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ORIGINAL RESEARCH

Traffic congestion relief associated with public transport: state-of-the-art

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Abstract
Public transport (PT) influences the urban road system in many ways, including traffic congestion, environment, society, safety and land use impacts. While there are many studies focusing on the benefits of PT, research on congestion impacts, a fundamental component of any analysis of transport performance, associated with PT has received little attention. This paper aims to review the traffic congestion impacts of PT and how they are assessed. Traffic congestion is most commonly related to vehicle travel; yet, the real measure of congestion in transport systems is people travel. This paper looks at the appropriateness of existing traffic congestion measures and how suitable they are for measuring the impact of an existing PT system in the short-term. The literature review indicates that most studies relating to the congestion impacts of PT have used vehicle-based congestion measures. People-based measures may be more appropriate in assessing PT impacts. The paper also proposes a new framework for looking at the short-term effects of an existing PT system on traffic congestion. It suggests a few areas where further work can be undertaken to improve our understanding of traffic congestion incorporating PT such as exploring the mode shift from PT to car, estimating network-wide PT congestion creation impacts and determining the net congestion impact of PT.

Keywords Public transport · Traffic congestion · Mode shift · Network-wide · People-based

1 Introduction

Traffic congestion is a major urban transportation issue as it can be a barrier to economic growth (Douglas 1993). Some authors have suggested that high quality, grade-separated PT would reduce traffic congestion and that improvement in urban PT can be a cost-effective investment when considering all economic effects

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(Aftabuzzaman et al. 2010a; Bollinger and Ihlanfeldt 1997; Pavkova et al. 2015). However, other researchers have argued that current transportation evaluation practices tend to overlook and undervalue the benefits of PT (Litman 2015; Rubin and Mansour 2013) due to the negative impacts that PT can have on creating congestion such as the operation of at-grade rail crossings (Okitsu and Lo 2010; Taggart et al. 1987), tram priority, bus stop operations (Chandler and Hoel 2004; Rymer et al. 1989). In addition, it has been suggested that investments on PT are ineffective at reducing traffic congestion and financially wasteful (O'Toole 2004; Stopher 2004; Taylor 2004). They believed that when a vehicle driver shifts mode to PT, another driver uses this open road space. In order to compare these arguments, understanding the net traffic congestion impact associated with PT is important.

Once congestion of traffic systems with PT components is understood, the routes or corridors facing congestion can be targeted for attention to seek a desired level of congestion relief. Further, appropriate PT policies that can encourage desired development in designated locations providing congestion relief can be explored. Recently, there has been a limited number of studies assessing the impacts of PT on traffic congestion. These will be explored in this paper.

There is a growing interest in understanding the impact of PT on traffic congestion in urban areas. PT is often seen to be increasing congestion when in fact there are considerable overall benefits to the system-wide level of congestion by its presence. This paper aims to look at the appropriateness of existing traffic congestion measures and how suitable they are for measuring the impact of a PT system in the short-term. The paper also proposes a new framework for looking at the short-term effects of an existing PT system on traffic congestion. Investigating traffic congestion relief impact associated with PT requires a good understanding of two major areas:

- The measurement of traffic congestion, particularly measurement of congestion levels for mixed traffic flow with existing PT systems; and
- The adaption of congestion measures into the estimation of congestion impact associated with PT.

In order to meet the research aim, a detailed literature review of published academic research papers and industry reports relating to the assessment of traffic congestion and PT transport congestion impact was undertaken. Google Scholar (https://scholar.google.com/) and the ISI Web of Knowledge (http://www.isiwebofknowledge.com) were two general databases searched. A number of different search terms were used to source relevant studies such as *traffic congestion, congestion measure, PT impacts, PT congestion relief, PT congestion reduction, PT congestion creation, PT congestion impact.* After reviewing the title and abstract of each searched publication, a total of 93 studies were found to be relevant. However, only 51 of these focused specifically on the assessment of PT congestion impacts and, therefore, provided the main basis for the literature review. A number of the remaining 42 publications were used to provide context as needed.

This paper is presented as follows. The detailed review of the impacts of PT on traffic congestion is first presented. There are three sub-sections: a review of various definitions of traffic congestion, the measurement of traffic congestion and the assessment of traffic congestion impacts associated with PT. The paper concludes with the identification of gaps in knowledge and a discussion on opportunities available to advance knowledge in the identified areas.

2 The impacts of PT on traffic congestion

The common way to determine the impact of PT on traffic congestion is to contrast congestion measures in a scenario 'with PT' and 'without PT'. Hence, it is necessary to understand how traffic congestion is defined and how to measure traffic congestion, particularly in mixed traffic conditions (PT vehicles operate with private vehicles). This section firstly provides the definition and measurement of traffic congestion. A review of traffic congestion impacts resulting from PT, including methods used for assessing the impacts and their associated results, is then presented.

2.1 Definitions of traffic congestion

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

- demand related;
- delay related; and
- cost related.

