Measuring traffic congestion- A critical review

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1 Introduction

Traffic congestion is a major urban transportation problem (Downs, 1992; Litman, 2004). Different researchers have provided alternative definitions of traffic congestion. However, there is no universally accepted definition of traffic congestion (Downs, 2004). Many measures have been developed to represent the magnitude of traffic congestion on roadways in urban areas. But there is a debate about what is the most appropriate measure of traffic congestion (Lomax et al, 1997).

Extreme automobile dependence is one of the major aspects of urban travel of modern cities, particularly in USA and Canada (Meyer and Miller, 2001). The most visible manifestation of this automobile dependence is the road traffic congestion problem (Miller, 1972). A balanced use of automobile and public transport can ensure a desired level of mobility for all in urban areas. But, what balance may be struck between private and public transport is not clear in the cities of the future (Owen, 1992).

Public transport plays an important role for mobility in urban areas, particularly with regard to work trips and trips to central areas (Black, 1995; Cervero, 1998; Pushkarev and Zupan, 1977). The travel demand for public transport is highly concentrated on morning and evening peak hours (Meyer and Gomez-Ibanez, 1981; Jones, 1985). Though the peak periods occupy a small proportion of a day, a high proportion of passengers travel during these critical periods (Thomson, 1977). Public transport systems have the potential to significantly affect peak-period traffic congestion (Rosenbloom, 1978; Kittelson et al, 2003). However, there are no indicators that quantify the impact of public transport on traffic congestion.

The primary objective of this paper is to propose a framework for developing a measure of public transport congestion relief. It is suggested in this paper that none of the measures of traffic congestion provides information on how much traffic congestion is relieved by public transport. In addition, previous studies related to traffic congestion relief have not quantified the relationship between the presence of public transport and the amount of traffic congestion of a city. The paper aims to develop a systematic and comprehensive approach for establishing a measure of the congestion relief impacts of public transport.

The **second section** provides a definition of traffic congestion. The **third section** reviews the desirable attributes of an appropriate traffic congestion measure and sets criteria for assessing a congestion measure. The **fourth section** provides a critique of traffic congestion measures. **Section five** provides the assessment of traffic congestion measures on the basis of the criteria set in section three. **Section six** describes some simple methods for measuring traffic congestion relief of public transport. **Section seven** proposes a systematic and comprehensive approach for developing a measure of the congestion relief impacts of public transport, followed by the concluding section.

2 Definition of traffic congestion

In examining measures of traffic congestion, it is worth exploring the definitions of congestion. The definition of congestion influences what measures are introduced to address it. Many definitions have been proposed to describe traffic congestion on roadways in urban areas. However, there is no universally accepted definition of traffic congestion (Downs, 2004). Table 1 presents a summary of definition of congestion from the research literature. These definitions can be broadly categorized into three groups: (i) demand capacity related, (ii) delay-travel time related, and (iii) cost related.

Table 1: Alternate definitions of congestion

	Definition	Author
Demand Capacity related	Traffic congestion occurs when travel demand exceeds the existing road system capacity.	Rosenbloom, 1978
	Congestion is a condition in which the number of vehicles attempting to use a roadway at any time exceeds the ability of the roadway to carry the load at generally acceptable service levels.	Rothenberg, 1985
	Congestion is a condition that arises because more people wish to travel at a given time than the transportation system can accommodate: a simple case of demand exceeding supply.	The Institute of Civil Engineers, 1989 cited in Miller and Li, 1994
	When vehicular volume on a transportation facility (street or highway) exceeds the capacity of that facility, the result is a state of congestion.	Vuchic and Kikuchi, 1994
	Congestion is the impedance vehicles impose on each other, due to the speed-flow relationship, in conditions where the use of a transport system approaches its capacity.	ECMT, 1999
	Congestion may be defined as state of traffic flow on a transportation facility characterized by high densities and low speeds, relative to some chosen reference state (with low densities and high speeds).	Bovy and Salomon, 2002
Delay- travel time related	Congestion is an imbalance between traffic flow and capacity that causes increased travel time, cost and modification of behaviour.	Pisaraski, 1990 cited in Miller and Li, 1994
	Traffic congestion is travel time or delay in excess of that normally incurred under light or free-flow travel conditions.	Lomax et al, 1997
	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 them.	Weisbrod, Vary and Treyz, 2001
	Congestion is the presence of delays along a physical pathway due to presence of other users	Kockelman, 2004
	Congestion can defined as the situation when traffic is moving at speeds below the designed capacity of a roadway.	Downs, 2004
	In the transportation realm, congestion usually relates to an excess of vehicles on a portion of roadway at a particular time resulting in speeds that are slower—sometimes much slower—than normal or "free flow" speeds.	Cambridge Systematics and TTI, 2005
Cost related	Traffic congestion refers to the incremental costs resulting from interference among road users.	VTPI, 2005

3 Criteria of an appropriate congestion Measure

A range of features have been suggested for a measure of congestion. Turner (1992) examined indicators of congestion and suggested that measures to quantify the level of congestion should (i) deliver comparable results for various systems with similar congestion level, (ii) accurately reflect the quality of service for any type of system, and (ii) be simple, well-defined and easily understood and interpreted among various users and audiences.

