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Modelling the net traffic congestion impact of bus operations in Melbourne

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ABSTRACT

Bus services can be seen as a way to reduce traffic congestion where they can encourage a mode shift from car. However, they can also generate negative effects on traffic flow due to stop-start operations at bus stops. This paper aims to assess the net impact of bus operations on traffic congestion in Melbourne. The methodology used to achieve this aim comprised of three main stages. First, a primary survey was conducted to determine the mode shift from bus to car when buses are unavailable. This figure was used to estimate the positive impact of buses on relieving congestion. Second, the negative impact of buses was investigated by considering the effect of bus stop operations on vehicle traffic flow using microsimulation. Finally, the net effect was estimated by contrasting congestion measures determined from a traditional four step model between two scenarios: 'with bus' and 'without bus'. The results indicated that Melbourne's bus network contributes to reduce the number of severely congested road links by approximately 10% and total delay on the road network by around 3%. The highest congestion relief impact was found in inner Melbourne with a 7% decrease in vehicle time travelled and total delay, and 16% decrease in the number of heavily congested road links. In inner areas, the level of congestion is relatively high so the mode shift from car to bus, even if not as high as middle and outer areas, have a significant effect on relieving traffic congestion. Areas for future research are suggested such as investigating the long-term effect of buses on traffic congestion.

1. Introduction

In order to tackle rapidly increasing traffic congestion, particularly in urban areas, public transport systems have been developed in many cities around the world (Litman, 2016, Nguyen-Phuoc et al., 2017, Mackett and Edwards, 1998). Public transport can support reductions in car use and if improved, its attractiveness can also provide a long term solution towards encouraging mode shift. With a number of advantages such as cost effectiveness, reliability and accessibility, buses have been able to attract car users (Waterson et al., 2003). In 2015–2016, the bus system in Melbourne carried 139 million passenger trips, with this figure expected to increase in the future (Public Transport Victoria, 2016a). A 'Better Bus Network' program, costing more than $100 million, will be delivered in 2018 to improve the existing bus system in Melbourne by providing more buses where they are needed, increasing access

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to trains, education, employment, health services and retail precincts (Public Transport Victoria, 2016b). However, the operation of buses also contributes to traffic congestion (Chand et al., 2014, Kwami et al., 2009, Tang et al., 2009). The capacity of roads with bus routes can be influenced by bus stop operations, particularly at curbside bus stops (Koshy and Arasan, 2005). During bus dwell time, the presence of a stopped bus creates a temporary bottleneck at the location of bus stops which reduces the road capacity. In addition, the relatively low acceleration/deceleration rate of buses at bus stops as well as at intersections can also cause delays for other vehicles on the road network.

Even though congestion relief is considered to be one of the main rationales for providing public transport in cities, research focusing on traffic congestion impacts associated with public transport in general and bus in particular is limited (Larwin, 1999, Gray, 1992, Nielsen et al., 2005, Vuchic, 2005). Understanding the congestion impacts associated with buses can help authorities to identify the effectiveness of bus operations in relieving congested areas or congested routes. From this, related policies or improvement projects can be proposed to seek a desired level of congestion relief.

While a number of studies have explored either the congestion relief impact or congestion generation impact of bus operations, no research has investigated the net impact of bus operations on an entire road network. This paper aims to fill that gap by exploring the net congestion impact associated with the operation of buses, using a case study of Melbourne. It considers both the positive effect of buses on reducing traffic congestion and the negative impact of buses on creating congestion to determine the 'net' impact. This paper also represents a methodological advancement from previous research that has explored the congestion relief impacts of public transport (Nguyen-Phuoc et al., 2017, Aftabuzzaman et al., 2010b). Firstly, a primary survey of bus users is conducted to explore the mode shift used for estimating the positive effect. Secondly, a more comprehensive range of factors affecting the negative congestion impact are investigated using calibrated traffic microsimulation models.

The paper is structured as follows: the next section outlines previous studies in relation to the traffic congestion impact of buses. The research context is then described, including a description of Melbourne's bus network. This is followed by a description of the research methodology. The results are then presented, followed by a discussion, concluding remarks and areas for further study.