Table 1 summarises the definitions of traffic congestion presented in the literature. There is no definition that presents the whole picture of traffic congestion. In terms of cause and effect, definitions are related:

- to demand (Rosenbloom 1978; Pucher et al. 1979; Rothenberg 1985; Vaziri 2002), which can be considered the cause of congestion (demand exceeds capacity);
- while delay-related definitions (Meyer 1997; Lomax et al. 1997; Weisbrod et al. 2001; Downs 2004; Lee and Vuchic 2005; Falcocchio and Levinson 2015) and
- cost-related definitions (Litman 2000; Vuchic et al. 1998; Verhoef 2000; Kockelman and Kalmanje 2005; Naudé and Tsolakis 2005) can represent the effect of congestion.

According to Calderdale Council (2015), traffic congestion is an inherently difficult concept to define as it has both physical and relative dimensions. In physical terms, congestion can be explained as the way in which vehicles interact to impede other vehicles. These interactions and their influence on individual journeys usually increase since travel demand approaches the capacity of a road or when capacity itself is reduced through road works or PT operations (such as trams). However, the

Table 1 Definitions of traffic congestion Source: author's synthesis

	Author	Definition
Demand-related	Rosenbloom (1978)	Traffic congestion occurs when travel demand exceeds the existing road system's capacity
	Pucher et al. (1979)	Congestion denotes any condition in which demand for a facility exceeds free-flow capacity at maximum design speed
	Rothenberg (1985)	Congestion is a condition in which the number of vehicles attempting to use a roadway at any time exceeds the ability of the roadways to carry the load at generally acceptable service levels
	Vaziri (2002)	Congestion occurs when traffic demand approaches and exceeds highway capacity
Delay-related	Meyer (1997)	Congestion means there are more people trying to use a given transportation facility during a specific period of time than the facility can handle with what are considered acceptable levels of delay or inconvenience
	Lomax (1997)	Traffic congestion is travel time or delay in excess of that normally incurred under light or free-flow travel conditions
	Weisbrod et al. (2001)	Traffic congestion is a condition of traffic delay (when the flow of traffic is slowed below reasonable speeds) because the number of vehicles trying to use the road exceeds the traffic network capacity to handle those
	Downs (2004)	Traffic congestion occurs when traffic is moving at speeds below the designed capacity of a roadway
	Lee and Vuchic (2005)	Congestion is the phenomenon of increased auto travel time due to increased travel demand
	Falcocchio and Levinson (2015)	Congestion in transportation occurs when the occupancy of spaces (roadways, sidewalks, transit lines and terminals) by vehicles or people reaches unacceptable levels of discomfort and delay
Cost-related	Litman (2000)	Traffic congestion represents the incremental costs resulting from interference among road users
	Vuchic et al. (1998), Verhoef (2000), Kockelman and Kalmanje (2005)	Congestion can be viewed as the result from under-pricing of the road network and marginal cost pricing can be used to internalise the congestion externality
	Naudé and Tsolakis (2005)	Congestion may be regarded as the point at which an additional road user joins the traffic flow and affects marginal cost in such a way that marginal social cost of road use exceeds the marginal private cost of road use at the 'optimal' level of congestion

physical definition ignores the fact that congestion can mean very different things to different people. In relative perspective, congestion can, therefore, also be defined in terms of the difference between the expectations of road users about the road network and how it actually performs.

Figure 1 shows that the majority of traffic congestion definitions relate to a homogeneous unit measure of vehicles. These could be vehicles or passenger car units. However, vehicles have been used more commonly than passengers. The base road capacity or vehicle free speed is determined for this homogeneous vehicle measure. Only few definitions relate to road network.

For mixed traffic conditions, that is those including cars, trucks, bicycles, PT means and private vehicles, the different behaviours of the vehicles must be taken into account. In particular, PT stop operations, acceleration and deceleration from stops and lower speeds influence capacity as well as free speed. The methods to recognise this diversity will be discussed later.

Further, the average occupancies of PT are generally much higher than those of private vehicles, so the definition of congestion for mixed traffic could take into account variations in the occupancy of the vehicles. The definitions of congestion that relate to people may be more suitable for congestion where PT and vehicles are occupying the road. This will be also discussed in this paper.

2.2 Measures of traffic congestion

The measurement of traffic congestion was initially related to homogeneous vehicle types on a road carriageway. For instance, car flow and delay were the major units of the measurement in the period of 1987–2005 (Lindley 1987; Lomax et al. 1997; Hall and Vyas 2000; Lomax and Schrank 2005). These values were estimated by comparing the real traffic flow on the width of road to free-flow travel

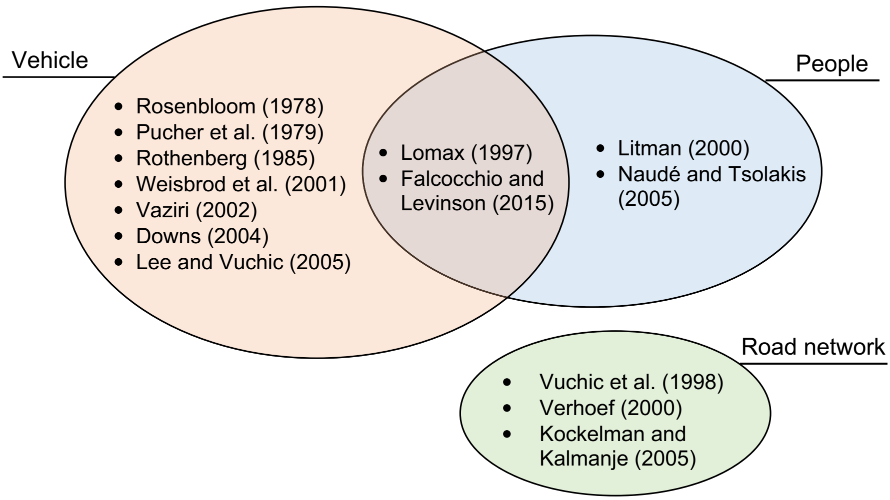

Fig. 1 Object focused in congestion measurement

or the acceptable travel time. A number of thresholds were used to identify the beginning of delay.

