in mixed traffic 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. A key concern for planners is the effects which tram operations have on traffic in terms of congestion and how this varies in different parts of the city.

This paper explores the net network-wide congestion relief impact caused by the operation of trams in Melbourne. 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.

The paper is structured as follows: the next section outlines previous studies in relation to the assessment of tram effects on traffic congestion. 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

There have been few studies that have attempted to assess the tram impacts on traffic congestion. 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 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 shares road space with congested urban traffic (Vuchic, 2007). However, the reallocation of a proportion of road space reduces road capacity and can increase the level of traffic congestion (Kittelson et al., 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 14-25%. Thus, the displaced traffic resulted in less congestion than expected. 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).

It can be seen that almost all previous studies focused on the negative impacts of tram operations on a road link or a corridor. In terms of the network-wide effect, there have been very few attempts to estimate the positive impact of tram operations on reducing traffic congestion on the road network. Bhattacharjee and Goetz (2012) analysed the level of traffic on highways in the study area before and after the opening the light rail corridors in Denver.

In this study, Vehicle Miles Travelled (VMT) data collected from field surveys from 1992 to 2008 was 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. This research required field data to be collected across many years in various areas. Due to this reason the light rail was only assessed on the highway network not all roads.

Another study using computer models to simulate and assess the congestion relief impact of trams on the entire road network was conducted by Aftabuzzaman et al. (2010b). The research assumed that there was a tram user diversion to cars when the tram system was removed. From secondary research, they suggested that on average 32% of PT users would shift to car. 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 as the amount of congestion saved by tram operations. They found that in inner Melbourne tram operations contribute to reduce congested links by approximately 28% and travel delay by 66%.

Gaps in knowledge

There has been only one study to examine the network-wide effect of trams on reducing traffic congestion with the help of simulation modelling (Aftabuzzaman et al., 2010b). In this study, the car mode shift share was determined by using secondary data in relation to <u>entire PT users, not specifically tram users</u>. Additionally, this study only estimated the positive impact of tram operations and <u>did not consider the negative effect</u> of trams such as traffic delay caused by curbside tram stops, low tram speeds and the allocation of priority tram lanes.

The paper is the first to provide a new methodology 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 car when trams are removed was adopted. A primary survey determining the car mode shift share from Melbourne's tram users was conducted in September 2015. The negative impact of trams was represented using traffic microsimulation modelling.

3. Research context

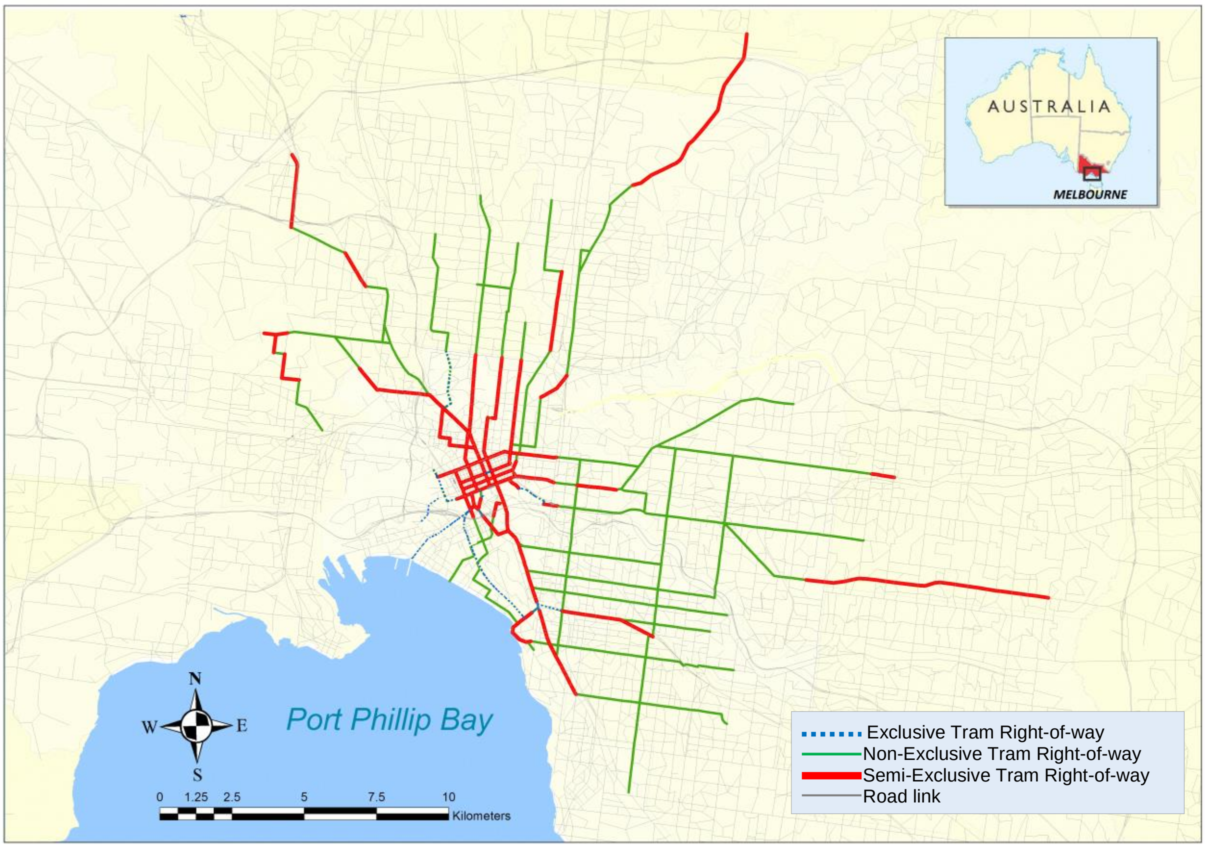
3.1. Melbourne's tram network

Trams are a major form of public transport in Melbourne, Australia. The tram network consists of 250 kilometres of tram track, 493 trams operating across 25 routes, and 1,763 tram stops (Yarra Trams, 2015). It is the largest urban tramway network in the world. Trams are the second most used form of public transport in Melbourne after the commuter railway network, with a total of 182.7 million passenger trips in 2012-13 (Yarra Trams, 2015). Although tram transit has several drawbacks such as unreliability, poor running speeds and safety issues, total tram ridership has still increased by 46% between 2001-2 and 2011-12 while the total public transport (all mode) ridership only increased by 9% (Delbosc and Currie, 2013).