2. Background

The congestion impact of bus operations on a road segment or a corridor has been explored by a number of researchers. In particular, the negative impacts of buses on generating traffic congestion has received much attention. These congestion effects mainly include the effect of bus stop operations and the effect of bus priority such as exclusive bus lanes or signal priority for buses. Zhao et al. (2007), Yuan et al. (2007) and Tang et al. (2009) used theoretical models to simulate the impact of bus operations at bus stops on traffic flow. Other researchers have investigated bus stop impacts on vehicle traffic by collecting field data and using statistical models to find the relationship between the impact and bus related parameters such as frequency and dwell time (Kwami et al., 2009, Ben-Edigbe and Mashros, 2011). The wide range of characteristics related to bus stops is normally very difficult to collect in the field so traffic simulation has commonly been used to analyse traffic flow at and around bus stops (Fitzpatrick and Nowlin, 1997, Koshy and Arasan, 2005). Parameters typically assessed include dwell time, bus frequency, bus stop location, bus stop type, number of road lanes and components of heterogeneous traffic flow. Results of traffic simulation research has found that curbside bus stops tend to have a much higher impact on vehicle traffic flow than bus bays.

In terms of measuring the impact of bus priority on traffic congestion, particularly the provision of exclusive bus lanes, several studies have been undertaken (Shalaby, 1999, Currie et al., 2007, Arasan and Vedagiri, 2010). Shalaby (1999), with the help of the TRANSYT-7F simulator, examined changes in the performance measures of through buses and adjacent traffic following the introduction of reserved bus lanes in an urban arterial in downtown Toronto, Canada. He found that the bus lanes resulted in an increase in bus ridership while adjacent traffic volumes showed a reduction. Currie et al. (2007) developed a comprehensive methodology to evaluate tradeoffs in the use of the limited road space in Melbourne, Australia for new bus and tram priority projects. Under this methodology, traffic microsimulation was used to assess the impact of road-space reallocation, while changes in travel patterns were assessed through travel behaviour modelling. Arasan and Vedagiri (2010) applied microsimulation techniques to explore the impact of reserved bus lanes on the flow of highly heterogeneous traffic on urban roads. They found that the addition of exclusive bus lanes contributes to a 3–8% increase in travel time of other vehicles on the road network.

Studies investigating the network-wide congestion effects of buses have been limited to date. One study using models to simulate and assess the congestion relief impact of buses on the entire road network was conducted by Aftabuzzaman et al. (2010b). This research assumed that a proportion of bus users would divert to cars if the bus system is removed. From secondary research, they found that, on average, 32% of all public transport users would shift to car. This fixed value was adopted for bus trips and applied to a transport network model in Melbourne to estimate the congestion relief impact of bus operations. The contrast between congestion measures obtained from two scenarios, 'with bus' and 'without bus', was considered to represent the amount of avoided congestion associated with buses. They found that Melbourne's bus operations contribute to reduce the number of congested road links by approximately 13% and total vehicle travel delay by nearly 37%.

2.1. Gaps in knowledge

While there has been several attempts to explore the congestion impacts of buses on a road link or a corridor, little is known about the network-wide impact of buses on traffic. Indeed, the operation of buses not only affects adjacent links but also results in traffic volume changes in surrounding areas due to traffic diversion and reassignment. To date, only one study has examined the network-wide effect of buses on reducing traffic congestion (Aftabuzzaman et al., 2010b). In this study, the mode shift from bus to car was