As traffic flows became more complex with a mix of traffic flows on the same carriageway, multi-modal performance indicators have been developed (Holian and McLaughlin 2016; Dowling 2009) and the equation measures of their impacts on the total vehicle flow were required. For instance, a multimodal level of service (MMLOS) for urban streets that takes into account interactions among transport modes (autos, buses, bicycles, and pedestrians) in the urban street environment was proposed by Dowling (2009). The MMLOS method estimates the level of service for each mode using a combination of readily available data and data normally gathered by an agency to assess auto and transit level of service. The concept of passenger car unit (PCU) defined as “the number of passenger cars displaced in the traffic flow by a truck or a bus, under the prevailing road and traffic conditions (HCM 1965)” was another appropriate way to account for the impact of big-size vehicles. A number of methods have been proposed to determine PCU in mixed traffic conditions (HCM 2000; Tiwari et al. 2000; Chandra and Kumar 2003). For example, guidelines developed by TfL (2010) in London suggested that buses have a PCU of 2.0 while the PCU of cars is 1.0. Bus occupancy is around 17 passengers in London (Transport Committee 2013) while car occupancy (all trip purposes) from UK National Travel Survey (Department for Transport 2017) is about 1.5 passengers. Hence, the occupants per PCU for cars is around 1.5 and for buses is about 8.5 in London.

The introduction of road space allocation and priority lanes moved the measures of congestion from a carriageway to a lane. Capacity for the lanes could be treated separately and congestion levels in the lanes considered separately. In general, the behaviour of vehicles in the above measures was similar. They both moved between an origin and a destination. If they stopped on route they would park, dismount and undertake the desired activity. The introduction of on-road PT into mixed traffic behaviour introduces a change in general behaviour. This main change being the stop on-route to allow passengers to board and alight. Similarly, the existence of PT at-grade level crossings influences the road congestion levels (Nguyen-Phuoc et al. 2017a). The consideration of these groups was needed, particularly in some countries where PT systems have been developing rapidly.

The measure of congestion can be categorised into three major groups:

1. basic congestion indicators;
2. level of service and;
3. indices.

The level of service (LOS) which represents a range of operating conditions is one of the most popular measures of traffic congestion (Aftabuzzaman 2007). There are six classes of LOS ranging from A to F, A being the highest level of service and F being fully congested. For the context of estimating the PT congestion impact, this is not suitable as it cannot provide a continuous range of congestion values. Congestion indices, such as travel rate index (TRI), Texas transportation institute (TTI) or roadway congestion index (RCI) were normally developed by aggregating several congestion-related elements into an equation to measure the congestion level for a road segment or a particular route, but not for a road network. Thus, most previous studies on the assessment of PT congestion impacts have used basic congestion indicators which commonly related to delay or capacity. Congestion indicators and metrics and congestion thresholds will now be reviewed to determine which indicators are suitable to apply for PT measurement.

2.2.1 Congestion indicators and metrics

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

- *Intensity* measures the amount of congestion delay experienced at an intersection approach, sections of route, several routes or an entire urban area (Falcocchio and Levinson 2015). Its metrics are expressed as a rate (e.g. min/km). The units of measurement used are travel delay, vehicle-hours of delay, person-hours of delay, a travel time index or a travel rate index. This congestion indicator is appropriate for PT measurement since delay per person is considered. Otherwise, in heterogeneous traffic conditions, there is a difference between free speeds of PT and private transport. Thus, the delay per person of delay per vehicle can be a metric to measure the level of traffic congestion of heterogeneous traffic flow.
- *Duration* reflects the amount of time that a road or system is congested. The duration of congestion depends upon the types of congestion (recurring or non-recurring). City size and the type of roadways also impact congestion duration. Congestion is generally of long duration on major roadways in large urban areas due to high traffic volume. In contrast, duration is less frequent in small urban areas. The amount of congested time (e.g. hours or minutes) is one of the key metrics used to measure this perspective of traffic congestion.
- *Extent* measures how far congestion spreads (the length of roads, the number of roads, the percentage of roads that are congested), and how many system users or components (vehicles, roads etc.) are influenced by congestion. The extent of congestion varies by the size of urban areas and the type of roadways. Freeways generally experience more delay than other types of road as they usually account for about half of all urban travel in the US (Schrank et al. 2012).
- *Variability* accesses the variation in the amount, duration and extent of congestion over time.

In assessing PT impact, there are other dimensions that need to be considered such as vehicle composition, person/vehicle delay, etc. They might have an influence on congestion for PT, PT and vehicles together and different vehicles.

