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Measuring Excessive Congestion Delay and Travel Time Reliability Cost for Multi-modal Travels

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Abstract

The paper presents initial findings from a recent TMR-ARRB project which aims to produce a methodology for estimating congestion costs associated with a range of road users and confirm this methodology through pilot case studies. The paper starts from a literature review, then proposes a methodology for estimating multi-modal congestion cost by considering excessive congestion delay and travel time reliability cost. It also provides main findings from two pilot case studies using data from automatic bus ticketing system (Go Card system) and STREAMS data.

The first case study found that the average excessive congestion cost for bus passengers per day was $44,013 for weekdays and $14,111 for weekends in March 2015 for the study site along Gympie Road. The travel delay cost was the largest contributor to total congestion cost, followed by passenger waiting time cost and travel time reliability cost. The second case study revealed that the multi-modal congestion cost methodology is feasible for freeway data analysis. It showed although the average daily VKT increased by 5% between the before-and after-periods of the Bruce Highway Managed Motorway project, the cost of congestion was reduced by 26% on a typical weekday during morning peak. A bulk of these cost-savings originated from reduced excessive delay cost, which experienced a 39% reduction. The travel time reliability cost also dropped by 7%.

Keywords:
congestion cost, multi-modal, excessive delay, travel time reliability.

Introduction

Austroads, ARRB and TMR have researched and implemented the measurement of vehicle-based congestion costs (Austroads 2009a and 2009b, Dekker et al. 2015, TMR 2015). The TMR cost of congestion currently includes heavy vehicles (HVs). However, the estimate is based on HV class percentages for the network and there is interest in breaking down the costs by roadway and HV class profiles across the day.

A multi-modal methodology including cars, HVs, buses, pedestrians and cyclists would provide a more complete understanding of user costs and whole-of-network congestion costs for TMR, as opposed to the original car and HVs based methodology. The paper presents initial findings from a recent TMR funded project which produced a methodology for estimating congestion costs associated with a range of road users and ultimately confirm this methodology through pilot case studies (ARRB 2015a, 2015b, 2016).

The paper starts from a literature review, then proposes a methodology for estimating congestion cost by considering excessive congestion delay for other modes and travel time reliability cost. It also provides the preliminary findings from two pilot case study using the data from an automatic bus ticketing systems (Go Card system) and the STREAMS.

The multi-modal congestion cost methodology discussed in this paper focuses on buses and HVs. The technologies for the detection of pedestrians and cyclists are available, but a network of sensors for their monitoring along a corridor or at specific sites is expensive. These sensors are unlikely to be available in the short term to provide online traffic data. However, it is still meaningful to address the impact of an infrastructure investment or traffic management scheme on pedestrians and cyclists in the context of a before-after or ex-post study. Readers should refer to ARRB (2015a) for further discussion on the congestion costs of pedestrians and cyclists.

Literature Review

Excessive Congestion Delay

The definition of congestion delay in this paper is the *extra delay* or *excessive delay* with reference to an optimal (spatial) speed for a road user group (spatial speed is the inverse of travel time). This definition is reported in BTRE (2007), Austroads (2009a) and Dekker et al. (2015). The traffic flow at this optimal speed leads to maximum overall road user benefit and is closely linked to the speed before flow breakdown in a traffic facility.

Austroads (2009a) performed a comprehensive review of relevant literatures on the definitions of congestion delay cost and summarised the considerations for the choice of a reference speed to define congestion as follows:

- There is no rational reason to achieve zero congestion with any congestion management measure or ‘build’ solution. Congestion delay cost will be overestimated if the free-flow speed or posted speed is used as a reference. This could result in policies that potentially encourage more road construction and car travel, with subsequent increases in pollutant emissions and fuel consumption.
- Economic analysis for costing congestion has always supported an optimal level of traffic flow, congestion toll and speed (or travel time). This optimal or efficient level of speed is recommended as a possible reference speed rather than the free-flow speed.

- The optimal speed is related to the freeway flow breakdown situation. It seems rational to identify the speed before flow breakdown as a possible reference speed.

Austroads (2009a) also discussed possible options for proposing optimal reference speeds, such as using volume-capacity ratios for freeways and using empirically determined speed-flow functions for arterials. Table 1 shows a table of initial reference speeds suggested by Austroads (2009a).