Turner et al (1996) suggested that selection of an appropriate set of congestion measures requires examining the context in which the measures will be used because the context affects the subsequent steps of congestion measurement relative to step, precision and methodology.

Levinson and Lomax (1996) discussed desired attributes of a congestion index and suggested that a congestion index should (i) be easy to communicate, (ii) measure congestion at a range of analysis level (a route, subarea or entire urban region), (iii) measure congestion in relation to a standard, (iv) provide a continuous range of values, (v) be based on travel time data because travel time based measures can be used for multimodal analysis and for analyses that include different facility types, and (vi) adequately describe various magnitudes of congested traffic conditions.

Boarnet et al (1998) identified three issues that must be addressed in measuring congestion. It should (i) reflect the full range of highway performance, (ii) be based on widely available data, and (iii) allow comparison across metropolitan areas.

Lomax et al (1997) indicate that an ideal congestion measure would have (i) clarity and simplicity (understandable, unambiguous and credible), (ii) descriptive and predictive ability (ability to describe existing conditions, predict change and be forecast), (iii) statistical analysis capability (ability to apply statistical techniques to provide a reasonable portrayal of congestion and replicability of result with a minimum of data collection requirements), and (iv) general applicability (applicability to various modes, facilities, time periods and scales of application).

Considering the different desirable attributes for a congestion measure suggested by the afore-mentioned researchers, the congestion measures in the subsequent sections will be assessed using the following criteria.

- demonstrates clarity and simplicity.
- describes the magnitude of congestion.
- allows comparison across metropolitan areas.
- provides a continuous range of values.
- includes travel time.
- relates to public transport congestion relief.

4 Measures of traffic congestion

Measures of traffic congestion can be categorized into four broad groups: (i) basic measures (ii) ratio measures (ii) level of service and (iv) indices. Subsequent sections examine in detail each group of measures. For this purpose, congestion measures have been defined and strengths and weakness of them have been analysed.

4.1 Basic Measures

Basic measures are related to delay estimation. Delay has been defined as the additional time experienced by a road user in comparison to the freeflow travel or the acceptable travel time. For delay estimation, researchers have used different threshold values for the beginning of delay.

- Lindley (1987) used a threshold of congestion to begin at a volume to capacity (V/C) ratio of 0.77 (or the speed of 55 mph corresponding to V/C ratio of 0.77).
- Lomax et al (1997) used certain specified values for different roadway categories based on consensus among technical and non-technical groups to determine acceptable travel time and threshold for the beginning of congestion (Table 2).
- Hall and Vyas (2000) considered the posted speed limit as the nominal freeflow speed.
- Schrank and Lomax (2005) used 60 mph for freeways and 35 mph for arterial roads as freeflow speed for comparison with congested speeds.
- TTI (2005) used the 85th percentile speed in the off-peak period as the freeflow speed.

Table 2: Peak period acceptable travel rate values (Lomax et al, 1997)

Area type	Acceptable travel rates (minutes per mile)					
	Freeway main lane	Freeway HOV lane	Major street	Bus on street	Rail in street	Bike
Central Business district	1.7	1.0	5.0	7.0	6.0	6.0
Major activity centre	1.5	1.0	3.0	5.0	4.5	5.5
Suburban	1.33	1.0	2.4	4.0	4.0	5.0
Fringe	1.2	0.9	2.0	3.5	3.0	4.0

Lomax et al (1997) developed (i) segment delay (equation 1 and 2), (ii) congested travel (volume or person weighted congested roadway length), and (ii) congested roadway length to estimate an individual segment delay. Total delay (volume or person weighted traffic delay) in a corridor or in an urban area is calculated as the sum of individual segment delays.

$$D_s = \left[TT_{ac} - TT_{ap}\right] \times V_p \quad \textbf{(1)}$$

$$D_s^{/} = \left[TT_{ac} - TT_{ap}\right] \times V_p \times V_{oc} \quad \textbf{(2)}$$

Where, D_s = segment delay (vehicle-minutes)
$D_s^{/}$ = segment delay (person-minutes)
TT_{ac} = actual travel time (minutes)
TT_{ap} = acceptable travel time (minutes)
V_p = vehicle volume in the peak-period (vehicles)
V_{oc} **=** vehicle occupancy (persons/vehicle)