Table 2 summarises congestion indicators and their metrics for measuring traffic congestion. There are a variety of congestion metrics which represent different perspectives and assumptions. Some metrics are used on route-based or whole area-based analysis. Some metrics reflect the per-capita or per-vehicle impact

Table 2 Overview of congestion indicators and their metrics Source: NCHRP 398, vol 1, Table S-5, p 7 (Lomax et al. 1997)

Congestion aspect	System type			Can be used for heterogeneous traffic with PT
	Single roadway	Corridor	Area wide network	
Intensity (e.g., level or total amount of congestion)	Travel rate; delay rate; relative delay rate; minute-miles; lane-mile hours	Average speed or travel rate; delay per PMT; delay ratio	Accessibility; total delay in vehicle-hours; delay per vehicle; total delay in person-hours; delay per person; delay per PMT	Yes (if indicators concern people)
Duration (e.g., amount of time system is congested)	Hours facility operates below acceptable speed	Hours facility operates below acceptable speed	Set of travel time contour maps; 'bandwidth' maps showing amount of congested time for system sections	No
Extent (e.g., number of people affected or geographic distribution)	% or amount of congested VMT or PMT; % or lane-miles of congested road	% of VMT or PMT in congestion; % or miles of congested road	% of trips in congestion: person-miles or person-hours of congestion; % or lane miles of congested road	Yes (if indicators concern people)
Reliability (e.g., variation in the amount of congestion)	Average travel rate or speed ± standard deviation; delay ± standard deviation	Average travel rate or speed ± standard deviation; delay ± standard deviation	Travel time contour maps with variation lines; average travel/time ± standard deviation; delay ± standard deviation	No

VMT vehicle-miles of travel, *PMT* person-miles of travel and others reflect the gross impact. Hence, based on the objective of measuring congestion and the availability of the required data, appropriate measures will be used. For instance, TfL (2013) used average vehicle delay (minutes per vehicle-km) as a relative measure of congestion to compare the performance of the road network in London, UK across years.

The level of congestion has been measured by contrasting the condition of traffic in the scenario of 'no congestion' (free speed, no delay) and 'with congestion'. However, in mixed traffic flow with PT operations such as buses or trams, how should the speed/capacity of mixed traffic flow be determined since PT normally has lower speed compared to private vehicles as well as stop operations at stations. This area needs to be explored. For PT congestion impact measurement, the intensity and extent of congestion are more appropriate to assess the level of congestion than the duration and reliability which only focus on vehicles. Indeed, total delay in person-hours, delay per person or delay per PMT can be used to show the intensity of traffic congestion of roads with PT operations as people are concerned rather than vehicles. In terms of determining the extent of congestion, person-miles or person-hours affected by congestion might be appropriate indicators to measure the congestion impact associated with PT. For example, DfT (2014) used delay per person as a congestion measure and suggested to use a higher weighted average value of time for car users than bus users when identifying the impacts of bus priority lanes on traffic congestion. This reflects the higher proportion of 'in work' travel time by car users than bus users. Similarly, Bayle (2012) used mean weighted journey time for bus passengers when assessing the performance of a Bus Rapid Transit system on the Sydney road network. This is considered to be an application of 'person delay' in the estimation of PT congestion relief.

2.2.2 Congestion thresholds

Traffic congestion reflects the difference between road traffic conditions (such as travel time, volume/capacity) during busy traffic periods and when the road is lightly travelled. In order to identify the level of traffic congestion of a roadway or an area, threshold values have been introduced. According to Falcocchio and Levinson (2015) traffic congestion thresholds can be defined as follows:

1. Using free-flow speed as a congestion threshold or,
2. Establishing an acceptable minimum speed for various types of facilities and operating environments and vehicle types.

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

- Lindley (1987) used a volume to capacity (V/C) ratio of 0.77 as a threshold for congestion (or the speed of 55 mph corresponding to V/C ratio of 0.77).
- Lomax et al. (1999) used the 85th percentile speed in the off-peak period as the free-flow speed.
- Hall and Vyas (2000) considered the posted speed limit as the nominal free-flow speed for comparing with congested speed.
- Lomax and Schrank (2005) used 60 mph for freeways and 35 mph for arterial roads as free-flow speed.
- According to WSDT (2011), congestion thresholds were established as 75% of posted speed limits.

The review shows that all of the congestion thresholds relate to vehicles, none of these thresholds relate to traffic with PT present. Thus, they can not be used effectively for PT congestion measurement when people should be considered. It is needed to develop a threshold for determining the level of congestion of roadways/networks with PT operations.

The congestion vehicle-based measures are usually used to quantify congestion intensity (the number of vehicles suffering from traffic congestion) but it does not reflect congestion exposure (the amount of people suffering traffic congestion). People-based measures may be more suitable for reflecting congestion exposure as well as considering the congestion relief impacts caused by mode shift from private car to PT. Hence, congestion exposure indicators which measure people (such as people delay per hour, people delay per kilometre) are useful for planning purposes as they can measure congestion costs. However, people-based measures require more detailed data on many factors such as travel demand, the occupation of PT means and PT travel conditions.