Table 1: Table of reference speeds expressed as a percentage of speed limits

Road user or vehicle classes	**Reference speeds as a % of speed limits**	
	Freeways	**Arterials**
Short vehicles	70%	55%
Medium vehicles/HVs	70%	55%
Long vehicles/HVs	70%	55%
Combination HVs	60% (Note 1)	55%
Buses	70%	Could be a profile (not a single value)

Note 1: The choice of 60% is for illustration but also to reflect the lower average speed of combination vehicles relative to other vehicle classes. Using 70% as a reference value similar to other vehicles will overestimate the congestion delay of combination vehicles.

Dowling et al (2015) reported that most road agencies have been focused on recurring congestion in congestion management plans, which have been easier to quantify from a monitoring standpoint, but has led to improvement strategies that focus on capacity expansion. Capacity expansion is becoming increasingly difficult and expensive to implement. There is an urgent need to expand the scope of congestion management to address non-recurring congestion that is caused by traffic incidents, weather, road work zones and special events.

Travel Time Reliability

The reliability or variability of travel times has received considerable attention in recent years in general traffic, freight and especially passenger transport (e.g. Austroads 2011, de Jong and Bliemer 2015). This section discusses relevant literatures on the importance of reliability, defining reliability and costing of reliability.

de Jong and Bliemer (2015) reported that in the presence of travel time unreliability, travellers typically allow more time for their trips in order to reduce the possibility of arriving late to their destination. Reducing the unreliability (in other words, increasing the travel time reliability metric) means that this extra time allowance could be decreased or avoided completely, presenting a clear user time benefit. Fosgerau and Karlstrom (2010) found that travel time uncertainty could account for about 15% of time costs on a typical urban road based on a Danish study. Dowling (2015) reported that travel-time reliability is a metric that is important to and innately understood by travellers and shippers. Variable or unpredictable travel times make it more difficult for travellers and shippers to plan their travel, often forcing them to add extra time to protect themselves against the uncertainty of arrival times. This uncertainty may lead to ineffective or even counterproductive travel decisions that waste time and money.

Dowling et al (2015) defined travel-time reliability as consistent travel times for the same trip as measured day-to-day or across different times of the day. If trip times are inconsistent, the travel time is considered unreliable, because it is difficult to generate consistent and accurate travel time estimates. In ATC (2006), travel time reliability is defined as unpredictable variations in journey times, which are experienced for a journey taken at broadly the same time very day. The impact is related to day-to-day variations in traffic congestions, typically as a result of day-to-day variations in flow.

Cambridge Systematics (2012), Wang (2014), de Jong and Bliemer (2015) and Dowling et al (2015) reviewed various methods/metrics of measuring the travel time reliability such as:

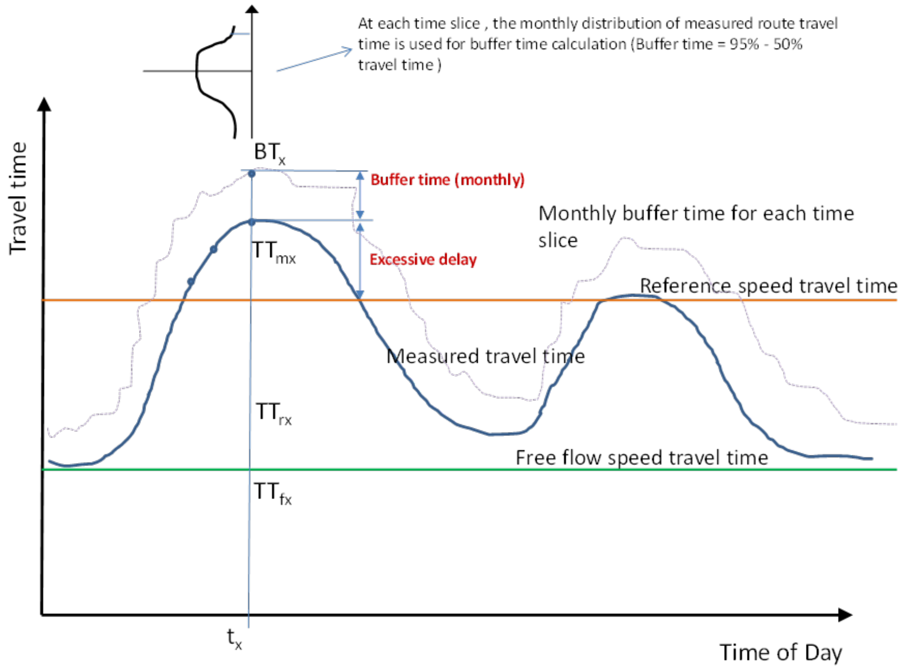
- dispersion measure of travel time by using the standard deviation (SD), variance or variability: e.g. using the standard deviation as the dispersion measure of travel time distribution, the cost of reliability/variability (COR) could be expressed by the marginal rate of the substitution (i.e. a ratio of SD of travel time and travel time)
- reliability ratio (RR): relates COR to the cost of travel time delay (COT), the RRs could be estimated by using SD, SD per unit distance, other variability index etc.
- buffer index: the percentage share of additional travel time that a traveller allocates on average in order to still be on time in 95% of the cases: T_{95} - M, where T_{95} is the 95th percentile of the travel time distribution and M is the mean travel time. M could also be replaced by median travel time.
- planning time index: the ratio of 95 percentile travel time and free flow speed or posted speed travel time.
- punctuality: deviations from the published time table (only relevant to public transport)
- robustness: what happens in the case of calamities or extreme events (refers to the far right-hand side of the travel time distribution)
- schedule delay: the scheduling consequences of reliability are expressed as the expectation of the number of minutes one arrives or departs earlier or later than one’s preferred arrival or departure time.

ARRB (2015) compared the available methods and identified that there are two commonly used measures in the Australian studies, the generic reliability ratio (RR) and buffer time. The generic reliability ratio is challenging to apply as the RR values vary significantly from different research (even when using the same reliability metric) and limited evidence is available for validation, although the RR method could be used when ongoing measurement of travel time reliability/variability is not available. In this project, as the travel time distribution could be analysed by empirical data, the buffer time method appears to be more suitable. The applicability factor recommended for NSW in Wang (2014) could also be adopted for the case studies.

Proposed Methodology of Estimating Congestion Delay Cost

Figure 1 illustrates the concept of aggregating the cost of excessive congestion delay with the cost of travel time reliability. If using freeway link/route travel time as an example, for each time slice t_x (e.g. every 15 min) during the monitoring period, there are a few travel time metrics as follows:

- free-flow-speed travel time (TT_{fx}), assuming free-flow-speed is equivalent to posted speed limit
- reference-speed travel time (TT_{rx}), e.g. the travel time calculated at 70% of free-flow-speed
- measured travel time (TT_{mx}), the mean of all measured travel times in that time slice
- buffer time (BT_x), is the indicator of travel time reliability and is calculated as the difference between the 95th percentile travel time and the median travel time based on a monthly distribution of route travel times (Wang 2014). In theory, travel time reliability only applies to the route level and should reflect the day-by-day variations.



Note: The reference speed travel time could be a constant as in the freeway scenario or a profile as in the bus scenario.

Figure 1: Aggregation of excessive delay and travel time reliability cost

The excessive congestion delay time (i.e. delay time) is represented by the difference between the measured travel time (TTmx) and the reference-speed travel time (TTrx) at each time slice. Buffer time is calculated based on monthly distribution of travel times and applies to each individual time slice. Note that buffer time is a constant value cross the month while excessive delay could be different every day.

For each time slice, the total delay is the sum of excessive delay and buffer time. The total congestion cost is therefore the sum of excessive congestion delay cost and travel time reliability cost.

TMR’s Intelligent Transport Systems platform can calculate the travel times between two inductive loop detector stations from spot speeds measured at these stations. For each route, it is possible to determine the travel time distribution and therefore the buffer times from the 95th and 50th percentile link travel times. Different applicability factors such as those in Table 1 can also be used for different vehicle classes: cars and three HV classes. The buffer time approach can be implemented quite easily and is intuitive.