Melbourne's tram system operates mainly on three types of right-of-way: semi-exclusive, non-exclusive and exclusive right-of-way (see Figure 1). On non-exclusive rights of way (on-street running), trams operate with vehicle traffic in the centre of the road. Pedestrians must walk from a curb to stops in the centre of a road, usually without protected crossing points. The mixed track arrangement (167 km) accounts for 67% of total tram tracks in Melbourne. There are approximately 1,200 curbside stops out of 1,780 tram stops (67%) and most of them are located on-street (Currie and Shalaby, 2007). Curbside stops are a major feature of on-street running services due to their impacts on the efficient use of road space. During each boarding and alighting, all road traffic behind trams must stop. Thus, it is clear that tram operations at curbside stops result in delays for vehicle traffic. Furthermore, the relatively short spacing between Melbourne's tram stops (approximately 270m) contributes to a reduction in tram operating speeds because of acceleration, deceleration and stop dwell time (Currie and Shalaby, 2007).

On semi-exclusive 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 semi-exclusive tram rights-of-way are located in the inner city where traffic congestion is generally more severe. Trams running on exclusive rights-of-way are not affected by road traffic because this type of tramway is constructed separately to the road network.

Figure 1 Melbourne's tram network



3.2. Spatial unit of analysis

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

4. Study methodology

The purpose of this section is to describe a new methodology that has been developed to estimate the net traffic congestion impact of tram operations on the entire road network. In the first subsection, the Victoria Integrated Transport Model (VITM) is described. The method including several steps for assessing the net network-wide effect of trams on reducing traffic congestion is then presented in the following parts.

4.1. The Victoria Integrated Transport Model (VITM)

VITM (macro-modelling) is a conventional four-step model which is created 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. 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. 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.

4.2. Method for modelling the net impact of trams on traffic

In this section a modelling procedure was developed to understand the net effect of tram operations on relieving traffic congestion. The procedure adopts an assumption regarding tram user diversion to car, a micro-simulation and a four-step model to incorporate both positive and negative impacts of trams on traffic. The modelling analysis was carried out for the week day morning peak (7am-9am).

In this research, the decrease in the number of car trips due to tram operations is considered as the positive effect of tram operations. Thus, in order to assess this positive effect, it is assumed that there is a car mode shift share from trams if trams are removed. The number of tram users shifting to car in the case of tram removal is represented by the number of car users attracted by tram operations. The negative impact of trams in terms of their contribution to traffic congestion includes: (1) the effect of road capacity reduction due to the occupation of a semi-exclusive tram rights-of-way and (2) the impact of trams on vehicle traffic on a non-exclusive tram rights-of-way due to the sharing of road space. Table 1 illustrates the methods adopted for estimating the negative effect of each tram right-of-way type on generating traffic congestion.

Table 1 Methodology for assessing negative impacts of tram operations on vehicle traffic

Tram right-of-way	Have tram	No tram	Method for assessing direct tram effect
Exclusive	Tramway is constructed separately to road networks; does not have any effect on vehicle traffic.	Does not have any effect on vehicle traffic.	Not applicable
Non-Exclusive	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 operation on a specific link by using microsimulation. - Incorporate this result into a 4 step model. - Compare the outcome of the 4 step model in two scenarios: “with tram” and “without tram”.
Semi-Exclusive	Trams share crossroads with general traffic but tram tracks are separated from traffic lanes.	Priority tram lane is returned to general traffic. Capacity of road link increases.	- Increase one lane for vehicle traffic on road links with trams in “without tram” scenario. - Use 4-step model to compare congestion measures in two scenarios: “with tram” and “without tram”.

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 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 car trip matrix is added to the modified tram trip matrix (tram trip matrix multiplied by the car mode shift share) to obtain a modified car trip matrix. This new 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.

4.2.1. Primary survey for estimating the car mode shift share from trams

In September 2015, Public Transport Victoria (PTV) conducted an online survey of PT users in metropolitan Melbourne to understand the potential impact of PT cancellations. Participants were asked about the impact of tram operation removal and their likely change in travel behaviour. A total of 306 users completed the online survey in which 209 members (68%) responded that they often used trams for their journeys and would be impacted if tram operations were cancelled in the morning peak. Findings of the survey regarding mode shift in the event of tram closure are related in the following results section.

4.2.2. Microsimulation approach

The purpose of this part is to demonstrate a methodology that can be used to estimate the effect of on-street tram operations on creating traffic congestion. It is expensive and difficult to collect field data from existing tram operations because of the varying geometry, traffic conditions and travel behaviour of drivers. In fact, these characteristics are unique to areas where tram routes are located. Thus, field data collection requires significant resources.

Simulation modelling is a more efficient approach for understanding traffic congestion impacts. Vissim 7.0 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 measure used in this research is travel time. This figure is estimated by averaging the travel time of each vehicle on a segment. The reason for choosing travel time as a key measure is that travel time is also calculated on each link in VITM and used as the main criteria 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. Firstly, these scenarios are tested without trams to obtain a baseline average travel time of traffic on links. The simulation is run with a range of input traffic volumes (100, 200, 300…900 vehicles/hour/lane) and tram frequencies (5, 8, 10, 13, 15, 17, 20 trams/hour) for a one-lane link and a different set of tram frequencies (5, 8, 10, 13, 15, 17, 20, 22, 25, 30, 35 trams/hour) for a two-lane link. These tram frequencies are representative of Melbourne's tram network on one and two-lane links. Finally, the results between the "base case" scenario and the "Tram operations on a one-lane link" and "Tram operations on a two-lane link" scenarios are compared to define the relationship between the percentage change in travel time and traffic volume for each tram service frequency.

In order to get an accurate result from the simulation, the simulation was firstly run for a 'warm up' period. It then continued running for one hour and recorded measures of performance for that period of time. A set of twenty runs were undertaken for each scenario to establish a variation in measures of performance to provide a mean and level of confidence in the results.

