Modelling the Direct Impact of Tram Operations on Traffic

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Abstract
This paper makes aggregate estimates of the negative impacts of the tram (street-car) network in Melbourne, Australia on vehicular traffic and congestion. These impacts are assessed by comparing the travel demand in two scenarios “without tram” and “with tram”. To investigate the effect of on-street running, a new method was developed which incorporates results from micro-simulation of a link with a non-exclusive tram right-of-way into a conventional four step model to make an aggregate estimate of impacts on all traffic. The effect of semi-exclusive tram rights-of-way is also assessed by considering the reallocation of tram lanes from traffic lanes which reduces road capacity.

Overall, Melbourne’s tram network results in an average increase in travel time of 20.5% for vehicle traffic in areas with tram operations. On average, a tramway acts to reduce the volume of vehicles on links by 19.6 %. The aggregate impact of Melbourne’s tram network on traffic in areas with tram operations is an increase in average travel time from 2.06 to 2.16 minutes/km (an increase of around 4.6%). This is associated with an increase of 14.7% in the numbers of severely congested road links.

Keywords:
Traffic congestion, street-car, tram.

Introduction
Traffic congestion is a major issue in many large cities around the world, particularly in inner cities. The congestion level in these areas is increasing because of a rise in population, economy, car ownership, urbanization, and suburbanization of population, housing, and jobs (TRC 2007). Light rail transit is considered an effective solution to deal with this problem (Vuchic, 2007). 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 carry a significant share of urban travel 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 (Currie and Shalaby, 2007). Streetcars can run on tracks along public urban streets (called street running), and also on a segregated right of way. Streetcar running directly along public streets without any separation has to share the street with vehicle traffic and pedestrians. Thus, trams generally travel with low speed for safety reasons and tram stops often lack platforms. Passengers may be required to wait on a distant sidewalk, and then to board or disembark directly among mixed traffic, rather than at a curbside (Currie and Smith, 2006a). This results in delays on vehicle traffic and these problems become more serious when the frequency of trams and traffic volumes increase. On the other hand, trams
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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 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, 2003).

Melbourne has the largest operating light rail system as well as a largest streetcar system in the world (Currie and Smith, 2006a). There are around 180 kilometres of tram tracks located in the center lanes of roads and nearly 1,200 curbside stops on these routes (Currie and Burke, 2013). Thus, 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 delay and how they vary for different road types, different tram service frequencies and service types.

This paper is an exploration of traffic delays caused by the operation of trams in Melbourne. It aims to quantify the order of impacts on traffic delay which occur on roads with tram routes in relation to the frequency of trams, traffic volumes and the capacity of roads.

This paper outlines a new methodology to determine traffic delays on road links with tram routes. In order to determine the impact of non-exclusive tram rights-of-way, micro-simulation is utilised to demonstrate vehicle travel time effects. Then, a conventional four step transport model (the Victorian Integrated Transport Model (VITM)) which takes the result from the micro-simulation as an input is used to forecast congestion levels caused by tram operations. The effect of semi-exclusive tram rights-of-way are also investigated by considering the reallocation of road space to provide priority for trams. VITM is also used to explore this reallocation impact. In addition, multiple performance measures that reflect many aspects of traffic congestion are selected from existing methods to present the impacts of trams on generating traffic congestion in relation to tram service frequency, traffic volume and road capacity. GIS is then used to illustrate the research results.

This paper is structured as follows: the next section outlines previous approaches to measure travel delay on links with tram routes 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.

Background

There has been a number of studies exploring various aspects of light rail systems. Safety at tram stops is one of the major concerns of published research (Currie and Smith, 2006b, Naznin et al., 2016). Other studies have investigated solutions to protect the operation of light rail vehicles. Traffic signal priority has been identified as a cost-effective way to improve the management of traffic systems in order to make on-street public transport more reliable, faster and more cost-effective, particularly at intersections (Currie and Shalaby, 2008, Garrow, 1997, McGinley and Stolz, 1985). With the introduction of hook turns, turning movements are banned in front of trams at key intersections but traffic can make the turn from the curbside lane instead (Currie and Reynolds, 2011).