It is also proposed that the reliability cost of bus travel times should also be considered using the buffer time concept. Given there is limited research in the area, it is suggested to assume that bus travellers have the same applicability factor as other vehicle travellers as suggested by Wang (2014). However, the reference speed/travel time for buses is the scheduled travel time and it won’t be a constant as was the case with the freeway scenarios shown in Figure 1.

A Case Study on Bus Congestion Cost Estimation

In discussions with TMR, Gympie Road, Brisbane was selected as a study site to test the suitability of using the proposed methodology to estimate bus congestion cost. The bus routes along Gympie Road 330, 333, 340 and 370 that fell predominantly within the study site area were used for analysis. This section discusses the data source, calculation methods and analysis results from the Gympie Road case study. Readers should refer to ARRB (2015b) for further information of the case study.

Data Source

TMR provided automatic ticketing system (Go Card) transactions between the 1st and the 29th of March 2015 for these four routes, from which bus travel times and occupancy data could be determined with good accuracy. The TMR data comes from the electronic ticket or Go Card that users need to touch on and off during each trip.

Calculation Method

A bus ‘route’ is divided into several road links ($i = 1, 2, \ldots, N$). A bus link is the distance along a bus route between two bus stops. The first bus stop is stop zero and the subsequent stop is stop 1. The distance between stop 0 and stop 1 is represented by bus link no.1.

On link *i* at time *t*, there will be zero, one or more buses (from all bus routes) travelling on the link, i.e. bus number b = 0, 1, …, B(*ti*). The measurement time period is again from *t* = 1, 2, …, *T*. Bus congestion delay considers the following three components:

- *In-bus travel time delay*: defined as the prevailing travel time of the bus at time *t* on link *i*, minus the scheduled bus travel time at time *t* on the same link. And the prevailing travel time could be estimated as the time difference between the last Go Card transaction time at an upstream bus stop and the last Go Card transaction time at the next downstream bus stop.

  For simplicity, if the bus arrives earlier than scheduled, the bus delay can be treated as zero. The bus arrival time is the first touch-on time or the first touch-off time at a bus stop, whichever is the earlier. The case of a bus not stopping at a bus stop must be identified with travel times adjusted for those links affected.

  As the bus timetable already takes into account the recurrent congestion, the bus travel delay here mainly reflects non-recurrent congestion delay, or excessive delay. Note that bus operators has been reviewing and updating the bus timetables periodically (e.g. every 6 to 12 months) to incorporate the change of recurrent congestion into bus operation.

- *Measured buffer time (MBT) for a bus route*: the variability or unreliability of bus travel times is considered in terms of a bus buffer time. When the variation of travel times is analysed at the route level, the measured route buffer time at time *t* (MBT_t) is determined from a route travel time distribution by the 95th and 50th percentile bus route travel times for each time slice *t*. The route travel time is simply the sum of measured link travel times on that route at time *t*. The reliability applicability factor is 1.0 according to ARRB (2015).

  Estimated buffer time for a bus link: from the measured route (MBT_t) and link buffer times (MBT_{ti}), the estimated buffer time (EBT_{ti}) for link *i* at time *t* is given in Equation 1.

  $$EBT_{ti} = MBT_t \times \frac{MBT_{ti}}{\sum_{i=1}^{N} MBT_{ti}} \qquad 1$$

  Note that the measured link buffer time is calculated based on link travel times collected in multiple days in the study period (e.g. one month).

- *Excessive passenger waiting time*: defined as the time difference between a passenger's Go Card touch-on time and the bus scheduled arrival time at a stop (or zero if the bus arrives early). Passenger waiting times at a stop due to late arrivals are also considered as part of the excessive congestion delay. Passenger waiting time (W_{tib}) on each bus *b* on a link *i* at time *t* is given by summing waiting times of all boarding passengers at the stop identified with link *i* in that time slice:

$$W_{tib} = \sum_{\substack{All\ boarding\\ passengers\ on\ bus\ b\\ at\ time\ t\ and\ stop\ i}} [Passenger\ touch\ on\ times - Scheduled\ bus\ arrival\ times]$$

The time slice can be selected as 15 or 30 minutes. The results therefore represent the average cost for that time slice making use of the travel times and their variability measured, based on the time resolution of their measurements that can be in seconds. Depending on the locations of the bus stops and the time of data collection, a longer time slice of 30 minutes may have to be used.