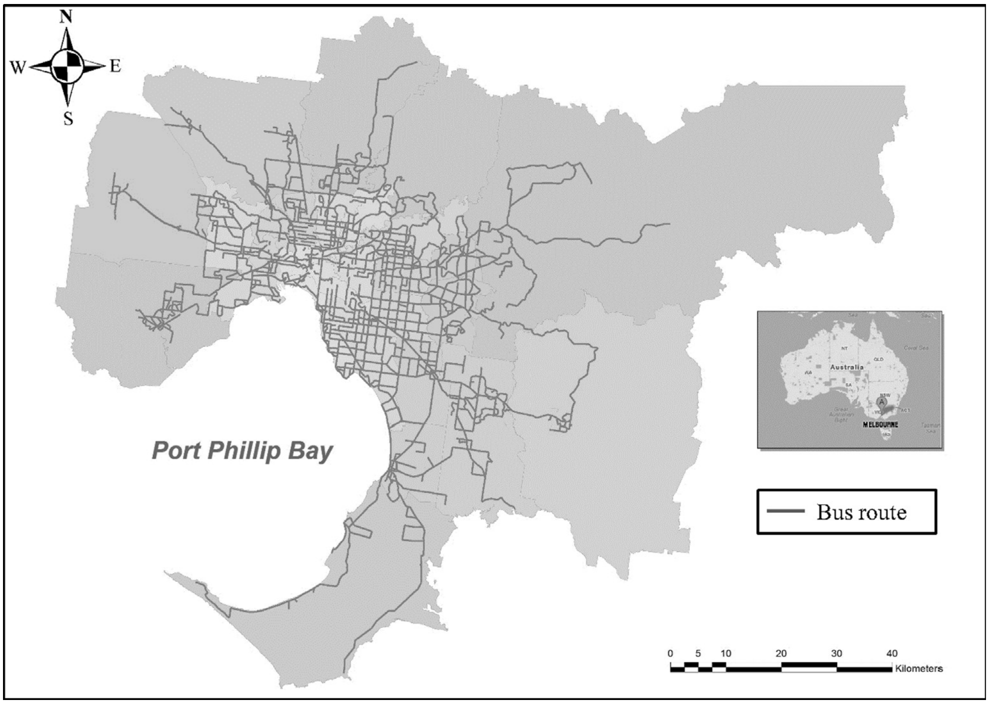

Fig. 1. Melbourne's bus network.

determined using secondary data and this figure was fixed for all locations. In addition, only the positive effect of bus operations was estimated; the negative effect of buses such as traffic delay caused by bus stop operations was not considered.

This paper is the first to provide a methodology to assess the net impact of bus operations on traffic congestion. To estimate the positive impact, bus user diversion to private car when buses are not available was estimated from a primary survey of Melbourne's bus users. The negative impact of buses was modelled with the help of traffic microsimulation.

3. Research context

3.1. Melbourne's bus network

The bus network in Melbourne (Fig. 1) consists of 346 routes operated by 32 privately owned bus companies (Public Transport Victoria, 2015). Bus is the third most used form of public transport in Melbourne with 137 million passenger trips in 2015–16 after the commuter railway network (233 million) and tram network (204 million) (Public Transport Victoria, 2016a). While the city relies on a radial train network and inner city tram network, the middle and outer suburbs are primarily serviced by buses (Currie and Loader, 2010). Buses normally operate in mixed traffic conditions although there are some exclusive bus lanes (accounting for only 0.7% of the bus network) provided for premium bus services

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

3.2. Spatial unit of analysis

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

4. Research methodology

This section describes the methodology that has been developed to estimate the net traffic congestion impact of bus operations on the entire road network. In the first part, a primary survey is described which aims to determine the mode shift from bus to car in the event of bus withdrawal. This is followed by an introduction of the Victorian Integrated Transport Model (VITM) and secondary data sources relating to Melbourne's bus operations. Steps involved in assessing the net effect of buses on traffic congestion is detailed in the final part.

4.1. Primary survey for estimating the mode shift from bus to car

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

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

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

4.2. Victorian integrated transport model

The Victorian Integrated Transport Model (VITM) is used in this research as part of estimating the net effect of bus operations on traffic congestion. The 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 (28,499 nodes), divided into 2959 zones. Nodes usually represent an intersection or a change in road characteristics, while links represent the segments of actual roads in the network. The 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.

4.3. Secondary data sources relating to Melbourne's bus operations

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

- *Bus Boardings and Alightings at Bus Stops:* This dataset presents the number of passengers boarding and alighting on a 'typical' weekday at each bus stop for the 7am to 7 pm period. This figure is estimated for the AM peak (7am-9am) by applying the proportion of patronage for each bus route in the AM peak compared to the 7am-7 pm period. The dwell time at bus stops was then estimated through a non-linear model using total passengers as the independent variable (Rajbhandari et al., 2003). By analysing data collected daily for the whole year of 2001 on a bus route in New Jersey, Rajbhandari et al. (2003) found that *Dwell time* $= a$ (total passenger)^b where $a = 7.26$, $b = 0.738$ ($R^2 = 0.741$, sample size = 8306).
- *Timetable and Geographic Information:* This dataset provides static timetable data and geographic information. It contains scheduled information for all metropolitan and regional bus services in Victoria. From this dataset, the frequency at each bus stop in the AM peak can be determined.
- *Bus Stop Infomation:* This dataset includes spatial objects (points) representing the location of public bus stops used by metropolitan bus routes, SkyBus routes, night bus routes, regional bus and regional coach routes. It does not include 'Country Free School Bus' stops. Each stop has a number of attributes including the stop ID, stop type, stop name, ticket zone and list of bus routes using the stop.