However, there have been few studies that have attempted to quantify the delay resulting from the operation of light rail systems. 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. They compared the tram operations on road “with” and “without” curbside stops in traffic simulation. They found that curbside stops reduce average tram and traffic speeds by 8% to 12% (Currie et al., unpublished data on VicRoads R&D Project 799, 2004).

The provision of segregated tram lanes has been identified as an efficient mean 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, 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 would result in less severe 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 only on the impact of tram operations on a road link or a corridor. There are no studies assessing the network-wide effect of an entire tram network on traffic congestion. This research paper presents a new methodology for undertaking the aggregate estimation of travel delay caused by tram operations when considering the movement of traffic flow, road capacity and tram service frequency. The impact of tram operations on road network performance is also a major focus of this research.

**Research context**

*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 speed 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% (Currie and Burke, 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 roads. 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.
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Figure 1 Melbourne’s tram network

Study methodology

The purpose of this section is to describe a new methodology that has been developed to estimate the impact of tram operations not only on road links with tram rights-of-way but also on the entire road network. Thus, both micro-simulation and macro-simulation are used to create a more precise method for identifying the negative effect of the tram system in contributing to traffic congestion. Table 1 illustrates the methods adopted for estimating the effect of each tram right-of-way type on traffic.

Table 1 Methodology for assessing tram impacts on vehicle traffic

<table>
<thead>
<tr>
<th>Tram right-of-way</th>
<th>Tram</th>
<th>No Tram</th>
<th>Method for assessing direct tram effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exclusive</td>
<td>Tramway is constructed separately to road networks; does not have any effect on vehicle traffic.</td>
<td>Does not have any effect on vehicle traffic.</td>
<td>- 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: “have tram” and “no tram”.</td>
</tr>
<tr>
<td>Non-Exclusive</td>
<td>Trams operate with vehicle traffic. Low speed of trams and tram stop arrangements may cause delay for vehicles.</td>
<td>Vehicles are not affected by tram operations. Speed of vehicle traffic increases.</td>
<td></td>
</tr>
<tr>
<td>Semi-Exclusive</td>
<td>Trams share crossroads with general traffic but tram tracks are separated from traffic lanes.</td>
<td>Priority tram lane is returned to general traffic. Capacity of road link increases.</td>
<td>- Increase one lane for vehicle traffic on road links with trams in “no tram” scenario. - Use 4 step model to compare travel demand in two scenarios: “have tram” and “no tram”.</td>
</tr>
</tbody>
</table>
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Victoria Integrated Transport Model (VITM)

VITM 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 and Trips 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.

Improved method for modelling the impact of trams in VITM

The negative impact of trams in terms of their contribution to traffic congestion consists of two parts: (1) the effect of road capacity reduction due to the occupation of a semi-exclusive tram right-of-way and (2) the impact of trams on vehicle traffic on a non-exclusive tram right-of-way due to the sharing of road space. A new methodology for modelling the effect of tram operations on road traffic includes three stages:

Stage 1: Modelling the impact of the tram priority network on traffic
- In the “base case” scenario (without tram network), it is assumed that a semi-exclusive tram right-of-way would be changed to a vehicle traffic lane. Hence, an additional lane is added to links with a semi-exclusive tram right-of-way which increases the capacity of the road.
- In the “with tram network” scenario, on links with semi-exclusive tram rights-of-way, traffic would share a lane with trams.

Stage 2: Modelling the impact of on-street running on road traffic
- In the “base case” scenario (without tram network), links with a non-exclusive tram right-of-way are considered as a normal road without tram operations. The travel time on these links is calculated using Akcelik’s formula.
- In the “with tram network” scenario, trams operating in mixed traffic result in vehicle delay. Thus, travel time on these links is adjusted by adding a percentage travel time change to model the impact of trams on road traffic. The percentage change in travel time is estimated using micro-simulation.

