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NET IMPACTS OF STREET CAR OPERATIONS ON TRAFFIC CONGESTION IN MELBOURNE

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ABSTRACT

In general public transit is widely recognized to reduce urban traffic congestion as it encourages car 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 act to reduce congestion by encouraging car drivers onto trams. So what is the net effect of streetcars on congestion?

This paper presents a new method to assessing the net traffic congestion effects associated with streetcar operations in Melbourne the largest streetcar network in the world. Impacts are determined by comparing congestion: “with tram” and “without tram” using a traffic network model. Positive impact of trams are estimated using mode shift from tram to car when tram services are removed and modelling traffic congestion impacts. Negative impacts are 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 travelled and total delay on the road network was established. It also contributes to reduce 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 car and the long-term effect of trams on traffic.

Abstract = 229 words (limit = 250 words)

Keywords: Streetcar, public transport, traffic congestion, tram.

INTRODUCTION

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 (*1*). There has been some attempts to improve or create new rail-based transit systems in order to reduce traffic congestion (*2*). Indeed, light rail transit is considered an effective solution to deal with this problem (*3*). 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 (*4*). 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 (*5*). 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 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 (*6*). 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 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 the level of congestion (*8*).

Melbourne has the largest operating light rail system as well as the largest streetcar system in the world (*6*). However, with around 180 kilometres of tram tracks located in mixed traffic in the centre lanes of roads (*9*), they are considered to be 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 in different parts of the city.

This paper explores the network-wide congestion impact associated with 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 impact of trams 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.

BACKGROUND

There have been few studies that have attempted to assess the impacts of trams on traffic congestion. In terms of exploring the negative effects of tram operations on congestion, Chandler and Hoel (*4)* investigated the effects of light rail crossings on average vehicle delay using microsimulation. This topic was also explored by Rymer et al., Urbanik II and Cline Jr (*10; 11*). 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 (*12*). However, the reallocation of road space reduces road capacity and can increase the level of traffic congestion (*8*). Cairns et al. (*13)* 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, however congestion might be moved to roads where traffic was diverted. 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 (*7*).

Almost all previous studies have focused on the negative impacts of tram operations on a road link or 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 (*2)* analysed the level of traffic on highways before and after the opening of 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.

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 (*14*). 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 public transport 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 to represent the amount of avoided congestion associated with tram operations. They found that in inner Melbourne, tram operations contribute to reduce congested links by approximately 28% and vehicle travel delay by 66%.

Gaps in knowledge

Only one study has examined the network-wide effect of trams on reducing traffic congestion (*14*). In this study, the mode shift to car (from tram) was determined using secondary data for all PT users, not specifically tram users. Additionally, this study only estimated the positive impact of tram operations and did not consider the negative effect 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 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 mode shift to car from trams in Melbourne was conducted in September 2015. The negative impact of trams was modelled using microsimulation. Context and methodology are detailed below.

RESEARCH CONTEXT

Melbourne's tram network

Trams are a major form of PT in Melbourne, Australia. The tram network consists of 250 kilometres 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 after the commuter railway network, with a total of 182.7 million passenger trips in 2012-13 (*15*). Although tram transit has several drawbacks such as unreliability, poor running speeds and safety issues, total tram ridership increased by 46% between 2001-2 and 2011-12 while total public transport (all mode) ridership increased by only 9% (*9*).

Melbourne's tram system operates on three types of right-of-way: non-exclusive, semi-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 traffic 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%); most of these are located on-street (*5*). Curbside stops are a major feature of on-street running of 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 (*5*).

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 higher. 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.