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

4.4. Method for modelling the net impact of buses on traffic congestion

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

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

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

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

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

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

4.4.1. Microsimulation approach

Traffic microsimulation (VISSIM 8.0) is used to estimate delays caused by bus stop operations at bus stops as well as at intersections (since the acceleration/deceleration of buses is lower than cars). For microsimulation purposes, the effect of buses on a particular road link is the focus of analysis. The main performance measure used is travel time. This figure is estimated by averaging the travel time of each vehicle on the segment. The reason for choosing travel time as a key measure is that travel time is calculated on each road link and used as the main criteria for assigning vehicle trips to the road network in VITM. Thus, the effect of buses on traffic is represented by the increase in average travel time between two scenarios: 'with bus' and 'without bus'.

The developed microsimulation model consists of a road link, a bus stop (curbside or bus bay), detectors and traffic signals. A bus stop is located at the mid-point of the road link as shown in Fig. 2. In VITM, the average length of links with bus operations is approximately 300 m, with around three intersections per kilometre. Thus, a 300 m road link with a bus stop and an intersection is modelled to estimate the impact of bus operations on vehicle traffic flow. The intersection is located at the end of the link in order to be consistent with the road links with bus operations modelled in VITM (Department of Transport, 2011).

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

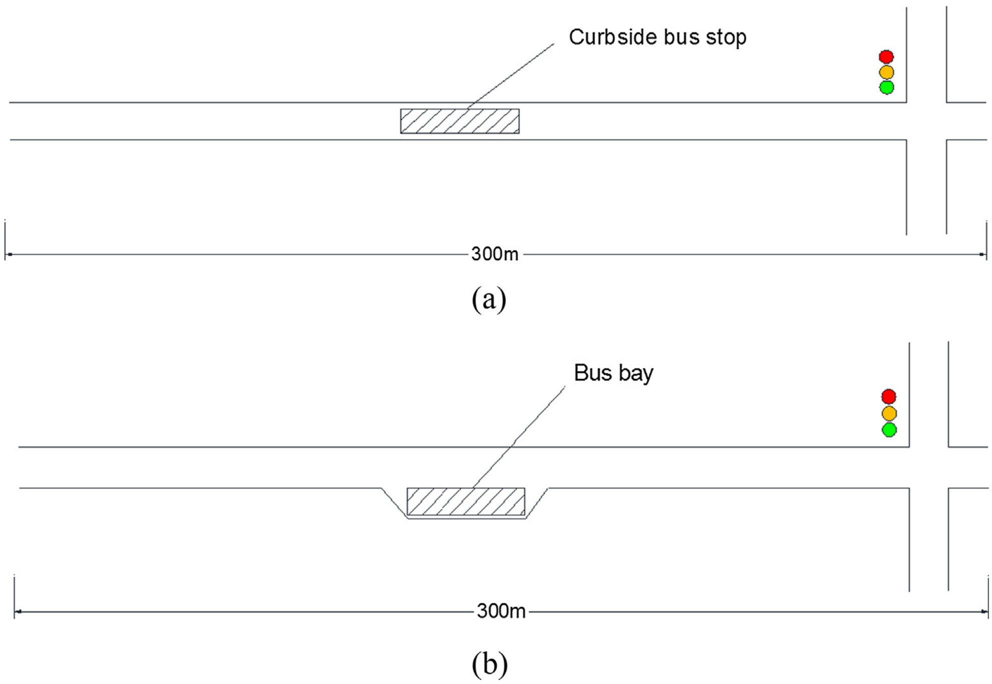

Fig. 2. Modelled road links with: (a) curbside bus stop and (b) bus bay.