2.3 Assessing traffic congestion impact associated with PT

The impact of PT on traffic congestion is often demonstrated by contrasting the level of vehicle congestion in two scenarios: 'with PT' and 'without PT'. In the scenario of 'without PT', it can be seen that the PT withdrawal would result in mode shift from PT to private car which increases the level of vehicle congestion. This increase in congestion is considered to be the benefit of PT in acting to reduce traffic congestion. Hence, mode shift to car when PT is removed is recognised a key parameter used to estimate PT congestion relief impact. This mode shift has also been used to determine congestion level increase in case of a PT disruption. On the other hand, PT also contributes to increase the level of congestion on the road network due to the operation of at-grade rail crossings, the slow moving of PT vehicles or the take up of road space for priority PT lanes. Thus, there is a need to understand the net traffic congestion impact associated with PT.

A comprehensive review of studies investigating the mode shift, congestion generation impacts of PT operations and their adaption into assessing the network-wide impacts of PT on traffic congestion are presented in the following sub-sections.

2.3.1 Mode shift when PT is unavailable

Existing studies have tended to focus on the congestion impacts of transferring PT trips onto the road network and the increase in congestion resulting from this move. However, only a few published studies focus on the travel mode shift of PT users to alternative transport modes when PT withdrawal occurs. Mode shift is often explored in the event of PT strikes.

Exel and Rietveld (2001) reviewed 13 studies of PT strikes in Europe and the United States to explore the behavioural response of PT users. They found that the impact of PT strikes varied depending on the type of strike, travel patterns and policy responses. In 2003, the Washington State Department of Transportation (WDOT 2003) developed a methodology to estimate the economic value of PT trips by comparing the difference between this value in two situations, 'with PT' and 'without PT'. A field survey was conducted in Wisconsin, America to examine the choices that PT riders might make if all PT was unavailable. The findings showed that 3.7–14.6% of PT users would shift to car as a driver, while 9–14.8% would switch to car as a passenger in the absence of PT. These figures varied depending on the purpose of trips.

Table 3 summarises the literature-identified behavioural response of users for a number of PT strikes around the world. It shows that there is a wide range in the mode shift to car as a driver (5–50%), which would directly contribute to the increase in traffic congestion. This can be due to the difference in demographic and trip characteristics of PT users in a particular area. For example, in the event of an urban PT strike in Leeds (UK) in 1978, only 5% of the users shifted to a car as a driver (Exel and Rietveld 2001). This was due to the low rate of household car ownership in the UK at the time (55%) and a majority of PT users who had no car in their households (Exel and Rietveld 2001).

Recently, only two studies have explored factors affecting mode shift from PT in the event of PT cancellations (Table 4). Exel and Rietveld (2009) investigated the actual behavioural reactions of train travellers to the rail strike in the Netherlands and explored the characteristic of travellers and trips that may affect chosen alternatives. They found that 24% of the train travellers shifted to a car as a driver and 14% shifted to another mode (as a passenger). A multinomial logit regression also showed that age, gender, trip distance, frequency of train use and trip purpose had an impact on the behavioural response of users when train operations ceased. However, the analysis in this study focused only on a limited number of variables that were available through secondary data and did not include important variables such as driver license holding, car ownership, or accessibility. More recently, Pnevmatikou et al. (2015) explored the changes in travel patterns of metro users during and following a metro disruption. Data was collected from two surveys (revealed preference and stated preference) carried out in Athens, Greece in 2011. A multinomial logit model and a nested logit model were developed to analyse the travellers'

Table 3 Evidence of mode shift when PT was unavailable Source: author's synthesis

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

[a]Urban traffic

[b]Interurban traffic

[c]Average value

Table 4 Factors affecting mode shift when PT was unavailable Source: author's synthesis

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

behaviour and mode choice during metro disruptions. They found that gender, income, trip purpose, travel cost and transfer inconvenience were important factors impacting mode decisions. It can be seen that mode shift from PT to car can be impacted by other factors such as park-and-ride (PNR) schemes. PNR schemes have been found to reduce car use to CBDs as PNR services are often subsidized to attract car users to use PT (Parkhurst 2000; Meek et al. 2008). When PT becomes unavailable, PT users who are using PNR services are likely to switch to using a car since they have already used a car for a part of their trip. Hence, it is necessary to do more research to explore factors influencing this mode shift.

It is clear that the mode shift of passengers from PT to private vehicles during strikes is considerable which can lead to a significant impact on congestion. To better understand this mode shift is very important for the assessment of traffic congestion relief impact associated with PT.

2.3.2 PT creating traffic congestion

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

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

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

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

2.3.2.3 Negative traffic impact of bus operations The effect of bus operations on creating traffic congestion includes the effects of bus stop operations and the impacts of a priority bus system such as exclusive bus lanes and priority signals for buses.

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

From the literature review, bus stops have been recognised to have impacts on the traffic flow and the impacts are different regarding bus stop design (such as curbside bus stop or bus bay), traffic conditions or bus parameters. Most studies have considered dwell time as one of the key parameters to estimate the impact of bus stops. The effect of bus arrival frequency, bus speed, traffic volume, stream speed or even legal constraints, bus driver behaviours have not received much consideration. Therefore, a model that can considers the impact of a wide range of parameters on the assessment of traffic delay associated with bus stops is needed.