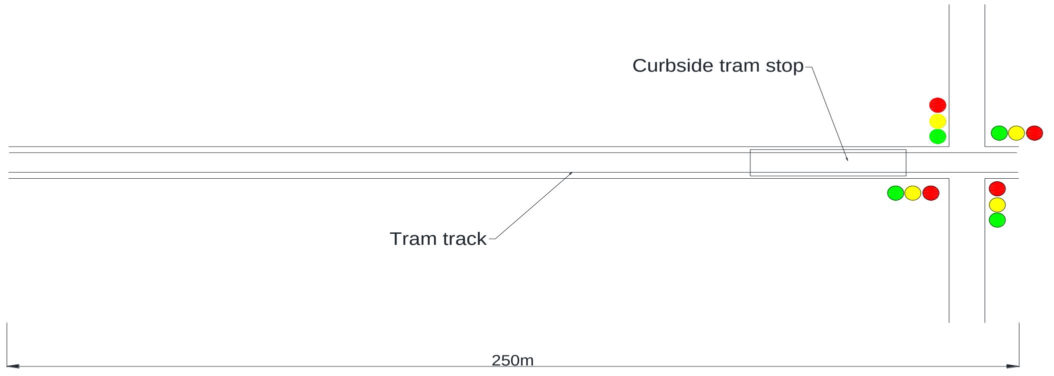
In the microsimulation model, traffic travels from the west to east as shown in Figure 2. In VITM, the average length of links with tram operations is around 245m and it is assumed there are four intersections per kilometre in Melbourne's inner areas. Thus, a 250m link with a tram route on the right lane and an intersection at the end of the link are modelled to estimate the impact of tram operations. In addition, there are nearly 1,180 curbside tram stops in Melbourne and most of them are located on-street with an average spacing of 270m. Hence, in order to have a simpler representation, it is assumed that a curb side tram stop is located on each 250m 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 modelled on the traffic lane behind the tram stop area. Thus, when a tram stops, vehicles behind have to also stop to give way to tram passengers boarding and alighting. The dwell time of trams at stops is taken as the average figure (13.9 seconds) from a survey previously undertaken in Melbourne by Currie et al. (2012).

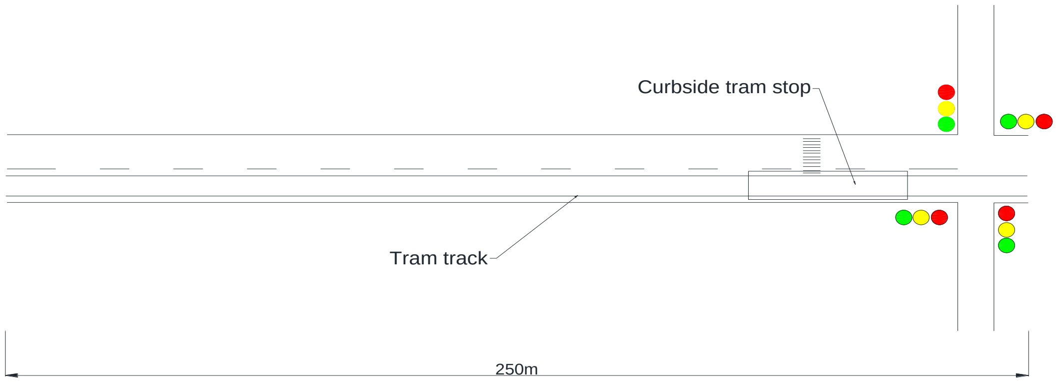
Tram priority programs at intersections have not yet been implemented for Melbourne's entire road network. Hence, trams are sometimes delayed by traffic signals at intersections. Morton (2007) observed tram delay caused by traffic signals on a road section between Princes Street and Collins Street in Melbourne (2.7km). He found that the total delay time of trams at 12 intersections is 6.35 minutes in the morning peak-hour (approximately 32 seconds 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 in order to be consistent with links with level crossings modelled in VITM (DOT, 2011). It is assumed that this intersection is controlled by fixed traffic signals with a cycle time of 60 seconds. The all red period and intergreen time are assumed to account for 6 seconds so the green time for each leg is 27 seconds.

There are many types of trams 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 23.63m) were chosen for use in this simulation. The speed of trams is set to range between 15.5 to 16.5 km/h because the average tram speed in Melbourne is around 16km/h (Yarra Trams, 2015). The frequency of tram vehicles are specified in Vissim by defining a deterministic "service rate" for the transit lines.

Figure 2 Modelled links with non-exclusive tram right-of-way



a) One-lane link



b) Two-lane link

In order 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 travel time change is estimated only in a one-lane link and a two-lane link. If links with non-exclusive tram rights-of-way have more than two lanes (accounting for only 0.5% of total links with non-exclusive 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 60km/h which is consistent with current practice in Melbourne

Table 2 Parameters set in Vissim

No	Parameter	Value	Source
1	Vehicle speed limit on road link	60 km/h	
2	Tram speed	16 km/h	(Yarra Trams, 2015)
3	Traffic signal cycle time	60s	
4	Dwell time	13.9s	Survey (Currie et al., 2012)
5	Tram length	23.65 m	B class Tram (Vicsig, 2015)
6	Acceleration, deceleration	1.3m/s^2	B class Tram (Andrews, 2014)(Andrews, 2014)(Andrews, 2014)(Vicsig, 2015)
7	Road link length	250 m	
8	Tram stop location	230m	(from the beginning of the link)
9	Tram delay caused by traffic signal	32s	(Morton, 2007)

4.2.3. Macro-modelling approach

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

In VITM, in order to assign vehicle trips on Melbourne’s road network, travel time is calculated for each link using Akcelik’s formula (Akçelik, 1991). This figure is one of major parameters for estimating the generalised cost route which 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 and leads 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 including non-exclusive tram rights-of-way is added as a percentage change in travel time, which is estimated by microsimulation, to model the negative impact of non-exclusive tram rights-of-way. This percentage is adjusted based on 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. So, 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:

$$Travel\ time = \mathrm{Travel\ time}_0 + \mathrm{p\%} * \mathrm{Travel\ time}_0 \quad (1)$$

Where:

p%: is the percentage change in travel time caused by non-exclusive tram rights-of-way; it is calculated from a function of traffic volume and tram frequency created from microsimulation.