Table 1
Parameters set in the VISSIM microsimulation.

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

– The headway of buses on a road link is the same even if the link is shared by various bus routes.
– On road links which have more than one bus stop, it is assumed that those links have one stop with the total equivalent bus frequency and number of passengers boarding and alighting.
– From the dataset '*Bus Stop Information*', the number of mid-block bus stops accounts for the majority of bus stops in Melbourne (more than 80%). Thus, it is assumed that bus stops are located at the middle of road links.
– It is assumed that intersections are controlled by fixed traffic signals with a cycle time of 60 s. The all orange period and intergreen time are assumed to account for 6 s so the green time for each leg is 27 s (see Table 1).

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

The number of parameters we would ideally like to calibrate is high, but this is seldom possible because of the computational effort involved and limited data availability. In this particular study, parameters such as look ahead distance (from 250 m to 100 m), observed vehicles (from 2 to 4), standstill acceleration (from 3.5 m^2 to 2.00 m^2), acceleration with 80 km/h (from 1.5 m^2 to 0.5 m^2) were adjusted through trial and error. More importantly, the desired speed distribution also changed which has a significant influence on highway capacity and achievable travel speeds. Since the speed distribution plays a critical role in roadway capacity and travel speed (PTV, 2015), adjusting a stochastic distribution of speeds has been carefully performed. The horizontal axis represents the desired speed whereas the vertical axis shows the cumulative percentage from 0 to 100. Compare to the default graph, the calibrated distribution is shown as a S-curve which can replicate more median values are simulated. As shown in Fig. 3, intermediate points also were adjusted from red dots to blue dots.

Fig. 4 plots speed against frequency for the observed data and simulated data. Intuitively, the results in simulation are well matched after calibration. This is supported by a statistical analysis of both datasets which shows an average speed of 80 km/h with less than 10 km/h standard deviation. The correlation (R^2) between two data sets is 0.97.

As with most traffic simulation software, VISSIM can be accessed by an external interface. The VISSIM COM interface defines a hierarchical model in which the functions and parameters of the simulator originally provided by the graphical interface can be manipulated by programming (Tettamanti and Horváth, 2015). With the use of the VISSIM COM interface, multi run tasks can be automated. In this research, the calibrated VISSIM models (six scenarios comprising two bus stop types and three types of road links) were run each combination of dwell time, speed limit, traffic volume, and bus arrival frequency (Table 2). In total, 6408 scenarios (2 * 3 * 3 * 4 * 8 * 9) were created. The simulation ran for an hour (3600 s) with intervals of 0.1 s. In order to consider the variability of microsimulation output, five random seeded runs were conducted for each set and the results for five runs were averaged. Hence, a total of 32,040 runs were conducted.

The results of microsimulation were used to develop a number of models (such as linear models and nonlinear models) that show

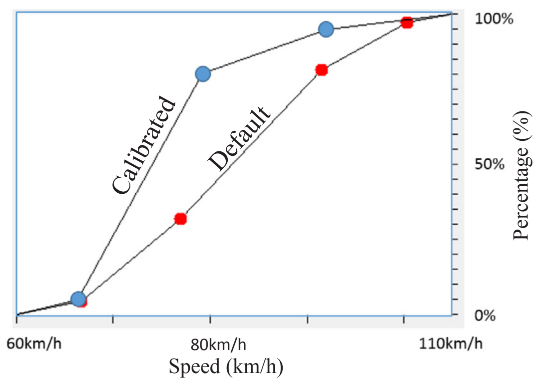

Fig. 3. Default vs. calibrated traffic speed distribution in VISSIM.

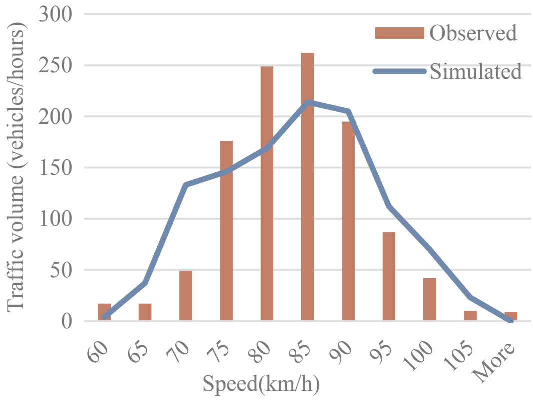

Fig. 4. Comparison of observed (field) data and simulated VISSIM output.