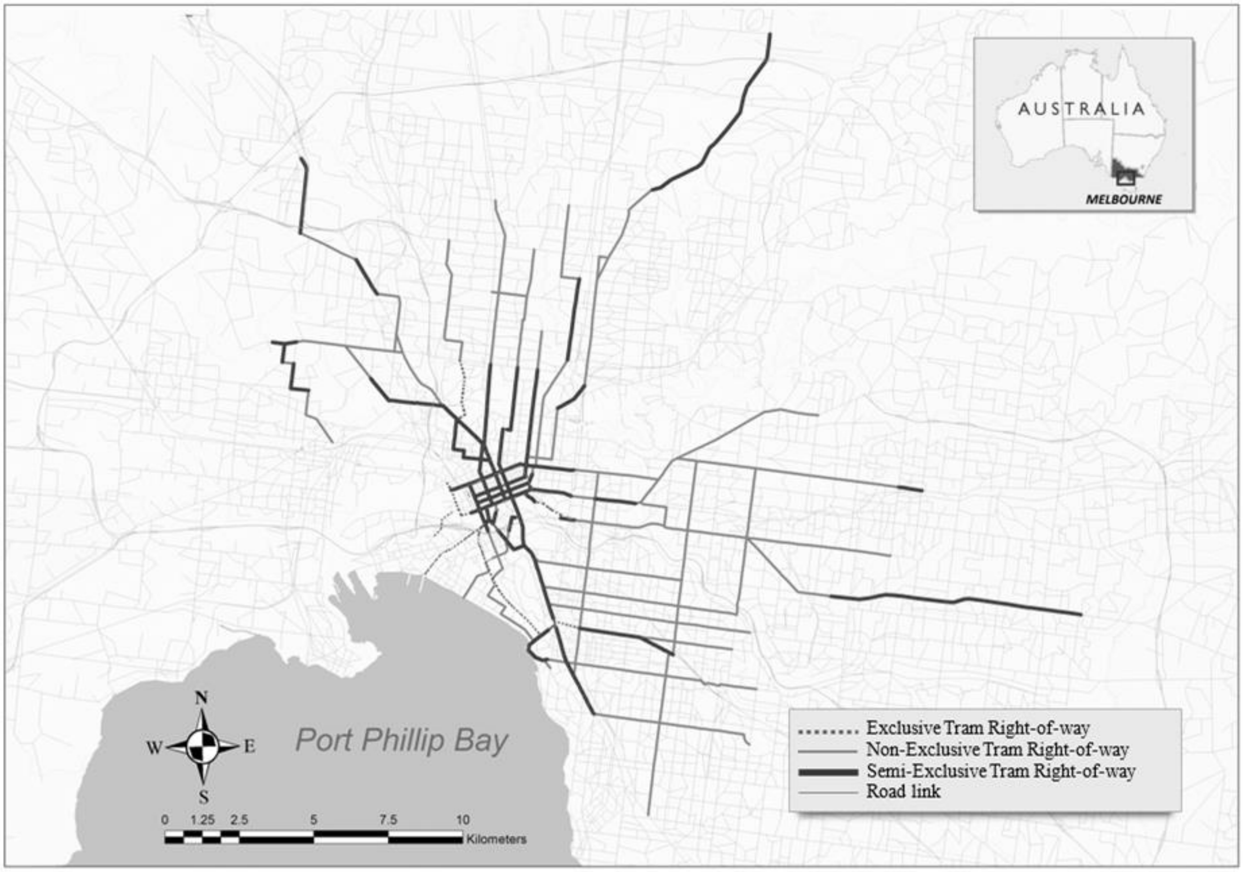


FIGURE 1 Melbourne's tram network.

Spatial unit of analysis

Local Government Areas (LGAs) are the base unit of analysis used this study. There are 31 LGAs in Melbourne (*16*) which are grouped into three categories. These include inner (4 LGAs), middle (14 LGAs) and outer (13 LGAs).

STUDY METHODOLOGY

This section aims 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 Victorian 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.

The Victorian Integrated Transport Model (VITM)

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, while links represent the segments of actual roads in the network. VITM contains a number of sub-models which work together to create the required output for each link such as speed, volume and travel time.

Method for modelling the net impact of trams on traffic congestion

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

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 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 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. 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	With tram	Without tram	Method for assessing direct tram effect
Exclusive	Tramway is constructed separately to road network; 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 operations on a specific link 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 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. - 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 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 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.