Analysis Results from Gympie Road Case Study

By using the method discussed above and the Go Card data from Gympie Road study site in March 2015, the followed results were obtained:

1. The average excessive congestion cost for bus passengers per day was $44,013 for weekdays and $14,111 for weekends. The total congestion cost was $880,259 for 20 weekdays and $126,995 for 9 weekend days in March 2015 (Table 3). The difference between the congestion cost in weekdays and weekends is expected as the weekend bus frequency is much lower than weekday bus frequency.

2. In weekdays, travel delay cost was the largest contributor to total congestion cost that occupies 42% of the total congestion cost, followed by passenger waiting time cost (36%) and travel time reliability cost (22%). In weekends, a similar pattern was identified with the percentages changed to 49%, 32% and 19% respectively (Figure 2). It is noticed that passenger waiting times are a significant proportion of the total costs associated with congestion.

3. The profile of congestion costs within a typical weekday displayed two distinct peaks between 7-9 pm and 3-6 pm, corresponding with the morning and afternoon peak commuting times. Figure 3 shows the congestion costs profile in a 24-hour time period by using the 30-min interval data, in a typical weekday, 2015. The congestion costs profile during a typical weekend day showed much less distinguished peaks with possible maximums at mid-morning, mid-afternoon and late-evening. Figure 4 shows the congestion costs profile in a 24-hour time period by using the 30-min interval data in a typical weekend.

Table 4: Total cost summary for 20 weekdays and 9 weekend days during the analysis period (in $2013)

	Weekdays	**Weekends**
Total Travel Delay Cost	$372,538.85	$62,621.97
Total Passenger Waiting Time Cost	$316,314.57	$40,874.58
Total Buffer Time Cost	$191,405.98	$23,498.84
Total Cost	**$880,259.40**	**$126,995.39**
Average Travel Delay Cost per Day	$18,626.94	$6,958.00
Average Passenger Waiting Time Cost per Day	$15,815.73	$4,541.62
Average Buffer Time Cost per Day	$9,570.30	$2,610.98
Average Cost per Day	**$44,012.97**	**$14,110.60**