Table 2
Parameter values used in microsimulation.

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

the relationship between the increase in travel time caused by bus operations and a number of related characteristics for six scenarios. All of these models were run to find the best line of fit based on the highest R^2 value. The models can be expressed as follows:

$$\text{Increase in travel time for each scenario} = \text{f(dwell time, traffic volume, frequency, speed limit)} \quad (1)$$

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

4.4.2. Macro-modelling approach

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

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

$$Travel\ \ time = \text{Travel}\ \ \text{time}_0 + \text{p}\% * \text{Travel}\ \ \text{time}_0 \quad (2)$$

where

p%: is the percentage change in travel time caused by bus stop operations; it is calculated using the regression functions created from the results of traffic microsimulation.
Travel time_0: Travel time on link with bus operations when the impact of bus stop operations is not considered.
Travel time: Travel time on link with bus operations.

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

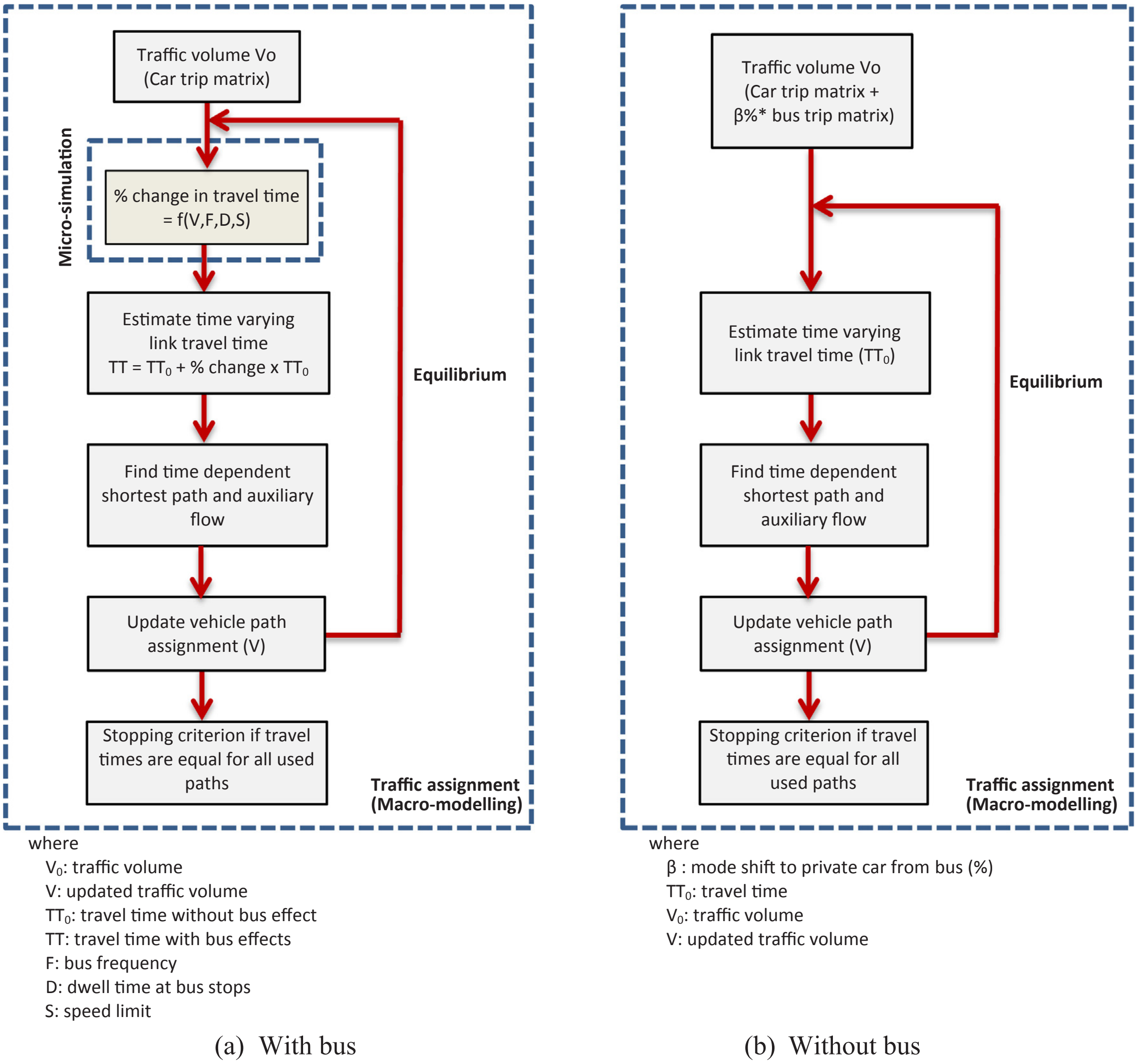

Fig. 5. Process of estimating travel demand in the two scenarios.

congestion. This increase represents the traffic congestion relief impact of bus operations.

Fig. 5 shows the modelling process for the two scenarios: 'with bus' and 'without bus'. The outcomes between the two scenarios are compared to explore the changes in congestion measures on the road network. These changes represent the net effect of bus operations on traffic congestion.

5. Results

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

5.1. *Mode shift from bus to car*

Primary research was conducted with bus users in Melbourne in April 2016. Table 3 presents the stated mode shift of bus users in the event of bus service cancellations. Around 29% of respondents said they would drive a car while 9.1% said they would travel by car as a passenger. Approximately 24% and 12% of respondents would switch to trains and trams respectively. Bus withdrawal is expected to generate a mode shift to walking of 11.2%. Cancelling the trip was chosen by 8.6% of respondents. These figures are substantially different for each part of metropolitan Melbourne, reflecting the different traffic and land use characteristics of those areas (Nguyen et al., 2015). For instance, in inner Melbourne if buses are not available, the mode shift to car as a driver is lower than

Table 3
Mode shift of bus users when bus services cease.

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

* Mode shift to car = mode shift to car as driver + ½ mode shift to car as passenger $n = 187$.

that in the middle and outer areas (23.1% compared to 32.4% and 28.6%). This is because people in inner areas have greater access to other public transport modes such as train or tram.

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

5.2. Microsimulation results