Stage 3: Running VITM in the “base case” scenario and “with tram network” scenario.
- The outcomes between the two scenarios are compared to explore the impact of tram operations on links with tramways and on the wider road network.

Using microsimulation to model the impact of trams on a non-exclusive tram right-of-way

Simulation modeling seems to be a more efficient approach to do this research because it is complicated to collect field data. Vissim 7.0 is the software package that was used to model 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. The reason for choosing “Tram operations on a one-lane link” and “Tram operations on a two-lane link” for simulation is that VITM estimates travel demand on each link in the road network so the results from microsimulation can therefore be used as an input to VITM. Firstly, these scenarios are tested without trams to obtain a baseline average travel time on links. Next, the simulation is run with a various 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. Finally, the results between the “base case” scenario and “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 with each identified tram service frequency.

In order to get an accurate result from the simulation, the simulation is firstly run for a warm up period. It then continues running for one hour and records measures of performance for that period of time. A set of five runs are undertaken for each scenario to establish a variation in measures of performance to provide a mean and level of confidence in the result.

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 [23]. 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 curb side 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.

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 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 the survey undertaken in Melbourne by Currie et al. (2012).

Tram priority programs at intersections have not yet been implemented for the 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 popular 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.

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In order to simplify the microsimulation, several assumptions are made:
- The headway of trams on a road link is similar 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 in a two-lane link.
- The vehicle limit speed of all links with tram routes is 60km/h which is consistent with current practice in Melbourne.

Using macro-simulation to model the impact of tram operations on the road network

In VITM, in order to assign vehicle trips on Melbourne’s road network, travel time is calculated for each link using Akcelik’s formula. 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 of traffic volumes. The travel time on links including non-exclusive tram rights-of-way is added a percentage of change in travel time, that 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:

\[
Travel\ time = Travel\ time_0 + p\% * Travel\ time_0
\]

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.

Figure 3 illustrates the process for estimating the effect of tram operations in contributing to traffic congestion based on the cooperation between microsimulation and macro-simulation.

**Figure 3 The process of estimating the effect of tram operations on traffic congestion**

In terms of modelling the impact of semi-exclusive tram rights-of-way on traffic, in the “base case” scenario, it is assumed that trams are not available; a semi-exclusive tram right-of-way is
changed to a traffic lane. Thus, links with semi-exclusive tram rights-of-way have additional road capacity by adding one more lane.

The outcomes between the two scenarios, “base case” (with tram network) and “without tram network” are then compared to estimate the changes in congestion on the road network. These changes are considered to represent the negative effect of tram operations.

**Results**

The results are presented in three parts. Firstly, the effect of tram operations on travel time on links with non-exclusive tram rights-of-way is shown. Then, semi-exclusive tram right-of-way impacts are estimated by considering road-space reallocation impacts from vehicle traffic lanes to on-road tram priority lanes. In the final part, the impact of tram operations on the entire road network is presented.

**Effect of tram operations on links with non-exclusive tram rights-of-way**

In this section, the impact of tram operations on a link with a non-exclusive tram right-of-way is estimated using micro-simulation. This result is then incorporated into VITM (macro-simulation) to determine the non-exclusive tram right-of-way impact on general traffic.

**Micro-simulation**

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 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 (5, 8, 10…35 trams/hour). As can be seen from the graphs, 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 4](image-url)

**Figure 4** Percentage change in travel time caused by a non-exclusive tram right-of-way on a: (a) one-lane link and (b) two-lane link

**Macro-simulation**

Figure 5a and 5b, illustrate the relationship between tram frequency and the percentage change in travel time on one-lane links and two-lane links respectively with on-street running. It can be seen from the two graphs that the tram impact on one-lane links is higher than that on two-lane links. This effect increases when the frequency of trams increases.
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Figure 5 Change in travel time caused by non-exclusive tram right-of-way with various service frequencies

Overall, Melbourne’s non-exclusive tram rights-of-way cause an average decrease in vehicle volume and travel time of 34.2% and 22.4% respectively on one-lane links. On two-lane links, these figures are smaller (12.4% for vehicle volume and 10.5% for travel time). The impact is higher on links with high tram frequencies and smaller on links with low tram frequencies.