Texas transportation institute (TTI) has been quantifying congestion in terms of total delay for major urban areas in the United States since 1982. The recent mobility report by Schrank and Lomax (2005) calculated total delay in terms of annual hours of delay per traveller. Lindley (1987) calculated total delay in terms of vehicle hours. The strengths and weaknesses of these measures can be summarized as follows:
Strength:

- Total delay can be a useful measure (i) to estimate the total duration of congestion of an urban area, (ii) to illustrate the effects of major improvements to one portion of a corridor that affects several other elements of the corridor, (iii) to perform economic or benefit/cost analysis that use information about the magnitude of the mobility improvements for cost-effectiveness decisions.

- Congested travel can be a useful measure for estimating the spatial extent of congestion of an urban area.
- Congested roadway length is simple to calculate and easy for the public and policy-makers to comprehend.

Weakness:

- Congested travel or congested roadway length does not represent the different magnitude of congestion.
- Congested travel or congested roadway length does not include travel time element in the measurement.
- All these measures require careful interpretation to compare across metropolitan regions.

4.2 Ratios

Ratio measures of traffic congestion are usually developed by dividing one travel time or delay element by another. Several ratio measures (delay rate, relative delay rate and delay ratio) were developed by Lomax et al (1997) based on travel rate. The travel rate (in minutes per mile) was defined as the rate at which a road segment is travelled. It is the reciprocal of speed multiplied by appropriate conversion factor. Acceptable travel rate was defined as the maximum rate of travel (or the lowest travel speed) at which a segment is traversed or a trip is completed without experiencing an unacceptable level of mobility (the threshold for acceptable level is shown in Table 2). Delay rate, relative delay rate and delay ratio can be estimated by using the following equations.

Delay rate, $DR = TR_{ac} - TR_{ap}$ **(3)**

Relative delay rate, $RDR = \frac{DR}{TR_{ap}}$ **(4)**

Delay ratio, $DRA = \frac{DR}{TR_{ac}}$ **(5)**

Where, Travel rate, $TR = TT/L_s = 60/v$
TT = travel time (minutes)
L_s = segment length (miles)
V = travel speed (mph)
TR_{ac} = actual travel rate (minutes per mile)
TR_{ap} = acceptable travel rate (minutes per mile)

The strengths and weaknesses of ratio measures can be summarized as follows:

Strength:

- Delay rate can be used to estimate the difference between system performance and the expectations for those system elements, which can be used to rank alternative improvements (Lomax et al, 1997).
- Relative delay rate can be used to compare the relative congestion on facilities, modes or systems in relation to different mobility standards for system elements such as freeways, arterial streets and transit routes (Lomax et al, 1997). Relative delay rate reflects the condition of flow that travelers' can relate to their travel experience (Hamad and Kikuchi, 2002).
- Delay ratio can be used to compare or combine the relative congestion levels on facilities with different operating characteristics like freeways, arterial streets and public transport routes (Lomax et al, 1997).

Weakness:

The use of ratio measures is limited for a particular road type or facility and the value cannot be used effectively for a geographic area.

4.3 Level of service measures

Traditionally, the use of level of service (LOS) has been one of the most popular measures of traffic congestion. The LOS concept as adopted in the 1985 Highway Capacity Manual (Roess et al, 1985) represents a range of operating conditions. The LOS of a facility is determined by traffic flow characteristics such as vehicle density, volume-to-capacity ratio, average speed and intersection delay, depending on facility type. The scale of LOS measure has six discrete classes ranging from A to F (Table 3). The main advantage of LOS measure is that it is comprehensible by most non-technical audiences. However, it possesses the following weaknesses*:*

- LOS cannot provide a continuous range of values of congestion.
- Byrne and Mulhall (1995) criticized level of service analysis a measure of congestion because it only represents location-specific congestion phenomenon and does not reflect overall or regional congestion condition.
- Hamad and Kikuchi (2002) have argued that the use of a stepwise LOS measure is sometimes misleading, especially when the condition is near a threshold.