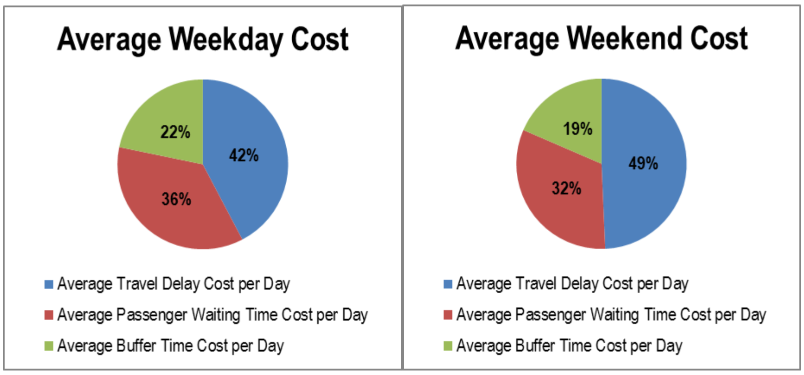


Figure 2: Average weekday and weekend congestion cost proportions

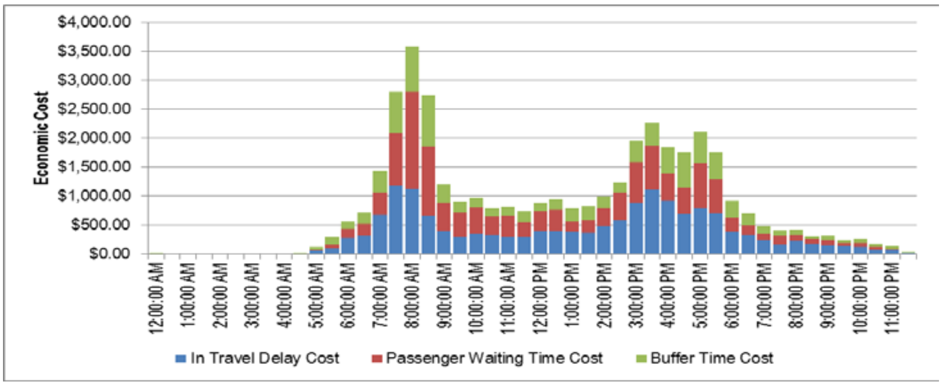


Figure 3: Congestion cost by time-of-day on 2nd March 2015 Monday

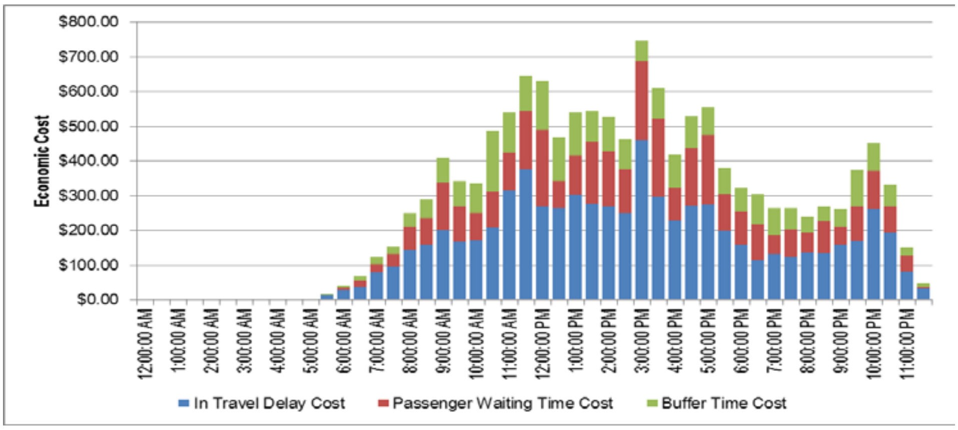


Figure 4: Congestion cost by time-of-day on 1st March 2015 Sunday

A Case Study on Before-and-after Evaluation of Freeway Congestion

Following the methodology discussed in the report, another case study was conducted for a before-and-after comparison of congestion cost for the Bruce Highway managed motorway project. It evaluated the possible impacts on freeway congestion cost following the installation of a ramp metering system along the Bruce Highway. A 30 km segment of the Bruce Highway on the southbound side surrounding the five ramp metering installation zone was selected as the study site. Four weeks' of before data and four weeks' of after data was collected from STREAMS and classified traffic counters. The congestion cost is calculated as the sum of excessive delay cost and travel time reliability cost in the case study. Readers should refer to ARRB (2016) for further information of the case study.

The preliminary result of this case study revealed that the multi-modal congestion cost methodology is feasible for freeway data analysis. The application of the costing methodology showed that the ramp metering system installed along the Bruce Highway was highly successful in reducing both excessive delay and reliability costs during the morning peak commute. Although the average daily VKT increased by 5% between the before-and after-periods of the study, the cost of congestion was reduced by 26% on a typical weekday. A bulk of these cost-savings originated from reduced excessive delay cost, which experienced a 39% reduction. The travel time reliability cost also dropped by 7%.

When normalising by VKT to control for the effects of natural traffic growth over time, more significant cost savings were identified, especially during the morning peak when ramp metering was active. Reductions of total congestion, excessive delay and reliability costs per 1,000 VKT were 30%, 42% and 12% respectively during morning peak.

Conclusions

This paper presents an excessive congestion delay analysis methodology that could be used for cars, HV classes and buses. This methodology considers travel delay by comparing prevailing travel times (or speeds) with reference travel times (or reference speeds) and also the buffer times to take into consideration the reliability cost of travel. Passenger waiting times at a bus stop are also considered in the bus delay cost framework. The work in this paper has improved TMR cost-of-congestion methodology by introducing the travel time reliability measures and using online classified counts other than uniformed percentages for different vehicle classes when calculating congestion cost.

The Gympie Road case study successfully tested the bus congestion cost method by using the electronic ticket data. The data analysis yielded reasonable congestion cost values that closely followed expected commuting patterns.

The Bruce Highway case study revealed that the multi-modal congestion cost methodology is feasible for robust freeway data analysis. The application of the costing methodology showed that the ramp metering system installed along the Bruce Highway was highly successful in reducing both excessive delay and reliability costs during the morning peak commute.

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