Primary survey for estimating the mode shift from tram to car

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 cancellations and their likely travel behaviour. A total of 306 users completed the online survey in which 209 respondents (68%) reported that they regularly used trams and would be impacted if tram services were cancelled in the morning peak. Findings from the survey are presented in the results section of this paper.

Microsimulation approach

Vissim 7.0 was 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. 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 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 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. A set of 20 runs were 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 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 approximately 2,000 curbside tram stops in Melbourne and most of these are located on-street with an average spacing of 270m. Hence, in order to provide 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 average dwell time of trams at stops (13.9 seconds) is taken from a survey previously 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 (*18*) 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, equivalent to 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 (*19*). 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, consistent with the average tram speed in Melbourne of around 16km/h (*15*). Table 2 summarises all parameters set in the Vissim microsimulation.

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 change in travel time 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, consistent with current practice in Melbourne.

TABLE 2 Parameters Set in the Vissim Microsimulation

No	Parameter	Value	Source
1	Vehicle speed limit on road link	60 km/h	
2	Tram speed	16 km/h	Yarra Trams 2015 (*15*)
3	Traffic signal cycle time	60s	
4	Dwell time	13.9s	Survey by Currie et al. (*17*)
5	Tram length	23.65 m	B class Tram (*20*)
6	Acceleration, deceleration	1.3m/s^2	B class Tram (*20; 21*)(*19; 20*)(*20; 21*)(*20; 21*)(*20; 21*)(*19; 20*)(*19*)
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 (*18*)

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 travelling from each origin to each destination is generated from the PT assignment. This matrix is modified by multiplying it by the mode shift to car 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 order to assign vehicle trips on Melbourne's road network in VITM, travel time is calculated for each link using Akcelik's formula (*22*). This figure is one of major parameters for estimating the generalised cost 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, 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 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:

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

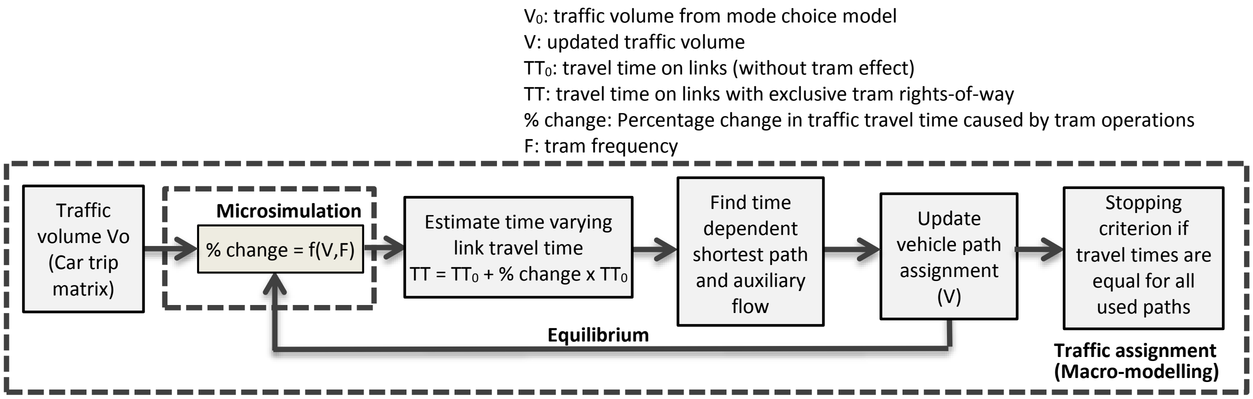
Where: $\mathrm{p\%}$: is the percentage change in travel time caused by non-exclusive tram rights-of-way; it is calculated from a function of traffic volume and tram frequency created from microsimulation.

$\mathrm{Travel\ time}_0$: 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.

