FINAL REPORT

Project Title:	R22 Measuring On-Road Congestion Costs for Multi-Modal Travel - Case Study 1: Gympie Road Bus Route Study (2014/15-2015/16)
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Client:	Queensland Department of Transport and Main Roads
Date:	July 2016

SUMMARY

Project R22 aims to produce a methodology for estimating excessive congestion costs associated with multiple road users that include: passenger cars, heavy vehicles (HVs), buses, cyclists and pedestrians. Two case studies, one for bus delay cost estimation and one for freeway before-and-after congestion cost comparison are proposed to test the methodology.

The first-year report of Project R22 proposed a framework that considered excessive travel delay by comparing prevailing travel times (or speeds) with reference travel times (or reference speeds) and also take into consideration the reliability cost of travel. Passenger waiting times at a bus stop are also considered in the bus delay cost framework.

This report contains the working process and main findings from the case study 1: Gympie Road bus congestion analysis. Bus arrival times, bus travel times between two bus stops and passenger waiting times were estimated from *passenger* touch-on and touch-off times of the TMR automatic ticketing system. In the bus delay estimation framework, the reference travel time is the bus schedule, already taking into account the recurrent congestion along the route. Excessive congestion costs arise when the actual route travel time exceeds the scheduled route travel time. The bus congestion delay cost was calculated as the sum of excessive in-bus travel delay cost, excessive passenger waiting time cost and travel time reliability cost.

The bus data analysis yielded reasonable congestion cost values that closely followed expected commuting patterns. Average total congestion cost per weekday for Gympie Road buses was found to be $44,013, while the cost was $14,111 for weekends. Additionally, analysis of daily variation in congestion cost showed this consistent pattern of low congestion cost for weekends and high congestion cost for weekdays explicitly.

In weekdays, travel delay cost was the largest contributor to total congestion cost, occupying 42% of the total congestion cost. This was followed by passenger waiting time cost (36%) and travel time reliability cost (22%). In weekends, a similar pattern was identified with the proportions being 49%, 32% and 19% respectively.

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. The congestion cost profile during a typical weekend day showed much less distinguished peaks with local maximums occurring at mid-morning, mid-afternoon and late-evening

The Gympie Road case study confirms that the bus congestion cost methodology developed in ARRB (2016) is feasible for the *go* card data analysis. The report also discusses the limitations of the Gympie Roads data analysis and possible future works. A separate report will be produced for the freeway congestion cost case study.

ACKNOWLEDGEMENTS

This project received funding under the *National Assets Centre of Excellence* (NACOE) program and direct funding from TMR. The authors appreciate the great contribution from the TMR project management team and stakeholders from TMR.

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1 INTRODUCTION

Project R22 is funded under the *National Assets Centre of Excellence* (NACOE) research agreement with additional funding from Queensland's Department of Transport and Main Roads (TMR). It aims to enhance TMR's 'cost of congestion' estimate, which is based on Austroads (2009a) and the national performance indicator (NPI) reporting system (Austroads 2009b, 2016, Walsh, Su & Luk 2008). The TMR cost of congestion currently includes four vehicle classes. However, the proportion of vehicles in each class was assumed to be in accordance with the vehicle registration statistics and to be uniform across the measured network. There is an interest in breaking down the costs further by roadway and specific classes by utilising the online data rather than the uniformed percentages.

Project R22 aims to produce a methodology for estimating congestion costs associated with multiple road users that include passenger cars, HVs, buses, cyclists and pedestrians. A literature review and proposed methodology of multi-modal congestion measurement was produced in the first year of this project (Luk, Han and Byrne 2016). The second year of work focuses on the refinement of the measurement method and its implementation through two case studies:

- case study 1: Bus congestion cost estimation for Gympie Road
- case study 2: A before-and-after comparison of congestion cost for the Bruce Highway managed motorway project

Data from STREAMS and automatic bus ticketing systems would be collected and analysed for the estimation of congestion costs in these case studies.

This report constitutes the case study 1 report and it discusses the data collection, analysis and reporting for Gympie Road bus congestion cost. The remaining contents of the report are as follows:

- Data analysis procedure (Section 2)
- Data analysis results (Section 3)
- Limitations of the research and possible future works (Section 4)
- Appendix A provides a comparison of data analysis results for 15 min and 30 min intervals.