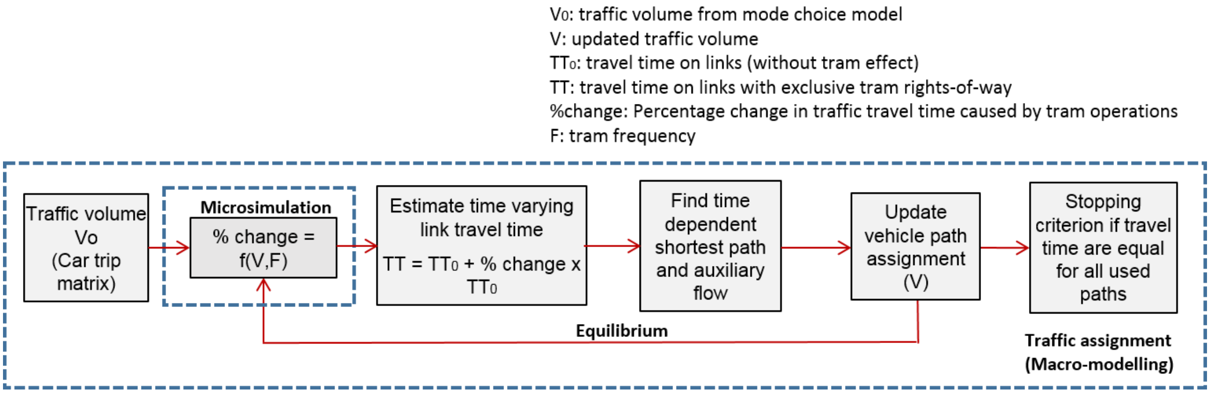
$Travel\ time_0$: Travel time on link with non-exclusive tram rights-of-way when impact of tram operations is not considered

$Travel\ time$: Travel time on link with non-exclusive tram right-of-way.

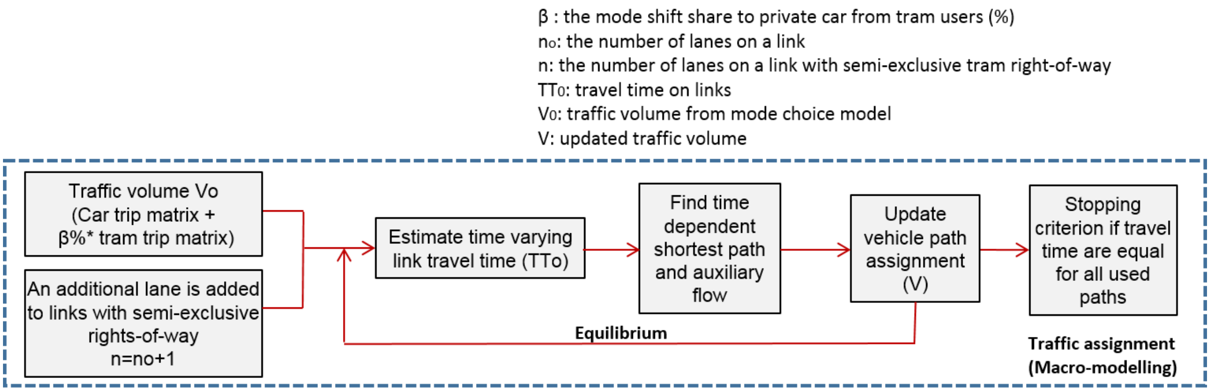
The negative impact of trams on semi-exclusive tram rights-of-way is represented by considering the allocation of tram lanes on links with semi-exclusive tram rights-of-way. Thus, in the “without tram” scenario, an additional lane is added to road links with semi-exclusive tram rights-of-way.

Figure 3a and Figure 3b illustrate the process for estimating the roadway travel data in the two scenarios: “with tram” and “without tram”. In the case of “with tram”, the negative effect of trams in contributing to traffic congestion is assessed by integrating the results from microsimulation into macro-modelling. When there is “without tram”, the expanded car matrix is assigned to the road network. In addition, the capacity of links with semi-exclusive tram rights-of-way increases because the priority tram lanes are returned to vehicle traffic lanes.

Figure 3 The process of estimating the travel demand with traffic assignment in two scenarios



(a) With tram



(b) Without tram

The outcomes between the two scenarios, “with tram” and “without tram”, are then compared to investigate the changes in congestion measures on the road network. These changes are interpreted to represent the net effect of tram operations on traffic.

5. Results

The results are presented in three parts. Firstly, the car mode shift share from trams obtained from the primary survey is described. The effect of tram operations on travel time on a link with a non-exclusive tram right-of-way using micro-simulation is then shown. The mode shift share and the results from micro-simulation are then incorporated in VITM (macro-modelling) to estimate the net congestion relief impact associated with tram operations. These results are shown in the final part.

5.1. Car mode shift

The data for this study is from an on-line travel survey of tram users in Melbourne. As shown in Table 3, females (58%) were over-represented in the tram user sample population. The age distribution of respondents shows that the younger age group dominates (16-29 year old) with a small under-representation of tram users aged 40-49 years. There is no significant difference between the distribution of gender and age in the sample in the survey and the actual PT user population of Melbourne (Census 2011). The difference is because the survey focuses only on tram users in the morning peak while the census data includes all PT users.