Effect of tram operations on links with semi-exclusive tram rights-of-way

Table 6 presents the average change in travel time and traffic volume on road links with semi-exclusive tram rights-of-way by number of traffic lanes. It can be seen from the table that tram operations cause a reduction in traffic volume and an increase in travel time on links with semi-exclusive tram rights-of-way. From data in Table 2, the relationship between the number of traffic lanes and the change in travel time resulting from the road space allocation of semi-exclusive tram rights-of-way is shown (Figure 6). Figure 6 shows that the percentage change in traffic volume decreases gradually following positive linear equation. If a road link has only one lane, the traffic volume increases by over 13% in the presence of semi-exclusive tram right-of-way. In contrast, an increase in the number of lanes leads to a reduction in travel time change caused by tram operations.

Melbourne’s semi-exclusive tram rights-of-way cause an average decrease of 19.6% in vehicle volume and 12.8% in travel time on links with tram priority. The impact is higher on road links with low capacity.

Table 2 Average change in travel time and volume on links with semi-exclusive tram rights of way

<table>
<thead>
<tr>
<th>Number of traffic lanes</th>
<th>Average percentage change in traffic volume on link (%)</th>
<th>Average percentage change in travel time on link (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-13.6</td>
<td>22.5</td>
</tr>
<tr>
<td>2</td>
<td>-12.5</td>
<td>20.1</td>
</tr>
<tr>
<td>3</td>
<td>-12.4</td>
<td>20.6</td>
</tr>
<tr>
<td>4</td>
<td>-12.1</td>
<td>11.9</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>-12.8</strong></td>
<td><strong>19.6</strong></td>
</tr>
</tbody>
</table>

Figure 6 Change in traffic volume and travel time caused by semi-exclusive tram rights-of-way

Overall, Melbourne’s entire tram operations result in an average increase of 20.5% in travel time on road links with tramways. On average, a tramway acts to reduce the volume of vehicles on links by 19.6%.
**Effect of tram operations on Melbourne’s entire road network**

In this section, the impact of both semi-exclusive and non-exclusive tram rights-of-way on the traffic of Melbourne’s entire road network is investigated.

Figure 7 shows the percentage of additional vehicles impacted by tram operations in relation to changes in travel time. It is clear that more vehicles suffer delay than the number of vehicles experiencing travel time reductions.

This illustrates that:
- Trams cause a significant increase in travel time (more than 10%) for approximately 10% of vehicles on Melbourne’s road network. Over 4% vehicles suffer an increase of more than 20% in travel time due to tram operations.
- In contrast, less than 1% of Melbourne’s vehicles experience a significant decrease (more than 10%) in travel time due to tram operations.

![Figure 7: Distribution of travel time changes due to tram operations](image)

Table 3 shows the level of congestion on Melbourne’s roads with tram operations in two scenarios “without tram” and “with tram”. The operation of trams in Melbourne increases actual travel time on average from 2.06 minutes/km to 2.16 minutes/km (an increase of around 4.6%). The number of severely congested links in Melbourne increases by 14.7% while the number of moderate congested links increases by 5.8%. Vehicle time travelled and total delay on the road network increases by 6% as a result of tram operations. The average road network speed drops from 35.4 km/h to 34.5 km/h (a decrease of 2.7%).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Base case (No tram)</th>
<th>Have tram</th>
<th>Absolute change</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of severely congested links (V/C&gt;=0.9)</td>
<td>1,051.0</td>
<td>1,205.0</td>
<td>154</td>
<td>14.7</td>
</tr>
<tr>
<td>Number of moderately congested links (0.9&gt;V/C&gt;=0.8)</td>
<td>973.0</td>
<td>1,029.0</td>
<td>56</td>
<td>5.8</td>
</tr>
<tr>
<td>Vehicle time travelled (millions veh-hr)</td>
<td>159.75</td>
<td>169.30</td>
<td>9.55</td>
<td>6.0</td>
</tr>
<tr>
<td>Total delay on road network (millions veh-hr)</td>
<td>9.50</td>
<td>10.08</td>
<td>0.58</td>
<td>6.0</td>
</tr>
<tr>
<td>Average travel speed (km/h)</td>
<td>35.4</td>
<td>34.5</td>
<td>-0.9</td>
<td>-2.7</td>
</tr>
<tr>
<td>Actual travel time per km (min)</td>
<td>2.06</td>
<td>2.16</td>
<td>0.1</td>
<td>-4.6</td>
</tr>
</tbody>
</table>