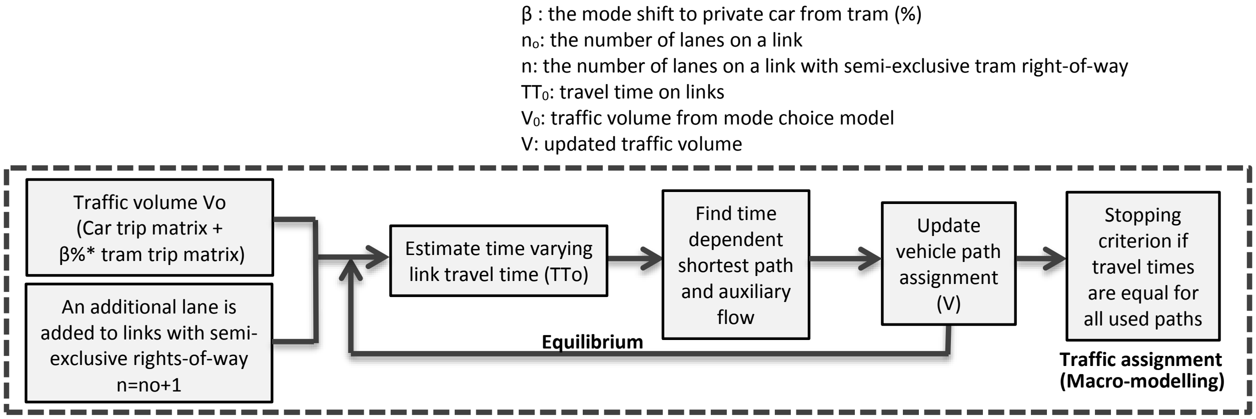
The negative impact of trams on semi-exclusive tram rights-of-way is represented by considering the allocation of tram lanes on links with semi-exclusive tram rights-of-way. Thus, in the "without tram" scenario, an additional lane is added to road links with semi-exclusive tram rights-of-way.

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 congestion. Figure 2 illustrates the process for estimating the roadway travel data in the two scenarios: "with tram" and "without tram".



V_0: traffic volume from mode choice model
V: updated traffic volume
TT_0: travel time on 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

(a) With tram



β : the mode shift to private car from tram (%)
n_0: the number of lanes on a link
n: the number of lanes on a link with semi-exclusive tram right-of-way
TT_0: travel time on links
V_0: traffic volume from mode choice model
V: updated traffic volume

(b) Without tram

FIGURE 2 Process of estimating the travel demand with traffic assignment in two scenarios.

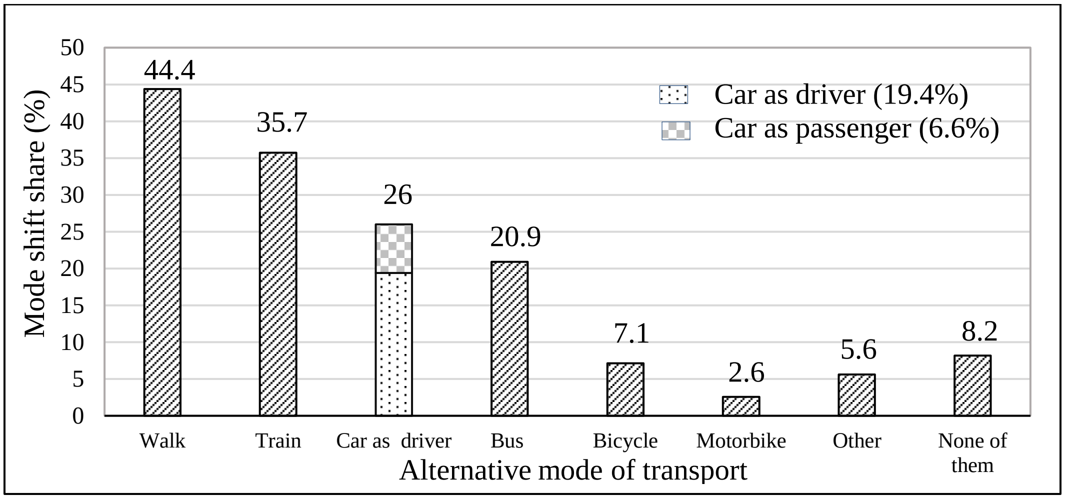
RESULTS

The results are presented in three parts. First, the mode shift to car from tram 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 to car and the results from micro-simulation are then incorporated into VITM (macro-modelling) to estimate the net congestion relief impact associated with tram operations. These results are shown in the final part.