From the results of microsimulation, both linear models (such as multilinear and quadratic models) and nonlinear models (such as exponential and logarithmic models) were developed. The exponential model, one of the simplest nonlinear regression models, was found to be the best fitting model as it had the highest R^2 value.

Six exponential models were developed to predict the percentage increase in travel time resulting from bus operations for six different road link types (as shown in Table 4). All selected parameters have a significant impact on the increase in travel time in these nonlinear regression models. The R2 values are all at least 0.80, indicating a relatively high level of correlation.

5.3. Macro-modelling results

There have been a number of measures used to determine the level of congestion on a road network. In this study, the most common congestion measures, which include the number of severely congested links, the number of moderately congested links, vehicle distance travelled, vehicle time travelled, total delay on road network, average travel speed and actual travel time per km, were used to measure the level of congestion.

Table 5 shows the level of congestion on Melbourne's road network and Melbourne's bus route network in two scenarios 'with bus' and 'without bus'. The changes in congestion measures between the two scenarios are recognised to be the net traffic congestion effect of Melbourne's bus operations on the entire road network and on the bus route network. Results in Table 5 detail that:

For the entire Melbourne's road network:

Table 4
Functions for estimating travel time increases caused by bus stop operations.

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

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

Table 5
Net impact of bus operations on Melbourne's road network.

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

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

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

For the Melbourne's road network with bus routes:

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

Table 6 compares the congestion impact of bus operations on the entire road network in various parts of Melbourne. It shows that the Melbourne's bus operations have the highest impact in inner areas and the lowest effect in outer areas. Table 6 shows that:

For inner Melbourne:

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

For middle Melbourne:

Table 6
Net impact of bus operations on Melbourne's road network in inner, middle and outer areas.

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

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

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

For outer Melbourne:

- The operation of buses results in a reduction in the number of severely congested links of more than 15% and in the number of moderately congested links of more than 7%.
- There is a decrease in vehicle time travelled and total delay on the road network of 2.1%.
- Travel time on average decreases slightly from 1.6 min/km to 1.5 min/km (1.5% decrease).