Table 3: Levels of service with operating conditions (Roess et al, 1985)

Level of Service	**Operating Conditions**	**V/C ratio for arterials**
Level-of-service A	Represents a free flow. Individual users are virtually unaffected by others in the traffic stream. Freedom to select desired speeds and to manoeuvre within the traffic stream is extremely high.	0.00 to 0.60
Level-of-service B	Represents the range of stable flow but the presence of other users in the traffic stream begins to be noticeable. Freedom to select desired speeds is relatively unaffected but there is a slight decline in the freedom to manoeuvre within the traffic stream from LOS A.	0.61 to 0.70
Level-of-service C	Represents the range of stable flow but the selection of speed is affected by the presence of others. Manoeuvring within the traffic stream requires substantial vigilance on the part of the user.	0.71 to 0.80
Level-of-service D	Represents high-density but stable flow. Speed and freedom to manoeuvre are severely restricted.	0.81 to 0.90
Level-of-service E	Represents operating conditions at or near capacity level. All speeds are reduced to a low but relatively uniform value. Freedom to manoeuvre within the traffic stream is extremely difficult.	0.91 to 1.00
Level-of-service F	Represents forced or breakdown flow.	Greater than 1.00

4.4 Indices

Some researchers have developed index measures of traffic congestion by including several congestion related elements in an equation to produce a single measure.

A congestion index was developed by Taylor (1992) and D/Este et al (1999) as a measure of congestion. This congestion index is the ratio of link delay (the difference between actual and acceptable travel time) to acceptable travel time. Texas transportation institute (TTI) has been quantifying congestion for major urban areas in the United States since 1982. The most recent report, the 2005 urban mobility report (Scharnk and Lomax, 2005), reported a travel rate index (TRI) of 85 urban areas. TRI compares travel conditions in the peak period to travel conditions during freeflow period. STPP (2001) developed a ‘congestion burden index’ to quantify congestion. The congestion burden index was calculated by multiplying the travel rate index for each metro area by the percentage of workforce driving to work. Roadway congestion index (RCI) was developed by Schrank et at (1990) and was refined by Schrank and Lomax (1997). This was a weighted average of vehicle miles travelled and lane miles of freeway and principal arterial. The congestion severity index (CSI) was originally developed by Lindley (1987) to measure freeway congestion in terms of total delay (vehicle-hours) per million vehicle miles of travel (VMT). Turner (1992) modified the CSI measure by including principal arterial street delay. Lomax (1990) developed a ‘corridor mobility index’. The corridor mobility index consisted of the speed of person movement value divided by some standard value. The speed of person movement was the product of passenger volume and average speed for a particular route and is typically expressed as person-miles per hour. Cottrell (1991) developed the ‘lane mile duration index’ (LMDI) to measure freeway congestion in urban areas. This index was the summation of the product of congested lane miles and congestion duration for all freeway segments. Though most of the indices can be used for an urban area wide application, they possess the following weaknesses:

- The application of congestion index is limited to a roadway segment or a particular route.
- Travel rate index or congestion severity index has used only two classes of roadway facilities. For an urban area whose substantial proportion of travel occurs on arterial class II and III (Roess et al, 1985) and on CBD streets, this measure represents a partial scenario.
- Gordon et al (1997) has rejected RCI as a measure of congestion by arguing that it is more of a traffic density measure that a true congestion measure.
- The use of corridor mobility index is limited to a particular corridor and it cannot be applied for an entire urban area.
- Lane mile duration index value requires careful interpretation to compare across metropolitan regions.

5 Assessment of traffic congestion measures

Traffic congestion measures and their suitability with respect to each assessment criterion are summarized in Table 4. The suitability is marked with Y or N (Y for yes and N for no). The assessment criteria are: (i) demonstrates clarity and simplicity (simplicity), (ii) describes magnitude of congestion (magnitude of congestion), (iii) allows comparison across metropolitan areas (city comparison), (iv) provides a continuous range of values (continuous value), (v) includes travel time (travel time) (vi) relates public transport congestion relief (public transport).

The following conclusion can be drawn from Table 4.

- None of the congestion measures fulfil all of the six assessment criteria.
- Most of the index measures and one of the basic measures fulfil four of the six assessment criteria.
- The basic measures, ratios and level of service measures are clear and simple but most of them except total delay do not fulfil more than three assessment criteria.
- Most of the index measures fulfil four of the six assessment criteria though they are relatively complex than other measures.
- Simple measures satisfy a few criteria and complex measures satisfy most of the criteria. For a good measure a trade-off between simplicity and complexity is necessary. In this regard, total delay measure may be considered a good measure of traffic congestion.
- None of the measures consider public transport effects and congestion.