Transit priority lanes as well as dedicated or intermittent bus lanes are one of many measures to improve the speed and reliability of PT services (Chen et al. 2010; Chiabaut and Barcet 2019; Ben-Dor et al. 2018). However, some applications are controversial as they may cause a reduction of road capacity for general traffic and increase the level of traffic congestion. The effect of bus lanes on traffic was evaluated in a number of studies using field surveys or simulation (Chen et al. 2010; Cherry et al. 2005; Shalaby 1999; Patankar et al. 2007; Eichler and Daganzo 2006; Chiabaut and Barcet 2019; Levin and Khani 2018; Ben-Dor et al. 2018; Chiabaut et al. 2018).

As shown in the above studies, the level of traffic congestion can increase due to the operation of PT such as the operation of at-grade rail crossings and tram/bus operations in traffic. While there have been attempts to explore these impacts on adjacent road links or corridors, little is known about the network-wide impacts of PT in generating congestion. Indeed, the operation of PT can result in traffic volume changes in the surrounding area because of the traffic diversion and reassignment. Assessing the negative impacts of PT operations on the road network is important since it can be used to aggregate with the positive impacts to more accurately evaluate the performance of PT services on traffic congestion.

2.3.3 Network-wide impact of PT on traffic congestion

A summary of research on assessing the PT congestion impact is presented in Table 5.

Many of the studies on the reduction in traffic congestion due to PT used mixed traffic flow conditions on a carriageway. However, they did not investigate mixed

Table 5 Traffic congestion relief associated with PT Source: author's synthesis

Source	Location	Method	Mode shift to car (%)	Other results
Crain and Flynn (1975)	Los Angeles, USA	Observing the traffic condition during a PT strike	–	On one important freeway, the additional travel time was 10–15 min in the morning peak
Lo and Hall (2006)	Los Angeles, USA	Observing the traffic condition during a PT strike	–	Average traffic speeds on highways decrease by 20% during the strike. The traffic speed is estimated by the freeway performance measurement system (PeMS) algorithm for real-time speed estimates from single-loop detectors installed on the highways
Aftabuzzaman et al. (2010b)	Melbourne, Australia	Comparing the level of congestion in two scenarios: 'with' and 'without' PT using a regional transport network model	32	Removing PT is estimated to increase the number of congested links by about 1400 or 30%. Average travel speeds decrease by 15.5%. Actual travel time per kilometer increased by about 18%. These congestion measures were calculated from the outcome of the model
Schrank et al. (2012)	498 urban areas in the USA	Using an analytical model and an assumption of all rail commuters shift to private cars travelling on freeways in the event of a PT service shutdown	100	The total delay on the road network increases by 15% (an additional 865 million hours of delay)
Anderson (2013)	Los Angeles, USA	Using a choice model and data from a sudden strike	–	The average highway delay would increase 47% (0.194 min per mile) during peak periods when PT ceases
Ewing et al. (2014)	Salt Lake, USA	Observing the traffic condition before and after the operation of a LRT	–	Daily vehicle traffic (vehicles per day) on the study corridor is reduced by about 50%
Adler and Van Ommeren (2015)	Rotterdam, Netherlands	Observing the traffic condition during multiple PT strikes	–	Average car speed on highway ring road is decreased by 3%, is reduced on inner city roads by 10%. Car speed was measured by independent speed measurements

Table 5 (continued)

Source	Location	Method	Mode shift to car (%)	Other results
Moylan et al. (2016)	San Francisco, USA	Comparing travel time before and during the PT strike using data from detectors and a non-parametric modelling technique	100	Morning peak conditions on a parallel road were at the 80th percentile of annual volume-weighted travel times. Using volume-weighted travel time as a performance metric gives a better picture of the strike's impact since the rail system preferentially serves busy corridors
Nguyen-Phuoc et al. (2017b)	Melbourne, Australia	Comparing the level of congestion in two scenarios: 'with' and 'without' tram operations using a regional transport network model	23	Total network delay and vehicle time travelled increase by 1.2%. These congestion measures were calculated from the outcome of the model

PT/private transport flow nor did they consider the change in vehicle occupancy or person delay. A popular method that has been used to investigate the benefit of PT systems is to explore the impact of a single transit strike on traffic flow (Crain and Flynn 1975; Lo and Hall 2006; Adler and Van Ommeren 2015; Moylan et al. 2016). Traffic conditions during the strike were measured to understand how transit actually affects congestion experienced by drivers. They measured the traffic speed, travel delay on freeways before and during a strike by using various sensors installed on the roads. The impact of PT was estimated by considering the increase in vehicles caused by the mode shift from PT operating in other roads to private vehicles, they did not consider the change in people flow. Thus, the results of these studies overestimated or underestimated the congestion relief benefit of PT depending on the validity of its base assumptions. The benefit of a PT system on reducing traffic congestion can also be estimated by observing traffic conditions before and after the operation of a PT system. Ewing et al. (2014) investigated the effects that Salt Lake City's University TRAX light rail transit (LRT) system has on vehicle traffic on parallel roadways. The study found significant declines in roadway traffic after the LRT line was completed, despite a significant development in the area.