Table 3 Demographic profile of respondents

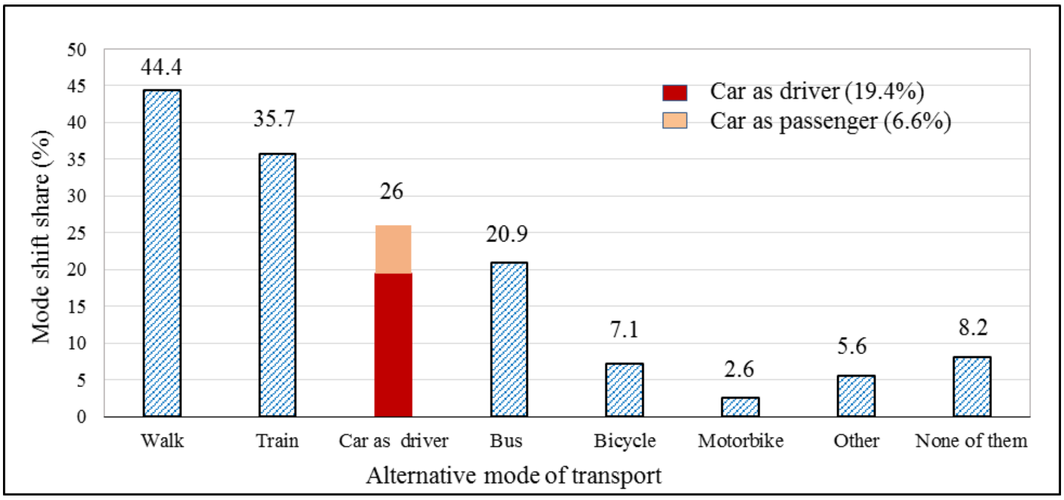
Characteristic		Survey*		Census**
		Number of respondents (n)	Proportion (%)	Proportion (%)
Gender	Male	82	41.8	49.1
	Female	114	58.2	50.9
Age	16 – 29	79	40.3	26.8
	30 – 39	45	23.0	18.6
	40 – 49	21	10.7	17.6
	50+	51	26.0	36.9
Total		196	100	100

* The survey conducted by PTV focuses on tram users.
**Census data includes all PT users in Melbourne

Figure 4 illustrates the transport mode shift of tram users if tram operations were cancelled. Around 45% of respondents would choose to travel by walking for their entire journey or a part of their journey. There are 70 (35.1%) and 41 (20.9%) respondents who would switch to train and bus, respectively. Tram users who would shift to car account for 26% of respondents in which 19.4% would shift to car as driver and 6.6% would shift to car as a passenger. Bicycle and motorbike were chosen as alternative transport modes by 14% and 5% of tram users respectively.

This research has assumed that tram user diversion to car when tram operations cease would result in an increase in traffic congestion. It is clear that the mode shift to car as a driver would directly increase the number of car trips on the road network (diversion to other PT modes, walk or bicycle is not considered because they would not influence congestion). However, in case of switching to car as a passenger, this may or may not influence traffic congestion. For example, Litman (2004) argued that 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. From Figure 5, the car mode shift share contributing to traffic congestion if tram operations cease would be 23% of tram users (19.4% + half of 6.6%). This figure is smaller than the car mode shift share from PT (32%) explored by Aftabuzzaman et al. (2010a). This is because the survey in this research only focuses on tram users, most of whom travel in a short distance in inner Melbourne. Thus, if tram operations cease, the car mode shift share is not particularly high because users have a choice of non-motorised modes or other PT modes.

Figure 4 Transport mode shift from tram if tram operations cease



Data source: PTV survey on tram users (2015)

5.2. Micro-simulation results

The effect of a non-exclusive tram right-of-way is explored in two scenarios: one-lane link and two-lane link with various tram service frequencies and traffic volumes. Figure 5 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 with various tram frequencies (5, 8, 10…20 trams/hour). As can be seen from the graph, there is a polynomial correlation between the volume of vehicles and the percentage change in travel time on links with non-exclusive 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.

Figure 5 Percentage change in travel time caused by a non-exclusive tram right-of-way on a one-lane link

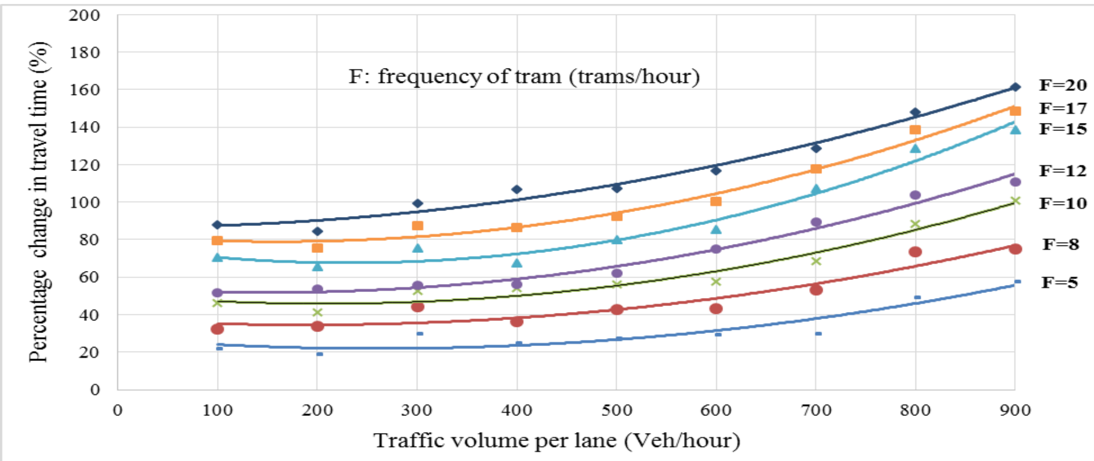


Figure 6 shows the relationship between the percentage travel time change caused by a non-exclusive tram right-of-way and volume of traffic on a two-lane road link with various tram frequencies (5, 8, 10…30, 35 trams/hour). Again, there is a polynomial correlation between the volume of vehicles and the percentage increase in travel time on links with non-exclusive tram rights-of-way. On links with low tram frequencies, the impact of non-exclusive tram rights-of-way on travel time increases gradually when traffic volume increases. However, the level of increase in travel time is much higher if tram frequencies increase. On a link with 35 trams per hour, the impact of trams on travel time increases rapidly from over 40% to around 120% when the traffic volume increases from 100 to 900 vehicles/hour.