Table 4: Traffic congestion measures and their suitability to assessment criteria

Congestion Measure \ Assessment Criteria		simplicity	magnitude of congestion	city comparison	continuous value	travel time	public transport
Basic measure	Total delay	Y	Y	N	Y	Y	N
	Congested travel	Y	N	N	Y	N	N
	Congested roadway	Y	N	N	Y	N	N
Ratio	Travel rate	Y	N	N	Y	Y	N
	Delay rate	Y	N	N	Y	Y	N
	Relative delay rate	Y	N	N	Y	Y	N
	Delay ratio	Y	N	N	Y	Y	N
LOS	Level of Service	Y	Y	N		N	N
Indices	Congestion index	N	Y	N	Y	Y	N
	Travel rate index	N	Y	Y	Y	Y	N
	Congestion burden index	N	Y	Y	Y	Y	N
	Roadway congestion index	N	Y	Y	Y	Y	N
	Congestion severity index	N	Y	Y	Y	Y	N
	Corridor mobility index	N	Y	N	Y	Y	N
	Lane mile duration index	N	Y	Y	Y	Y	N

6 Measures of traffic congestion relief of public transport

Public transport plays an important role for mobility in urban areas, particularly, in central business district (CBD) of major cities and in other concentrated employment centres (Black, 1995; Downs, 1992; Cervero, 1988; Pushkarev and Zupan, 1977). Public transportation systems can carry a significant amount of trips during congested hours and can substantially improve the overall transportation capacity and can release burden on congested road networks. Numerous papers (Kittelson et al, 2003; Meyer and Gomez-Ibanez, 1981; Meyer and Miller, 2001; Rosenbloom, 1978; VTPI, 2005) have mentioned the utilization of public transport as a strategy for relieving congestion. However, none of the previous studies have provided any systematic and comprehensive analytical framework to estimate the effect of public transport in congestion relief. Some studies have investigated the impact of public transport on traffic congestion by using some simplified methods. The following sections will review three studies which have estimated the congestion relief impacts of public transport.

6.1 ‘No public transport’ congestion impact assessment

An estimation of the congestion reduction effects of public transportation, HOV lanes, traffic signal coordination freeway incident management and ramp metering was made in a study of

85 US cities (Schrank and Lomax, 2005). The report has determined the delay benefits by using the "what if transit riders were in the general traffic flow" case. Additional traffic on already crowded road networks would effect all the other peak period travellers. In the 85 urban areas studied, there were approximately 43 billion passenger-miles of travel on public transport systems in 2003. The transit ridership ranged from 17 million in the small urban areas to about 2.7 billion in the very large areas. Overall, if the riders did not use public transport systems they would contribute an additional roadway delay of approximately one billion hours i.e. public transportation lowered the travel time index by 0.037 (9.3 percent) and accounted for a reduction of 29.4% of total delay (table 5).

Table 5: Delay increase if public transport (PT) service were eliminated - 75 areas

Population group & number of areas	System Travel Time Index			System Hours of Delay (million)		
	Base	With public transport	Reduction due to PT	Base	Reduction due to PT	Percent of base delay
Very Large (13)	1.522	1.461	0.061	2,526.1	919.2	36.4
Large (26)	1.304	1.292	0.012	874.8	148.3	17.0
Medium (30)	1.187	1.182	0.005	287.9	26.5	9.2
Small (16)	1.107	1.105	0.002	34.3	1.5	4.4
85 area average	1.399	1.362	0.037	3,723.1	1095.5	29.4

Source: Schrank and Lomax, 2005

An inconsistency in the above analysis is the assumption that all the riders using the public transport would drive if public transport did not exist. The Center for Urban Transportation Research (1998) reported that 70 percent of American public transport riders do not have either a car or a driving license. Probably some people will be in carpools and some will abandon the trip. Exel and Rietveld (2001) studied 13 cases of strikes in public transport sector and concluded that on average 10-20% of trips are cancelled during strikes. Inversely, if the user patterns of new public transport service are analysed, it can be seen the most of them are existing public transport users (Anlezark et al, 1994; Currie, 2006).

6.2 Regression analysis with congestion index and public transport supply

Hahn et al (2002) tried to explain the congestion of freeway and principal arterial roads in terms of supply related factors (freeway and principal arterial lane miles, public transport supply) and demand related factors (population density, land area) by applying multiple regression models. The regression of a dependent variable (travel rate index) on several predictors were performed by applying a backward elimination procedure with a level of significance of 0.05. For the combined freeway and arterial travel rate index (TRI) model, a positive correlation between combined bus transit service revenue miles and combined TRI. Hahn et al (2002) interpreted that a positive correlation between combined bus transit service revenue miles and combined TRI appears to contradict what one might expect (i.e. an increase in public transport supply is usually considered to be a strategy for the alleviation of traffic congestion). For this reason, they suggested a more detailed analysis to understand the implications of bus transit supply on highway traffic congestion.