Mode shift to car

The primary data for this study is 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. Around 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 car accounted 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 to influence congestion). However, in the case of switching to car as a passenger, this may or may not influence traffic congestion. For example, Litman *(23)* 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. The mode shift to car contributing to traffic congestion if tram operations cease would therefore be 23% of tram users (19.4% + half of 6.6%).



Data source: PTV survey on tram users (2015)

FIGURE 3 Transport mode shift from tram if tram operations cease.

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 4a and Figure 4b illustrate 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. As can be seen, 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.

These curves 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.

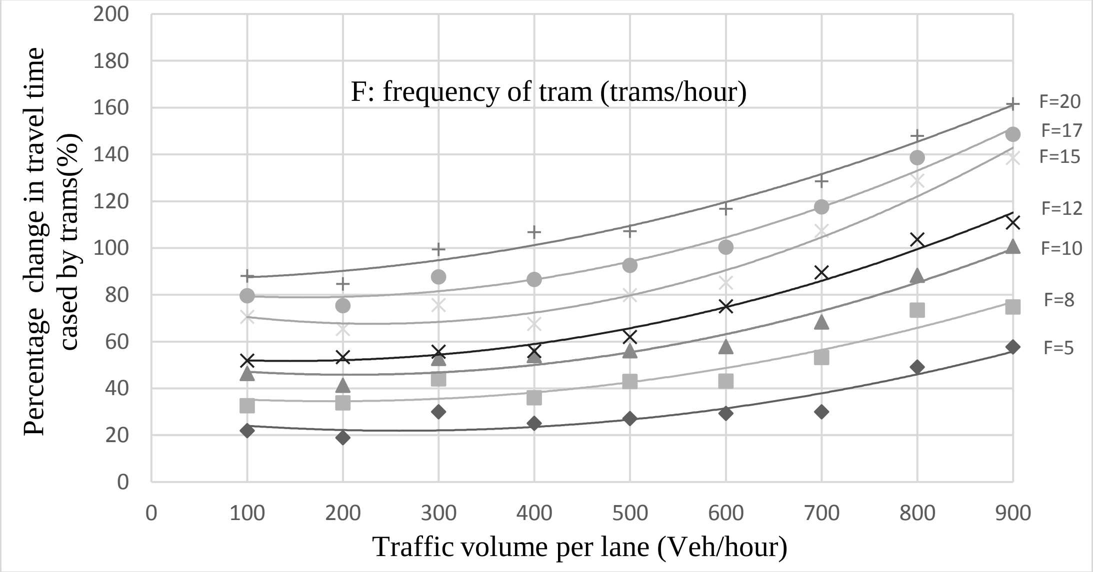


FIGURE 4a Percentage change in travel time caused by a non-exclusive tram right-of-way on a one-lane link.