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

In general these aggregate impacts on the network are not large compared to the impacts on tram rights-of-way. When the tram network is removed, traffic volumes increase as traffic is attracted to roads which previously had tram right of-ways. The aggregate impact of tram operations on traffic includes these effects.
Discussion and conclusion

This paper has presented the results of research aimed at making an aggregate estimate of the impacts of tram operations in Melbourne on vehicular traffic. A literature review revealed that almost all previous studies focused only on the effects on road links with trams. There was no attempt to explore the network-wide impact of tram operations on travel time and traffic volume changes. Thus this paper created a new methodology to estimate the impact of tram operations not only on road links with tram but also on the entire road network. The method includes two parts. Firstly, micro-simulation is undertaken to investigate the relationship between travel time delay and traffic volume for various tram frequencies. These relationships are then incorporated into VITM (macro-simulation) to estimate the impact of trams on Melbourne’s road network. Secondly, VTTM is used to explore the effect of reallocating tram routes from vehicle traffic lanes. The reduction in capacity of road links is considered to be a negative impact of non-exclusive tram rights-of-way.

Using microsimulation, a relationship between the change in travel time and traffic volume was developed as a polynomial function. This function varies based on the tram frequency on a link. When applying these functions into VITM, the impact of non-exclusive tramways is determined in terms of travel time changes. The analysis shows that there is a relationship between tram frequency and the percentage change in travel time on a one-lane link \( y = 1.6422x + 4.8962 \) and two-lane link \( y = 1.0384x - 0.3488 \). These equations can be used to predict changes in travel time caused by non-exclusive tramways under different tram frequencies. In terms of the negative impacts of semi-exclusive tram rights-of-way, the relationship between the number of lanes and traffic volume \( y = 0.474x - 13.81 \), and travel time changes \( y = -3.159x + 26.675 \) caused by road space allocation of priority tram routes has been explored. In this study, the effect of exclusive tram rights-of-way on road traffic is not considered because they account for a very small part of the tram network. Overall, Melbourne’s entire tram network results in an average increase of 20.5% in travel time for vehicle traffic in areas with tram operations. On average, a tramway acts to reduce the volume of vehicles on links by 19.6%. The aggregate impact of Melbourne’s tram network on traffic in areas with tram operations is an increase in average travel time from 2.06 to 2.16 minutes/km (an increase of around 4.6%). This is associated with an increase of 14.7% in the number of severely congested road links. Vehicle time travelled and total delay on the road network increase by 6% as a result of tram operations. It was also found that tram operations not only increase but can also decrease congestion on a number of road links. However, the number of road links experiencing an increase in congestion are greater than the number of uncongested links caused by tram operations.

These network wide effects are not large compared to localised modelling but network effects include representation of traffic diversion impacts which will counter-act some of the immediate impacts on a localised scale.

The main contributions of this paper are:
- Development of formulas for forecasting travel delay and traffic volume changes on links with tram operations.
- Investigating the network-wide effect of tram operations.

A limitation of the research underlying this paper is that additional delay experienced by vehicles associated with tram priority at intersections is not modelled. A key area for future research would be to address this limitation. This research is part of a wider project exploring how to evaluate the impacts of public transport on traffic congestion. In this project, both positive and negative impacts of public transport on traffic congestion are explored, with a range of opportunities investigated to improve methodological approaches.

Overall the new method described in this paper is considered as an advance in knowledge regarding approaches to aggregate estimation of the effects of tram operations on road network.
References