6.3 Transportation choice ratio

STPP (2001) measured the relative availability of transportation choices in metropolitan regions through a "Transportation Choice Ratio (TCR)." This ratio compares the relative supply of public transportation to major roads in a metropolitan area. The TCR is calculated by dividing the miles of public transportation service per household offered over the period of one hour by the number of lane miles of freeways, expressways and principle arterials per household in that area. A low Transportation Choice Ratio (TCR) means that an area's road network dwarfs its public transportation system. A high TCR means an area offers a relatively high level of transit service in comparison to the size of its road network. The importance of transportation choice ratio is reflected in the comparison of the TCR with the percent of workers vulnerable to congestion because they drive to work (Figure 1). A simple bi-variate correlation of the two variables reveals a relatively strong relationship with R^2 = 0.73. The places with the lowest Transportation choice Ratio have the highest percentage of the workforce driving to work.

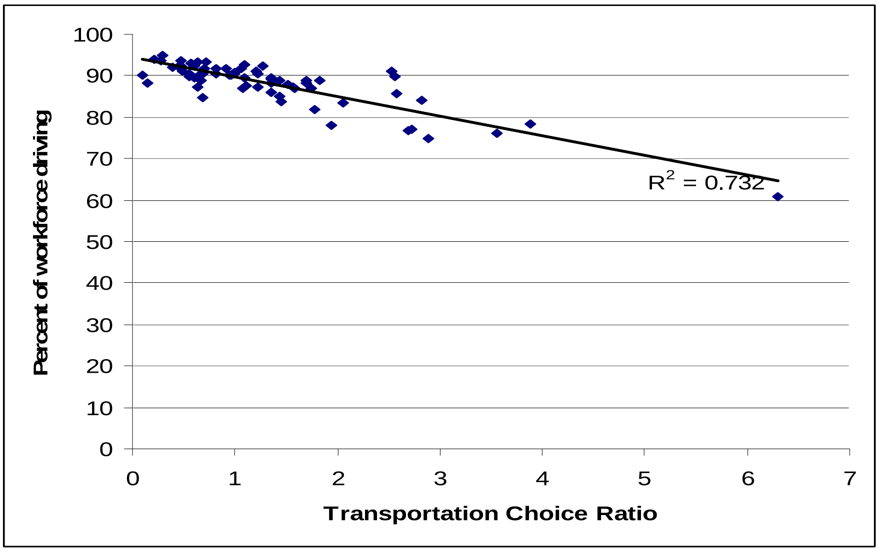

Figure 1: Relationship between the percentage of workforce driving to work and TCR
Source: STPP, 2001

The percentage of workforce driving to work and transportation choice ration has a high correlation but the analysis fails to encapsulate the congestion relief potential of public transport. Though the percent of workforce driving to work influences traffic congestion, this percentage is a measure of automobile dependence rather than a measure of traffic congestion.

7 Developing a measure of public transport congestion relief

In light of the preceding sections, it is apparent that: (i) none of the traffic congestion measures consider public transport effects and congestion, and (ii) the few studies which have investigated the impact of public transport on traffic congestion have used extremely simplified methods. This section proposes a methodology for quantifying the congestion relief impact of public transport.

A methodological framework for measuring congestion relief impacts of public transport is illustrated in Figure 2. In attempting to identify the influence of public transport on traffic congestion it is very important to understand clearly the characteristics of urban travel. The spatial distribution and temporal pattern of trips will be simulated by utilizing Melbourne city data in TRANUS modelling system (Modelistica, 1982-2007). A detailed city level analysis can provide insight on how public transport influences traffic congestion relief. For developing a methodology for quantifying the impact of public transport on traffic congestion relief, two prominent foundations of information are: (i) inferences obtained from experimentation using a multi-modal city transport model and (ii) comparative primary data accumulated from global cities. Data for global cities can be collected by exploring published secondary data sources (Kenworthy and Laube, 1999; Kenworthy and Laube, 2001).

A congestion relief index can be theorized with the factors affecting congestion relief impacts of public transport of global cities. In order to check the statistical fit of the hypothesized index with the real world data, a number of statistical analyses will be carried out: (a) bivariate correlation analysis, (b) factor analysis, and (c) multiple regression analysis / structural equation modelling. If a significant statistical goodness-of-fit is not achieved, the congestion relief index will be modified. The statistical analyses will be performed again. The process will be repeated until a considerable statistical goodness-of-fit is achieved.