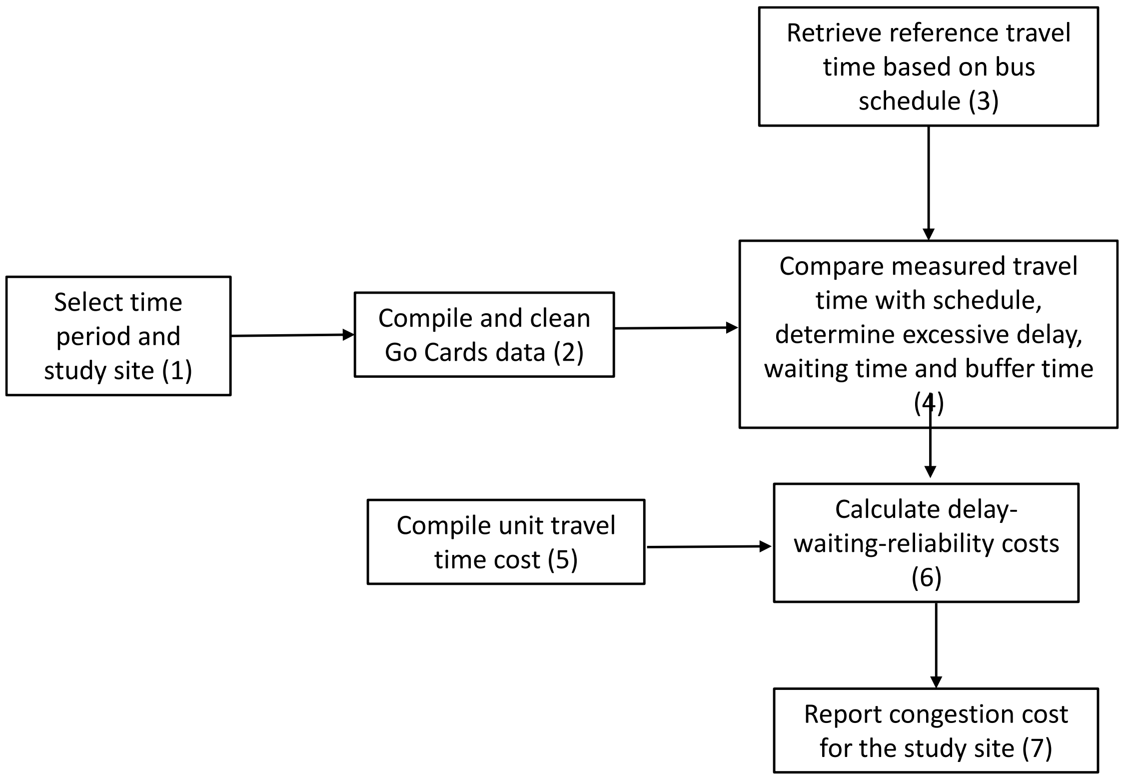
A separate report will be produced for case study 2.

2 DATA ANALYSIS PROCEDURE

The R22 methodology report (Luk, Han and Byrne 2016) has provided the methodology framework of estimating the bus congestion cost by using the electronic bus tickets data. This section discusses a seven-step process that is used to apply the methodology to case study 1: Gympie Road bus congestion cost estimation.

Figure 2.1 shows the seven-step data process procedure that was used for the Gympie Road case study.

Figure 2.1: Data analysis procedure for bus congestion cost



2.1 Step 1: Select Study Site and Time Period

In discussions with TMR, Gympie Road, Brisbane was selected as a test site and all bus routes along Gympie Road would provide data for bus congestion cost analysis. Data from bus routes 330, 333, 340 and 370 that fell predominantly within the study site area was used. The analysis period can be the time periods similar to those used in the online NPI reporting, 24 hourly, peak-time periods, etc.

TMR provided Gympie Road bus movement data derived from the *go* card system that passengers need to use to touch on and off during each trip. The bus travel times and occupancy data could be determined from these data with good accuracy.

The bus movement data between the 1st and the 29th of March 2015 for these four routes was provided.

2.2 Step 2: Compile and Clean *go* card Data

This section discusses the initial investigation of bus movement data derived from *go* card transaction records (Section 2.2.1), various assumptions that were used to fill in data gaps and screen out outliers (Section 2.2.2), abnormal values identified and excluded during data compiling stage (Section 2.2.3) and some sensitivity analysis that was performed to select a proper time interval in order to minimise the data gaps for travel time reliability estimation (Section 2.2.4).

2.2.1 Investigation of go card Transaction Data

The bus movement dataset provided by TMR covered the following items:

- Bus timetable information including scheduled start and finish times for each link of every bus route. The route number, link number and link length for every individual link was also provided.
- The movement of every measured bus along these four routes during the study period was recorded following the format of the above bus timetable.
- When a bus travelled along its designated route, an entry was provided to record the measured start and finish time for each link it travelled through paired with the route number, link number, link length and scheduled start and finish times. Note that not every entry row has measured or recorded *go* card transaction times as the bus may not have stopped at every link.
- If *go* card transactions occurred, times for the first and last *go* card transactions (touch-on or touch-off) at the start and end of each link were recorded to the corresponding data entry row.
- The bus occupancy for each link, and the sum of boarding times of passengers were also provided when available – used to calculate passenger waiting time.