There was also another approach for estimating PT congestion relief which adopted analytical models of the transportation system and field data (Parry and Small 2009; Schrank et al. 2012; Anderson 2013; Moylan et al. 2016). Parry and Small (2009) estimated the optimal transit operating subsidy by developing an analytical model of a transportation system and using a costing measure of congestion. They assumed that each passenger mile travelled on PT diverts nearly 0.9 passenger miles from roadways. Anderson (2013) used a choice model and data from a strike in 2003 by Los Angeles transit workers for calibrating his model. He explored that the transit generated a much larger congestion relief impact than earlier estimates.

The third approach to explore the PT congestion impacts is using transport modelling, taking separate PT travels and transferring them onto the existing road system (Aftabuzzaman et al. 2010b; Nguyen-Phuoc et al. 2017b, 2018a, b). The difference between the level of congestion in two scenarios 'with PT' and 'without PT' is recognised to be the PT congestion effects. The assumption of mode shift from PT to vehicle when PT ceases was used in the study of Aftabuzzaman et al. (2010b). In the scenario 'with PT', they assumed that PT means sharing a vehicle traffic lane which has no impact on vehicle traffic so they defined congestion in relation to the travel delay of vehicles. On the other hand, in the scenario 'without PT', the allocation of priority PT lanes to vehicle traffic lanes was ignored. Hence, the results of these studies showed only the positive impact of PT rather than the net impact as the potential congestion generation impact of PT operations was not taken into account. Recently, Nguyen-Phuoc et al. (2017b) conducted a study to assess the net impacts of a light-rail system on traffic congestion in Melbourne. They considered both positive and negative effects of trams on traffic. They used microsimulation to model the impacts of trams on increasing traffic congestion on a road link. However, their microsimulation models were not calibrated and relatively simple, since a limited number of factors was considered. For the positive effects, a fixed mode shift from PT to car in the event of a strike, obtained from a field survey, was adopted. The microsimulation results and the mode shift were incorporated into a transport network model to explore the net network-wide effect of PT. In these above studies, the intensity and extent of congestion were used to assess the PT congestion relief effects.

The review shows that there are three major approaches to assess the traffic congestion impacts of PT: (1) comparing the traffic flow conditions before and after PT strikes using field data, (2) using analytical models and field data and (3) using simulation models. Collecting field data can be resource-intensive, with PT strikes occurring infrequently. A traffic simulation approach may, therefore, be a more economical and faster tool to investigate this phenomenon. Microsimulation can model the interactions of PT means with surrounding vehicles and traffic conditions, so the impact of PT on creating traffic congestion on a road segment can be investigated. In contrast, simply doing direct observation of traffic movements may not show more complex vehicle interaction, capacity and network effects. However, it is still necessary to have empirical data to correctly model those interactions, capacity and network effects. Macroscopic models can then be used to incorporate microsimulation results into an entire road network to assess the network-wide impacts of PT on traffic congestion.

For the simulation approach, mode shift from PT to car is recognised to be a main parameter used for estimating PT congestion relief impacts (Aftabuzzaman et al. 2010a). Most previous studies assessing PT congestion relief impacts used a simplistic assumption, a fixed share of mode shift to car if PT was not available. However, the mode shift varies for cities around the world and is influenced by demographic and trip characteristics of the PT users (Nguyen-Phuoc et al. 2018c, d). Thus, identifying factors affecting mode shift is needed. A better understanding can help to vary the share of mode shift to car when PT is unavailable for different areas (e.g. inner, middle, and outer city). Hence, a more precise methodology for estimating the impacts of PT on traffic congestion can be undertaken.

All approaches assessing PT congestion impact used vehicles as a key object. No study looks at the congestion measure of mixed traffic flow with PT for the 'with PT' scenario. The impact of PT could be underestimated because in the scenario 'with PT', PT which is usually occupied by a number of people is considered a normal vehicle when determining the level of congestion. However, in a scenario 'without PT', PT users can shift to the car as a driver which leads to the increase in the number of vehicles or shift to the car as a passenger which leads to the increase in the car occupancy rate. Thus, assessing the benefit of PT by comparing the delay of vehicles between two scenarios is unsuitable. In this case, the average delay per person or total delay of persons should be more appropriate.

Most previous studies have just looked at vehicle congestion as a result of removing PT. They neglect the capacity impact of the PT vehicles in the scenario 'with PT'. The lack of comprehensive and balanced impact assessments on PT congestion impact is identified as a key research gap. Further the influence of vehicle occupancy before and after the study needs to be included in the analysis to determine the change in person travel or congestion. Hence, in conclusion it appears most studies have not looked comprehensively at the capacity of heterogeneous traffic.

3 Discussion and conclusion

The paper has reviewed the literature on traffic congestion assessment focusing on recent studies of the estimation of a traffic congestion impact associated with existing PT systems. The review shows that there has been a variety of definitions of traffic congestion but most of them are concerned on vehicle congestion. Few studies have attempted to look at the congestion levels where PT and other modes on a carriageway are mixed. In the context of measuring PT congestion impacts, definitions related to people delay are considered to be more appropriate as PT is different to other types of vehicles in terms of occupancy. Some congestion indicators concerning people such as total delay in person-hours, delay per person or delay per PMT are suggested to determine the intensity of traffic congestion of roads with PT operations. In terms of estimating the extent of congestion, person-miles or person-hours affected by congestion should be appropriate indicators to assess the congestion impact caused by PT. In addition, the use of people-based indicators can also help to evaluate a part of traffic congestion cost using the time loss (value of time) and money wasted of road users because of travel delays. However, this cost not only comes from travel delays but also from an increased impact on the environment, increased vehicle costs from travel delays or increased chance of vehicle collisions. The impact of PT on reducing congestion cost is worthy to investigate in further research.