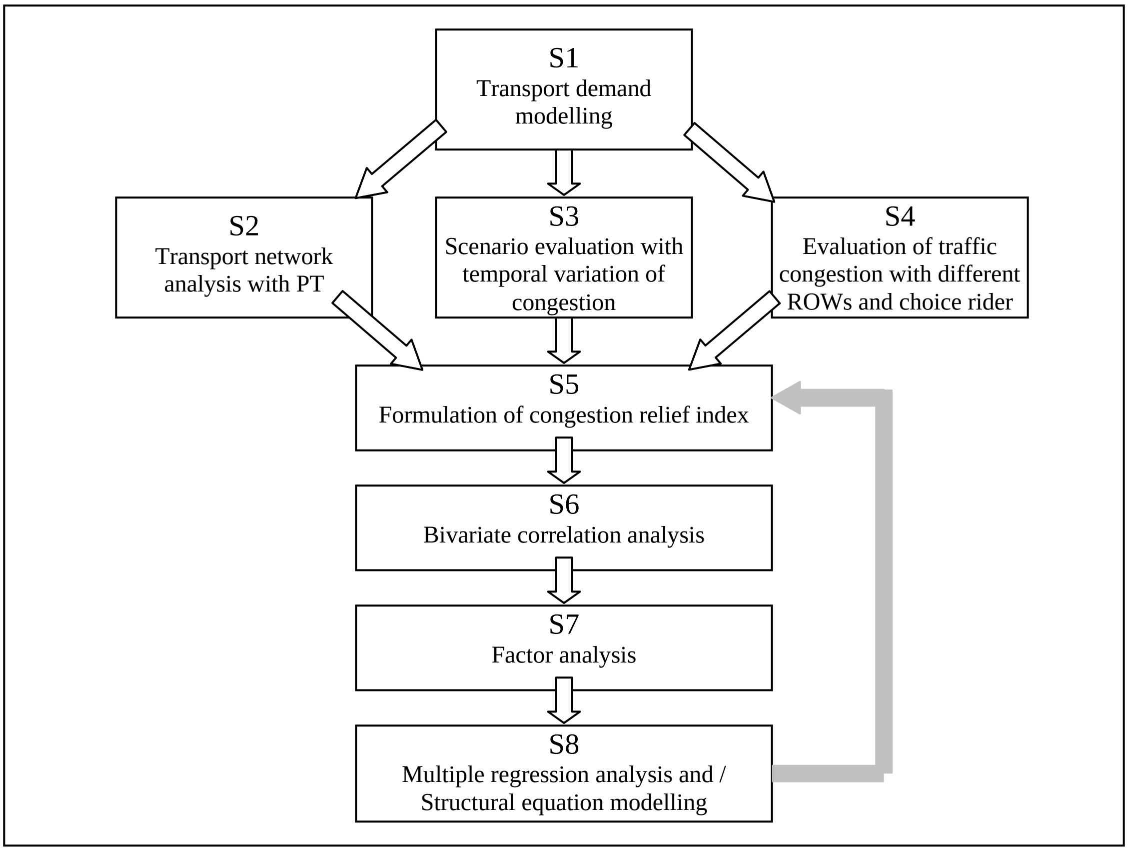

Figure 2: Methodological framework for developing congestion relief index

The following subsections provide a detailed description of each step of the process for quantifying the congestion relief impact of public transport.

S1 – Transport modelling

In order to aid our understanding of the multi-modal transport system of Melbourne, TRANUS will be used. TRANUS is an integrated land use and transport modelling system developed and maintained by Modelistica, 1982-2007. The system can be used as a stand alone transport model. The modelling system will be used to represent the movements of passengers using public and private modes. In the Melbourne application, importance will be given to replicate existing travel pattern and to simulate its contribution to road traffic congestion. In this regard, the modelling platform will be customised through the input of relevant data of the transport network and operational conditions of Melbourne’s transport system. The customised modelling system will form the fundamental basis for analysing the traffic congestion responses of the transport network under different scenarios.

S2 – Transport network analysis without the presence public transport
A range of scenarios will be tested to asses the effects of public transport (PT) on road traffic congestion. One of the scenarios will analyse the response of transport network related to the volume of travel at different times and spaces in absence of public transport. The scenario will be tested in two phases: complete withdrawal and withdrawal of public transport in selected corridors. The removal of public transport will result in mode shift, trip redistribution, trip retiming and trip suppression. The degree of impact on ridership due to the removal public transport will be analysed by secondary research (evidence from other similar situations, such as Exel and Rietveld, 2001). The absence of public transport contributes to an increased car volume on road. In addition, an expanded road capacity for car can be achieved due to absence of on-road public transport. The changes in road volume and capacity in absence of PT and the resulting impacts on road traffic congestion will be simulated in TRANUS modelling system.

S3 – Scenario evaluation with temporal variation of traffic congestion
The demand for public transport (PT) is not even throughout the day. This demand has a highly peaked phenomenon. Therefore, it is expected that the traffic congestion impacts of public transport will demonstrate significant variability throughout the day. For understanding temporal variability of PT impacts on traffic congestion, two separate occurrences will be simulated in TRANUS modelling system (i) peak period PT impacts and (ii) off-peak period PT impacts. The corresponding change in congested conditions can provide information on the extent to which public transport contributes to congestion relief for each occurrence.