Figure 6 Percentage change in travel time caused by a non-exclusive tram right-of-way on a two-lane link

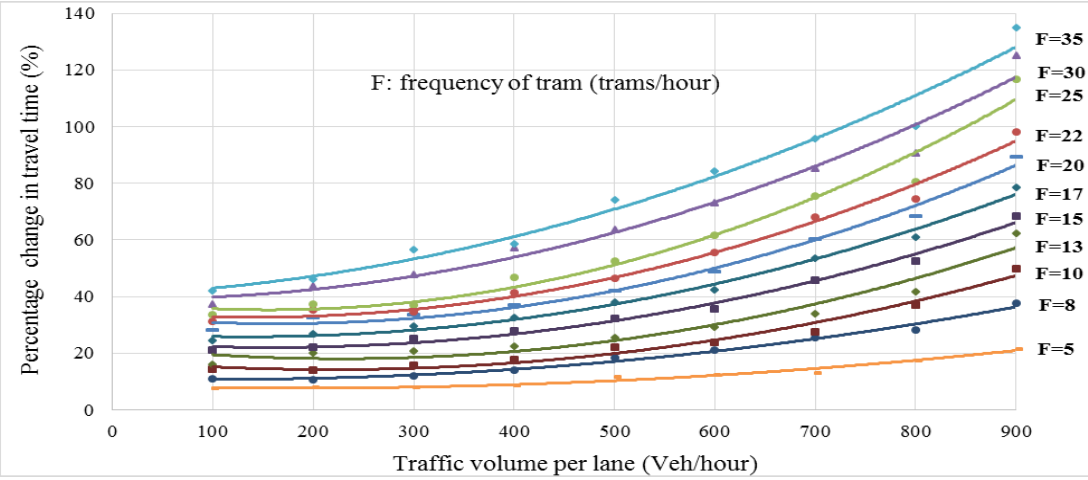


Table 4 and 5 manifest the polynomial functions of the relationship between vehicle volume and the percentage travel time change for various tram service frequencies on a one-lane and two-lane road link respectively. These equations are utilised to adjust the travel time on road links with non-exclusive 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 4 The relationship between traffic volume and the percentage change in travel time on a one-lane link with a non-exclusive tram right-of-way

Frequency (trams/hour)	Function	R^2
20	$y = 0.00009x^2 - 0.0005x + 86.605$	0.98
17	$y = 0.0001x^2 - 0.0421x + 82.277$	0.98
15	$y = 0.0002x^2 - 0.078x + 76.639$	0.97
13	$y = 0.0001x^2 - 0.0323x + 54.084$	0.98
10	$y = 0.0001x^2 - 0.0463x + 50.636$	0.96
8	$y = 0.00008x^2 - 0.0317x + 37.519$	0.91
5	$y = 0.00008x^2 - 0.0428x + 27.479$	0.89

Table 5 The relationship between traffic volume and the percentage change in travel time on a two-lane link with a non-exclusive tram right-of-way

Frequency (trams/hour)	Function	R^2
35	$y = 0.00009x^2 + 0.0147x + 40.569$	0.97
30	$y = 0.0001x^2 - 0.0032x + 39.098$	0.97
25	$y = 0.0001x^2 - 0.0419x + 38.544$	0.97
22	$y = 0.0001x^2 - 0.0297x + 34.688$	0.99
20	$y = 0.0001x^2 - 0.0339x + 33.162$	0.99
17	$y = 0.00009x^2 - 0.023x + 27.3$	0.99
15	$y = 0.00008x^2 - 0.0251x + 23.964$	0.99
13	$y = 0.00009x^2 - 0.0397x + 22.531$	0.95
10	$y = 0.00007x^2 - 0.031x + 17.543$	0.98
8	$y = 0.00004x^2 - 0.0085x + 11.183$	0.99
5	$y = 0.00003x^2 - 0.0093x + 8.4764$	0.97

5.3. Macro-modelling results

Table 6 reveals the congestion measures for the entire Melbourne road network in the “with tram” scenario and “without tram” scenario. The difference between these two scenarios is interpreted as the ‘net’ traffic congestion impact associated with tram operations during peak hours. Results in Table 6 points out that for the entire road network:

- More than 65 road links become moderately congested as a result of tram removal whereas only 12 road links become heavily congested.

- An increase of 1.7% in the number of vehicles experiencing congestion occurs when removing trams.
- Total network delay and vehicle time travelled increase by 1.2%.
- Average travel speed decreases from 47.9 km/h to 47.7 km/h (a decrease of 0.5%).

Table 6 Overall impact of tram operations on the entire Melbourne road network

Measure	With tram	Without tram	Absolute change	Change (%)
Number of severely congested links (V/C>=0.9) (Semcog, 2011)	2,125.0	2,137	12	**0.6**
Number of moderately congested links (0.9>V/C>=0.8) (Semcog, 2011)	1,931.0	1,997	66	**3.3**
Number of vehicles experiencing congestion (millions)	16.94	17.23	1.7	**1.7**
Vehicle distance travelled (millions veh-km)	15.02	15.13	0.11	**0.7**
Vehicle time travelled (millions veh-hr)	0.384	0.389	0.004	**1.2**
Total delay on road network (millions veh-hr)	22.84	23.12	0.28	**1.2**
Average travel speed (km/h)	47.9	47.7	0.2	**-0.5**
Actual travel time per km (min)	1.82	1.84	0.02	**0.6**

Notes: V/C: volume to capacity ratio = traffic volume divided by road capacity

Table 7 gives information about the net congestion relief effect of tram operations in inner Melbourne by contrasting the congestion measures in the two scenarios. Results in Table 7 indicate the following:

- The number of moderately congested links increases by 16% with tram removal while there is a decrease of 4.6% in the number of severely congested links.
- Vehicle time travelled and total delay on the road network increases by 3.4%.
- The average road network speed decreases from 41.9 km/h to 41.6 km/h (a decrease of 0.9%).
- The operation of trams reduces the actual travel time on average from 2.14 minutes/km to 2.13 minutes/km (a decrease of around 0.3%).

Table 7 Overall impact of tram operations on the road network in inner Melbourne

Measure	With tram	Without tram	Absolute change	Change (%)
Number of severely congested links (V/C>=0.9) (Semcog, 2011)	458.0	438.0	20	**-4.6**
Number of moderately congested links (0.9>V/C>=0.8) (Semcog, 2011)	330.0	393.0	63	**16.0**
Number of vehicles experiencing congestion (millions)	4.03	4.24	0.2	**5.0**
Vehicle distance travelled (millions veh-km)	1.63	1.70	0.07	**3.7**
Vehicle time travelled (millions veh-hr)	0.052	0.054	0.002	**3.4**
Total delay on road network (millions veh-hr)	3.14	3.25	0.11	**3.4**
Average travel speed (km/h)	41.9	41.6	0.7	**-0.9**
Actual travel time per km (min)	2.13	2.14	0.01	**0.3**

Notes: V/C: volume to capacity ratio = traffic volume divided by road capacity

The net traffic congestion relief associated with tram operations in middle Melbourne is presented in Table 8. A comparative assessment of all congestion measures between the two scenarios suggests the following:

- Removing trams in middle Melbourne contributes to an increase of 32 severely congested links (2.9%) and 6 moderately congested links (0.6%).
- Trams reduces the total delay on the road network by 170,000 vehicle hours (1.6%).
- With the operation of trams in middle Melbourne, actual travel time per kilometre reduces by 0.8% while average travel speed increases by 0.5%.