6. Discussion and conclusions

This paper presented a new methodology to assess the net impact of bus operations on traffic congestion. Consideration was given to the impact of buses in both reducing road traffic through mode shift as well as their negative impact in creating congestion. There are a number of advancements to the research methodology compared with previous research that has explored the congestion relief impacts of public transport (Nguyen-Phuoc et al., 2017, Aftabuzzaman et al., 2010b). Firstly, a primary survey was conducted with Melbourne's bus users to investigate the mode shift to car when buses are not available. This figure varied for different areas (inner, middle and outer) was used to assess the positive impact of bus on reducing traffic congestion. Secondly, the method for estimating the negative effect of buses involved incorporating travel delays estimated from calibrated traffic microsimulation models into a traditional four step model (VITM). Here, a wide range of factors affecting congestion generation from bus operations were included such as bus service frequency, traffic volume, speed limit, dwell time, number of lanes and bus stop type.

The results of the primary survey showed that if bus services cease, bus users would change their travel behaviour. The mode shift to car (as car drivers or passengers) accounts for the highest share of bus users (over 30%). This is followed by mode shift to other public transport modes (23.5% for train and 11.8% for tram). The mode shift to car in middle and outer areas is found to be higher than that in inner areas (36.7 and 35.1% compared to 24.4%). The explanation for this could be that the trip distance of bus users in these areas is much higher than that in inner areas, so car would be an appropriate alternative mode when buses are not available. Additionally, public transport service coverage and frequency is lower in middle and outer Melbourne so a higher share of bus users are likely to transfer to car in these areas.

The findings show that although there are some negative effects, the net congestion impact of bus operations on the entire road network, including both roads with and without bus operations, is positive. The operation of buses in Melbourne acts to reduce the number of severely congested links and moderately congested links by approximately 10% and 6% respectively. There is a reduction of nearly 3% in vehicle time travelled and total delay on the road network. The congestion relief effect of buses on the bus route network is not much higher compared to the impact on the entire road network. Hence, the operation of buses not only reduces traffic congestion on roads with bus routes but also decreases congestion on other surrounding roads.

Melbourne's bus services have the largest congestion effect on the road network in inner areas. Vehicle time travelled and total delay on the road network decreases by 7% due to the bus operations. The operation of buses also contribute to reduce the number of heavily congested links by 16% and the number of moderately congested links by 6%. Indeed, the level of congestion in these areas is highest, with many road links at capacity in peak periods, so the mode shift from cars to buses (even if it is not as high as that in the middle and outer areas) has a significant effect on reducing traffic congestion. This is consistent with the findings of Thomson (1968). He found that once roads reached capacity, even small reductions in traffic can reduce delays significantly. In contrast, in the outer areas, although bus is the major form of public transport and the mode shift from car to bus is higher than that in inner areas, the congestion impact of buses is lower compared with inner and middle areas. Bus operations in outer Melbourne reduces vehicle time travelled and total delay on the road network by only 2%. This is despite a reduction in the number of heavily congested links of more than15%, compared to only 6% in middle areas.

The results from microsimulation show that bus bay stops have much less impact on traffic than curb-side bus stops. In order to reduce the effect of buses on traffic congestion, bus bay stops should be considered where sufficient land is available. However, buses themselves at bus bays can be delayed by having to wait for a gap in traffic since cars can block a bus leaving the bay.

This paper makes a number of key contributions. First, it has helped understand likely change in travel behaviour among bus users when bus operations cease. Second, a new methodology for estimating the net effect of bus operations on traffic congestion has been developed. Third, the spatial variation of congestion reduction impacts of buses was explored.

In this research, the buses were assumed to travel at the speed limit. However, in reality buses may travel at a slower speed which may have a greater impact on congestion. Additionally, the impact of specific bus stop locations is not considered in this study. These aspects should be explored in the future research. This research has assessed the traffic congestion impact of bus operations under the assumption of short-term removal of buses. When bus services are unavailable in the long-term, the reaction of bus users might be different. Thus, the effect of bus removal in the long-term should be explored in future research.

In summary, this research has found that Melbourne's bus operations results in a net reduction in traffic congestion on the road network. This is an important finding that helps to demonstrate the contribution that bus services make to transport objectives and wider urban sustainability goals.

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