S4 – Evaluation of traffic congestion with different public transport ROWs and mode shares
Right-of-way (Vuchic, 2005) is one the most fundamental public transport (PT) system elements which strongly influences the traffic congestion relief potential of public transport. For example, if all movements of the public transport riders occur in Right-of-way (ROW) category A, there will be no conflict between public transport and road traffic and thus, the congestion relief impact of PT will be independent of road traffic conditions. On the other hand, if all movements of public transport riders occur in ROW category C, there will be interaction between public transport and road traffic and consequently, the congestion relief impacts of PT will depend on road traffic conditions. The congestion impacts of PT will be tested under two phases in TRANUS system: (i) the "what if all PT riders were transported in the PT system of ROW category A" case (ii) the "what if all PT riders were transported in the PT system of ROW category C" case.

The percentage of choice riders in total public transport ridership is expected to influence the traffic congestion relief potential of public transport. For instance, if only the captive riders are using the public transport, there may be little impact of public transport in relieving traffic congestion. In contrast, existence of a significant number of choice riders may have a substantial impact of public transport in relieving traffic congestion. The share of choice riders will be increased from 0% to 100% with a 10% increment in TRANUS modelling system and the corresponding traffic congestion impacts of public transport will be simulated for each increment of choice riders' share.

S5 – Formulation of public transport congestion relief index
Based on the insights gained from the experimental modelling analysis of Melbourne's public transport network and the available data of global cities from published sources, a public transport congestion relief index (CRI) will be hypothesized by the following equation.

$$CRI = C_n \sum_{i=1}^{n} w_i \, p_i \qquad \textbf{(6)}$$

Where, *CRI* = congestion relief index value

C_n= constant to normalize the maximum index value to a particular value
p_i = value of performance measure x
w_i = weight of performance measure x

S6 – Bivariate correlation analysis

A number of statistical procedures will be applied to seek links between different characteristics of a city and the index hypothesized in Step S5. Bivariate correlation analysis will be the preliminary stage of the process for seeking links between city characteristics and congestion relief index. To estimate the importance of each city characteristic, Pearson correlation coefficients will be calculated between each characteristic's value and the congestion relief index of public transport. These are bivariate correlations, which disregard the intercorrelation that occurs among the city characteristic variables. The bivariate correlations can be used as a tool for ranking the relative importance of city characteristics.

S7 – Factor analysis

Factor analysis is a set of multivariate statistical techniques whose primary goad is to condense the information contained in a large number of variables into a smaller set of composite, mutually independent dimensions (factors). Factor analysis may provide a better understanding of how various characteristics of city influencing the congestion relief of public transport. Also, the factors extracted from the factor analysis will provide a more manageable number of variables for performing next level analysis.

S8 – Multiple regression analysis and / Structural equation modelling

The statistical goodness-of-fit of the congestion relief index (hypothesized in Step S5) will be checked by using multiple regression analysis and / structural equation model. A multiple regression model will be formulated using the factors generated in the factor analysis. The purpose of the regression model will be to assess the relative importance of each factor and to set the overall explanatory power of the set of factors as a whole. In the regression model the factors serve as independent variables and the value of congestion relief index of public transport act as the dependent variable. Finally, if a statistically appropriate number of sample is available, a causal model consisting of observed and unobserved (latent) variables regarding the congestion relief impact of public transport will be theorized. The goodness-of-fit the theorized causal relationship will be tested using structural equation modelling.

If a reasonable statistical goodness-of-fit of the hypothesized congestion relief index is not achieved, the relationship in the Step S5 will be modified and the activities of S6, S7 and S8 will be repeated. The recursive process will be continued until a considerable statistical goodness-of-fit is achieved.

8 Conclusion

The paper has provided a critique of traffic congestion measures. A review of desirable attributes of an appropriate traffic congestion measure has been presented and a standard set of criteria has been proposed to assess traffic congestion measures. Assessment of traffic congestion measures reveals that none of the measures provides information on how much traffic congestion is relieved by public transport. Numerous papers have mentioned the utilization of public transport as a strategy for relieving congestion. In fact, none of the previous studies have provided any systematic and comprehensive analytical framework to quantify the relationship between the presence of public transport and the amount of traffic congestion of a city. In addition, the few studies which have investigated the impact of public transport on traffic congestion have used extremely simplified methods. The paper has aimed to develop a systematic and comprehensive approach for establishing a measure of the congestion relief impacts of public transport. The paper has developed an eight-step process for quantifying the congestion relief impacts of public transport in terms of congestion relief index. It is expected that the practical implementation of this proposed approach will be published in future papers.

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