Table 2.1 shows a snapshot of the bus movement dataset provided by TMR. Time values were provided as the number of seconds after midnight of the day the bus began its route, and could be transferred to the time-of-day for reporting purpose.

In total, 352,307 bus movement entries were provided for the 29 day analysis period. 74% of these entries were associated with weekdays, while 26% were for weekends. Weekends were separated from weekdays during cost calculations, as different bus timetables are in place.

Note that the *go* card data and therefore the bus movement data is not reported in regular time intervals as is the case of other traffic data such as loop data. The touch-on and touch-off transactions were recorded with timestamps, therefore the estimated link travel times and passenger waiting times (from entered transaction times) need to be allocated to specific time slices based on the bus departure time.

2.2.2 Assumptions for Data Cleaning

This section explains three assumptions that were used to clean the raw data or fill in data gaps including:

1. Data gaps due to no transaction at a specific time slice for a link

The main purpose of using the *go* card transaction data was to calculate the bus travel times for each link, and the amount of time people spent waiting at the bus stop between the scheduled arrival time and the actual arrival time (passenger waiting time). As described in the methodology report (Luk, Han and Byrne 2016), the measured link travel time is the time difference between the last *go* card transaction time at an upstream bus stop and the last *go* card transaction time at the downstream bus stop.

This requires *go* card transactions at either end of a bus link, i.e. passengers would have to alight and/or board at both the start and end of the link. This commonly does not occur however, as buses frequently drive past stops if no one needs to alight or board. This is demonstrated in Table 2.1, where the bus drove through links 7 to 11 without stopping. Travel times for the intervening links are unknown and cannot be directly calculated using the *go* card transaction data.

For these links, a distance-weighted interpolation was used to estimate the bus travel times for individual links. It was to assume that the travel time between two recorded stops was distributed to all links between these two stops based on link lengths, in another word, a consistent speed between the two stops was assumed. However, this method was not suitable before the first *go* card transaction of a route or after the last, as in those cases there is no pair of times to facilitate interpolation. This situation is shown for all links before 7:00 am in Table 2.1. For these links, it was assumed that the bus arrived at its scheduled time, with the values added during the data cleaning phase.

In total, 44.3% of the bus movement entries in the dataset contained no transaction times and were amended with the above estimated link travel times.

2. Data gaps due to no bus at a specific time slice for a link

Travel time reliability cost is to be estimated from the measured route level buffer times. Route travel time is calculated as the sum of all link travel times at each time slices. However, there are many possible scenarios where there are no buses travelling along a particular link at a specific time slice and this makes the estimation of total route travel time very difficult. The main reasons for these gaps are the limited bus frequency (especially during off-peak or at less busy roads) and random depart and arrival times at each stop.

To fill in these data gaps, it was assumed that if there was no travel time entry for a specific time slice for a link, the scheduled bus travel time at that time slice for the link would be used as an assumed or theoretical link travel time.

To reduce the number of these gaps, longer time intervals of data collection might be used. Section 2.2.4 provides further discussions on the comparison of amount of data gaps that need to be filled if using two different time intervals, 15 min and 30 min.

3. Maximum link travel time threshold

A maximum threshold value of 1800 seconds (30 minutes) for link travel time was implemented, with all link travel times that exceeded this threshold replaced with values of 30 minutes. A total of 79 entries (0.02%) had a link travel time that exceeded 30 minutes, which was deemed unrealistic even in the heaviest of traffic conditions.

Due to the small number of entries, this would not have had a noticeable impact on calculated congestion cost.

2.2.3 Abnormal Data Values

There were also three types of abnormal values that were identified and cleaned as follows:

1. Negative scheduled travel time values

There were 86 entries (0.02%) that had negative scheduled travel time values, because the scheduled link start and end times had been reversed. The absolute values of these scheduled travel times were used to solve this problem.

2. Negative occupancy

There were 350 entries indicated a negative occupancy within the bus. These negative values were replaced with zero occupancy. This only represents 0.1% of the dataset so the impact of these errors was small. However, the cause of these values should be investigated.

3. Negative link travel time

Link travel times were calculated directly from *go* card transaction data where available. After the calculation, there were 1525 negative link travel times. This occurred as the provided *go* card transaction data for these entries showed end of link actions occurring before start of link actions. These negative values were replaced with the scheduled travel time for the link. These errors only represented 0.5% of the dataset provided so replacement of these values would have a noticeable impact on calculated congestion cost. However, the cause of these values should be investigated.