Table 8 Overall impact of tram operations on the road network in middle Melbourne

Measure	With tram	Without tram	Absolute change	Change (%)
Number of severely congested links (V/C>=0.9) (Semcog, 2011)	1,083.0	1,115.0	32	**2.9**
Number of moderately congested links (0.9>V/C>=0.8) (Semcog, 2011)	939.0	945.0	6	**0.6**
Number of vehicles experiencing congestion (millions)	8.62	8.70	0.08	**1.0**
Vehicle distance travelled (millions veh-km)	6.12	6.18	0.06	**0.9**
Vehicle time travelled (millions veh-hr)	0.178	0.181	0.002	**1.6**
Total delay on road network (millions veh-hr)	10.61	10.78	0.17	**1.6**
Average travel speed (km/h)	44.6	44.4	0.2	**-0.5**
Actual travel time per km (min)	1.94	1.96	0.02	**0.8**

Notes: V/C: volume to capacity ratio = traffic volume divided by road capacity

Figure 7 visualises the congestion relief impact of tram operations across metropolitan Melbourne. It is clear that the effect of trams is not strong because the tram system is only located in a part of the Melbourne road network, particularly the inner areas and middle areas. However, tram operations have a greater impact on relieving traffic congestion in inner areas where a large number of tram routes with high frequencies serve a large number of passengers. The congestion effects in these areas range from 0.3% to 16%. Their impacts are less in middle Melbourne with the range of congestion measures from 0.5% to under 2.9%.

Figure 7 Spatial variation of congestion effect of trams

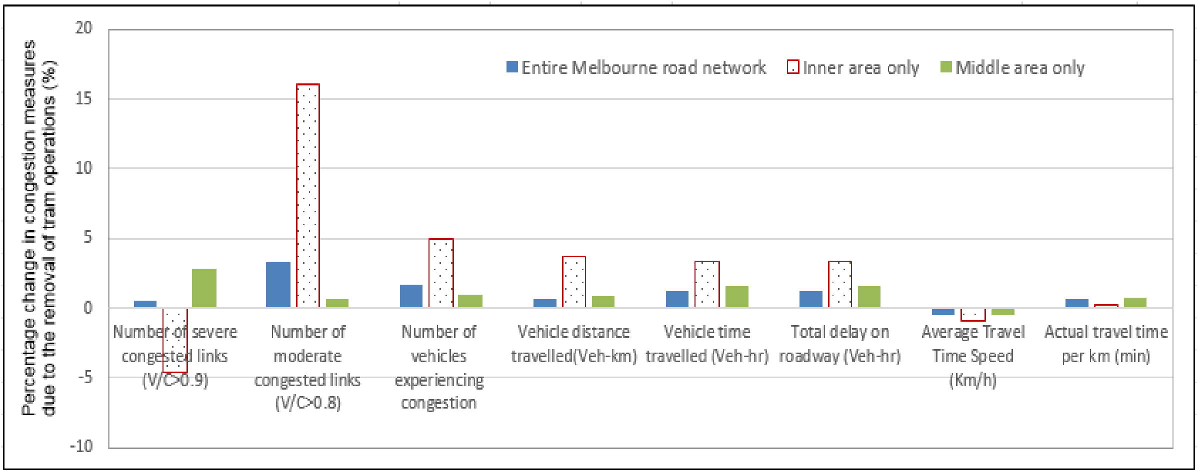
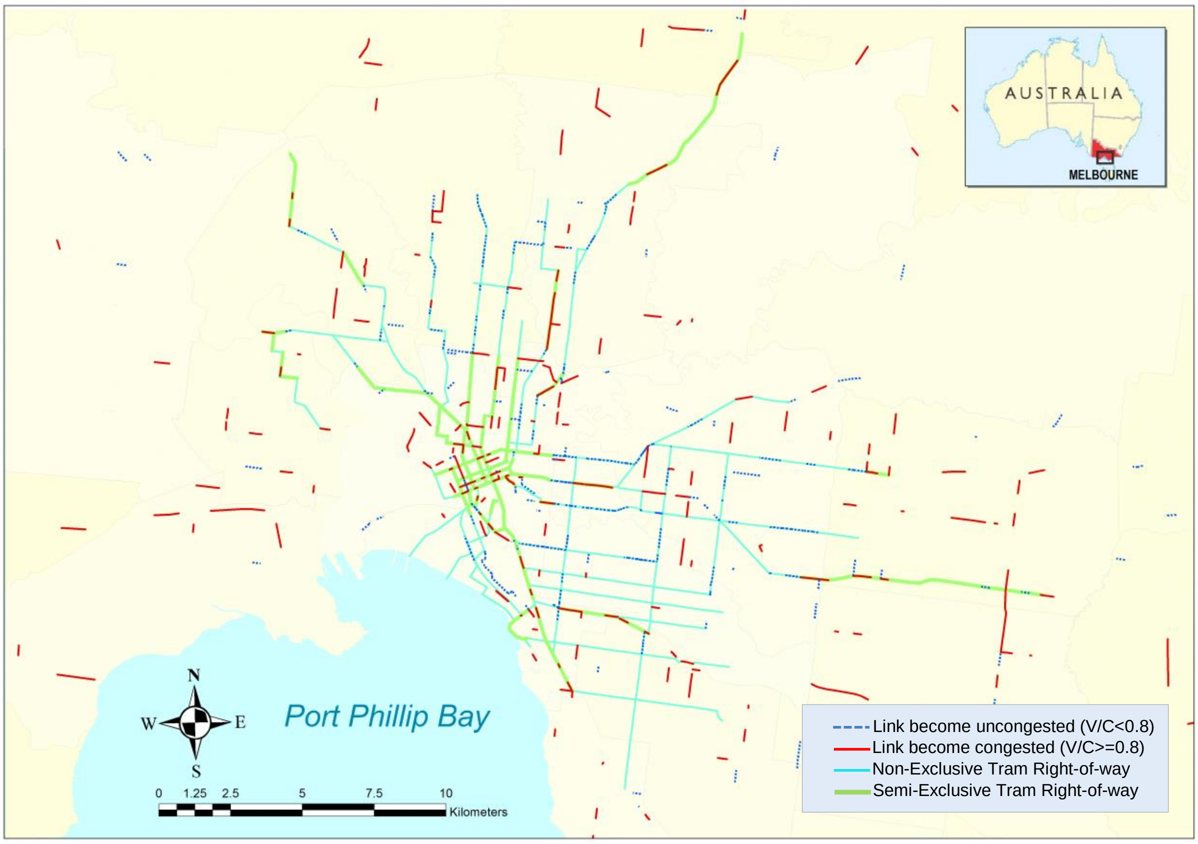