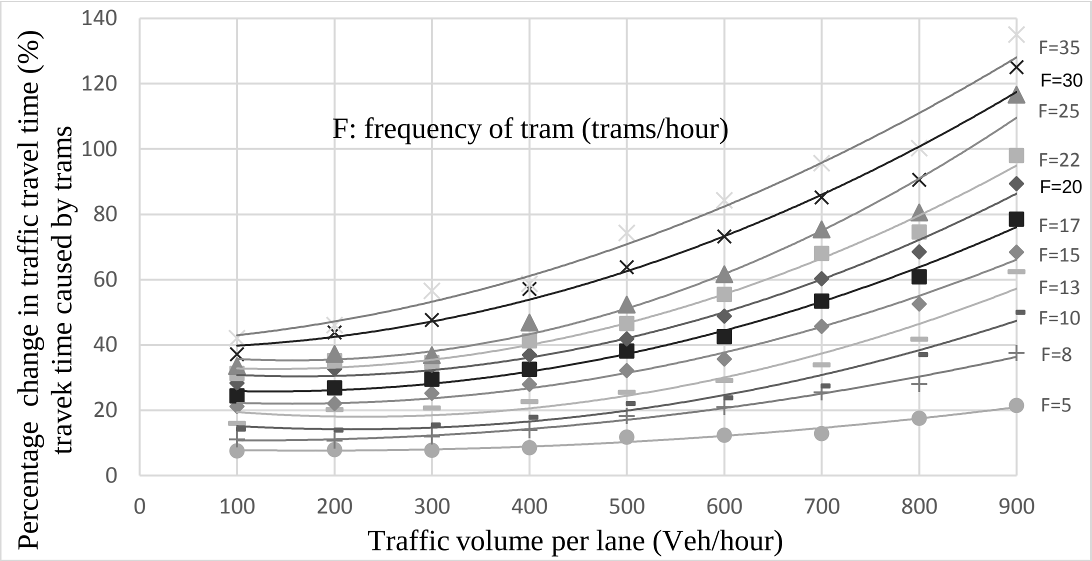


FIGURE 4b Percentage change in travel time caused by a non-exclusive tram right-of-way on a two-lane link.

Macro-modelling results

Table 3 details the estimated net congestion relief effect of tram operations in Melbourne by contrasting congestion measures in the two scenarios: "with tram" and "without tram". Results in Table 3 show that:

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 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%).

For inner Melbourne:

- 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%).
- Travel time on average increases slightly from 2.13 minutes/km to 2.14 minutes/km (0.3% increase).

For middle Melbourne:

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

TABLE 3 Overall Impact of Tram Operations on the Entire Melbourne Road Network

Measures	**Entire Melbourne**			**Inner Melbourne**			**Middle Melbourne**		
	With tram	Without tram	Change (%)	With tram	Without tram	Change (%)	With tram	Without tram	Change (%)
Number of severely congested links (V/C>=0.9) (*24*)	2,125.0	2,137	**0.6**	458.0	438.0	**-4.6**	1,083.0	1,115.0	**2.9**
Number of moderately congested links (0.9>V/C>=0.8) (*24*)	1,931.0	1,997	**3.3**	330.0	393.0	**16.0**	939.0	945.0	**0.6**
Number of vehicles experiencing congestion (millions)	16.94	17.23	**1.7**	4.03	4.24	**5.0**	8.62	8.70	**1.0**
Vehicle distance travelled (million veh-km)	15.02	15.13	**0.7**	1.63	1.70	**3.7**	6.12	6.18	**0.9**
Vehicle time travelled (million veh-hr)	0.384	0.389	**1.2**	0.052	0.054	**3.4**	0.178	0.181	**1.6**
Total delay on road network (million veh-hr)	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 km (min)	1.82	1.84	**0.6**	2.13	2.14	**0.3**	1.94	1.96	**0.8**

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

DISCUSSION AND CONCLUSION

Almost all prior studies regarding trams and traffic congestion have focused on the effects of streetcars in creating congestion on road links. This paper presented a new methodology to assess the net impact of trams on traffic congestion including their impacts in reducing road traffic through mode shift.

The analysis of field data found that when tram operations cease, tram users are likely to change their travel behaviour. Walking was chosen as an alternative transport mode by the largest share of tram users (approximately 45%). The second most popular mode was train with more than 35%. Car travel resulted for about 26% of tram users (19.4% as car driver, 6.6% as car passenger). In this research, mode shift to car was investigated since it directly contributes to congestion on the 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 additional road links would become congested due to an increase in car 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 are generally consistent with those of several prior studies. According to Lane (*25)*, there was no considerable difference in traffic congestion between 13 cities with rail and 22 cities without rail in the US. Mackett and Edwards (*26)* 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 (*27)* 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. 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. 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 tram lanes. Thus, a proportion of these links become more congested.

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 are less routes 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%). In the middle areas, trams act to 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 kilometre 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 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:

- An understanding of the change in travel behaviour among tram users when tram operations cease.
- The development of a new methodology for estimating the network-wide effect of tram operations on traffic congestion.
- A preliminary understanding of the spatial variation of congestion reduction impacts of trams.

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 area (*28*). Understanding this spatial distribution would therefore lead to a more precise estimate of congestion reduction impacts. 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.

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