The review shows that a key benefit of PT is relieving traffic congestion; however, there are limited studies focusing on traffic congestion impact assessments concerning PT. Whilst most of the research assesses the congestion impact of PT on a road segment of a corridor, a limited group of studies explores the network-wide impact of PT with simple approaches. In transport networks, traffic flows always form self-adjusting relationships among different routes. The ground transport system's equilibrium can result from the operation of PT since it directly impacts the existing traffic flow on roads with PT. Thus, there is a need to assess the network-wide impacts of PT by considering the movement of traffic. For instance, if an effective PT vehicle operates on a congested road, a number of people would switch from car to PT and reduce the level of congestion. But once traffic moves faster, other people from other routes, other modes could shift onto the improved road. The traffic congestion relief caused by PT on that road could not be significant but the level of congestion of other surrounding roads would decrease.

There is a difference among the impacts on congestion of different types of PT modes. For instance, some PT systems such as subways have only positive effects on reducing congestion by attracting people from car to PT. For other PT systems that operate on shared roads with vehicles such as trams or buses, beside their congestion relief impacts they have negative effects on creating congestion caused by slow-moving PT vehicles or the occupation of priority PT lanes.

Some key research gaps in the study of the congestion impacts of PT are detailed in Table 6. A better understanding of mode shift when PT is unavailable will contribute to develop a more precise model which aims to assess the impact

Table 6 Summary of research opportunities based on research gaps

Research topic	Gaps in knowledge	Need for more research	Research approach
Measure traffic congestion	The level of congestion of mixed traffic flow with PT operations is not measured accurately	To measure the speed/capacity of mixed traffic flow with the consideration of PT stop operation impact as well as the lower speed of PT than private vehicles. People should be focused in these measures	Using microsimulation to model the impact of PT operations on traffic flow
	There is no congestion threshold related to people	To create congestion threshold regarding to people	
Impact of PT on reducing traffic congestion	The factors impacting mode shift from PT to car when PT is unavailable are not clearly understood	To have better understanding of factors affecting mode shift from PT to car when PT is unavailable	Conducting qualitative interviews of PT users to identify these factors Conducting a survey of PT users' actual behaviour to investigate which factors have a significant impact on the mode shift
	The share of mode shift from PT to car is assumed to be constant for all areas in the PT system resulting in errors in the assessment of PT congestion relief	To vary the share of mode shift to car for different areas	Developing a method for estimating mode shift to car when PT is removed that varies for different areas based on traffic characteristics
	Most research on the assessment of PT congestion relief impact adopted the fixed share of mode shift from PT to car which might lead to inaccurate results	To assess the positive impact of PT on reducing traffic congestion with the consideration of the various mode shift for different areas	Modelling the traffic flow on the network in a scenario 'with PT' and 'without PT' (using the mode shift data) to estimate traffic congestion relief associated with PT
Impact of PT on creating traffic congestion	No studies exploring the network-wide impact of PT (at-grade rail crossings, tram operations and bus operations) on generating traffic congestion to date	To assess the negative impact of PT operations on generating traffic congestion	Modelling traffic flow on the network in a scenario 'with PT' and 'without PT' to estimate the impact of PT on creating traffic congestion

Table 6 (continued)

Research topic	Gaps in knowledge	Need for more research	Research approach
Net impact of PT on traffic congestion	No research assessing the net impact of PT on the ability to mitigate traffic congestion Previous studies on PT congestion impact focused only on the positive impact of PT on relieving traffic congestion and did not consider the impact of PT on generating traffic congestion	To assess the net impact of PT on traffic congestion	Modelling traffic flow on the network in a scenario 'with PT' and 'without PT' to estimate the net impact of PT on traffic congestion using the mode shift data and the simulated negative impact data as inputs

of PT on reducing traffic congestion. In addition, the network-wide impacts of PT on creating traffic congestion is not understood clearly. The research in this area is needed to develop comprehensive and balanced impact assessments of PT.

The literature regarding the assessment of traffic congestion impacts associated with PT demonstrates clear gaps in the knowledge. They are:

- The appropriate congestion measures of mixed traffic flow with PT operations have not been clearly defined.
- The nature and scale of the mode shift from PT to car when PT is not specified.
- The network-wide impact of PT operations in relieving traffic congestion has not been assessed accurately.
- The network-wide impact of PT operations in creating traffic congestion is not well understood.
- The net impact of PT on traffic congestion is not known.

These research gaps are diverse and offer much opportunity for advancing knowledge, particularly in terms of understanding the net network-wide congestion impact of PT. It can help traffic authorities to identify the effectiveness of PT on relieving congestion on congested routes or corridors. From that, policies or improvement projects related to PT can be proposed to reduce traffic congestion. However, congestion relief can have adverse impacts such as increasing delay for modal shifters from car to PT due to overcrowding, increasing PT congestion costs or increasing public finance costs. Hence, these potential issues need to be considered alongside attempts that aim to seek congestion relief.

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