Figure 8 illustrates the spatial distribution of congested and uncongested links impacted by tram operations in the results. In this paper, a link with a volume capacity ratio over 0.8 is considered to be a congested link (V/C>=0.8) (Semcog, 2011). It can be seen that tram operations result in a change in the level of congestion for a number of road links. Thus, some links become congested (red links) and some links become uncongested (blue links). However, the number of links that are congested as a result of trams are lower than the number of links becoming uncongested and this is interpreted as the net congestion relief effect of trams. A proportion of congested links caused by existing trams are links with semi-exclusive tram rights-of-way due to the decrease in road capacity. Another proportion of congested links are surrounding links which experience an increase in travel demand as road users tend to avoid using roads with tram operations. In contrast, due to the reduction in traffic volumes on links with a tramway (trams attract a share of car users and reduce the number of car trips), particularly non-exclusive tram rights-of-way, there are a number of links (blue links) which become less congested (V/C<0.8).

Figure 8 Spatial distribution of road link performance as a result of tram operations



6. Discussion and conclusion

This paper explores the net traffic congestion impact of tram operations in Melbourne. A literature review revealed that almost all prior studies focused on the effects of trams on creating congestion on road links. There was only one attempt to assess the network-wide impact of tram operations with the help of simulation models but this study did not consider the negative effects of trams particularly streetcars on creating congestion in mixed traffic roads. This paper presented a new methodology to incorporate both positive and negative impacts of trams on traffic. The method includes two parts. Firstly, it is assumed that when trams are removed, the share of car mode shift from trams would contribute to traffic congestion. In this study, the car mode shift share is identified from data obtained by a field survey. The positive effect is estimated based on the share of car users attracted by trams. Secondly, the negative impacts of trams on contributing to congestion are assessed by considering the impact of curbside tram stops on non-exclusive tram rights-of-way and the occupation of priority tram lanes on semi-exclusive tram rights-of-way.

The analysis of field data has found that when tram operations cease tram users would change their travel behaviour. Walking was chosen as an alternative transport mode by the largest share of tram users (approximately 45%). This might be because of a high proportion of users using trams for short distance trips so if trams are not available they are able to walk. Additionally, some people could combine walking with other transport modes for their journeys such as walk-rail or walk-bus. The second popular alternative mode was train with more than 35%. Car was chosen by about 26% of tram users (19.4% as car driver, 6.6% as car passenger). In this research, the mode shift to car is investigated because it directly contributes to congestion on road network.

Based on the findings, tram operations contribute to 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 shows that 12 (increase of 0.6%) and 66 (increase of over 3%) additional network links become heavily congested and moderately congested, respectively, because of the increase in the number of car trips when trams are removed. The total delay on the network also rises by around 1.2% whereas average speed decreases by 0.4%. Indeed, these values are much lower than the values of tram impacts identified in previous research (Aftabuzzaman et al., 2010b) which did not consider the negative effect of trams on generating congestion. Thus, by comparing two results, it can be seen that the negative effect of tram operations is relatively high and needs to be considered when estimating tram impacts on traffic. The results of this research are consistent with the results 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.

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 (an increase of 0.9%). The operation of trams in inner Melbourne increases actual travel time on average from 2.14 minutes/km to 2.13 minutes/km. Although trams contribute to reduce the number of car trips on the road network, the average travel speed increases slightly. This is because the travel speed on links with non-exclusive tram rights-of-way decreases due to the low speed of trams and boarding/ alighting passengers. The tram network contributes to reduce 16% of the number of moderately congested links in inner Melbourne. Interestingly, the number of heavily congested link increases by 4.6%. It can be seen that when there are tram operations, road links with semi-exclusive tram rights-of-way which are largely located in inner areas have a reduced level of capacity due to the allocation of priority tram lanes. Thus a proportion of these links become more congested.

In contrast, the impact of trams on reducing traffic congestion in middle Melbourne is less significant. Tram operations in these areas only contribute to a decrease in 32 severely congested links (2.9%) and 6 moderately congested links (0.6%). Trams act to reduce the 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 kilometre rises by only 0.8% while average travel speed decreases by 0.5%. It should be noted that a very small part of the tram network is located in outer areas so the effect of trams in these areas is assumed to be negligible.

It can be seen that the congestion relief impact of tram operations in inner areas is much higher than that in middle areas. Indeed, the density of tram route network in the inner area of Melbourne is much higher than its middle areas.

This paper has shown that the Melbourne tram network makes an important, yet modest, contribution towards reducing traffic congestion on the road network. This contribution is more pronounced in the inner area of Melbourne thereby providing an important role in sustaining the liveability of the city.

The main contributions of this paper are:

- Understanding the change in travel behaviour of tram users when tram operations cease.
- Investigating the net network-wide effect of tram operations on traffic congestion.
- Exploring the spatial variation of congestion reduction impacts of trams.

This research has assumed that car diversion from tram is fixed for all areas. However, in reality, the car mode shift share varies across and within each area (Nguyen et al., 2015). Understanding this spatial distribution would there for lead to a more precise method. 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 finding other jobs or moving house to reduce their travel distance. Thus, the car mode shift share would be different in terms of the long-term effect.

Overall the new method described in this paper is considered as an advance in knowledge regarding approaches to estimate the net network-wide effect of tram operations on traffic congestion relief.

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