Table 2.1: A snapshot of bus movement provided by TMR on the 1st of March 2015

Route	Link Order	Link Code	Link Length (km)	Occupancy	Scheduled Link Start*	Scheduled Link Finish*	Scheduled Link Travel Time (sec)	Start Of Link Min *go* card Action*	Start Of Link Max *go* card Action*	End Of Link Min *go* card Action*	End Of Link Max *go* card Action*
330	1	000516 - 003136	0.5	0	21420	21480	60				
330	2	003136 - 003145	0.29	0	21480	21480	0				
330	3	003145 - 003148	0.57	0	21480	21540	60				
330	4	003148 - 003169	0.65	0	21540	21600	60				
330	5	003169 - 003168	0.54	0	21600	21660	60				
330	6	003168 - 003166	0.47	0	21660	21720	60			21729	21729
330	7	003166 - 003171	0.68	1	21720	21840	120	21729	21729		
330	8	003171 - 010702	0.41	1	21840	21840	0				
330	9	010702 - 003182	0.58	1	21840	21960	120				
330	10	003182 - 010575	1.24	1	21960	22020	60			22012	22012
330	11	010575 - 010533	0.74	2	22020	22140	120	22012	22012	22108	22117
330	12	010533 - 003360	0.32	4	22140	22140	0	22108	22117	22163	22163
330	13	003360 - 003364	0.68	3	22140	22200	60	22163	22163		
330	14	003364 - 003351	0.32	3	22200	22260	60				
330	15	003351 - 003343	0.53	3	22260	22320	60			22291	22297
330	16	003343 - 003340	0.64	1	22320	22380	60	22291	22297		
330	17	003340 - 010901	0.84	1	22380	22500	120				
330	18	010901 - 003421	0.23	1	22500	22560	60				

*Time values are given in the number of seconds after midnight, e.g. 6 AM would be represented by 21600 (6 x 60 x 60)

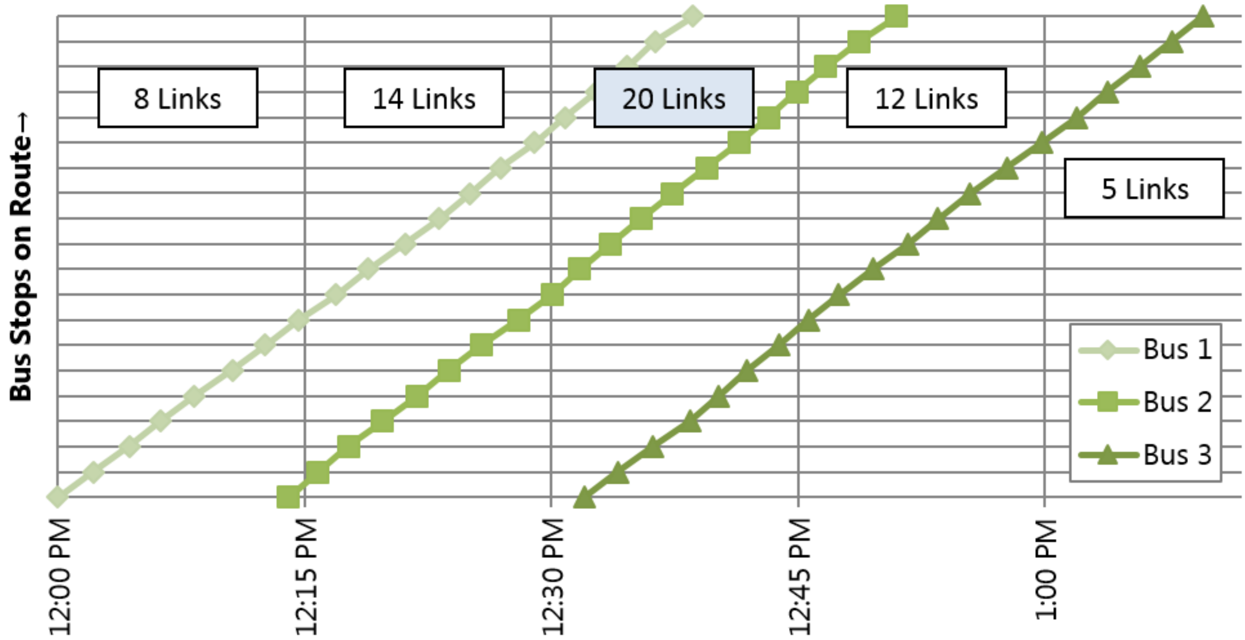
2.2.4 Sensitivity Analysis for Choosing a Proper Time Interval

The calculation of bus travel time reliability cost required the analysis of route buffer time variation day-by-day. Route travel time was calculated as the sum of all link travel times at each time slices. However, there were many scenarios where there was no bus traveling along every link at a specific time slice due to the limited bus frequency and random depart and arrival times at each stop. For each day, the number of available links that contributed to the measured route travel time values during a specific time slice could be very inconsistent.

For example, consider a hypothetical scenario where three busses are travelling along the same route comprised of 20 links (see Figure 2.2). In this simplified situation, only the time slice between 12:30 to 12:45 PM contains travel time data for all 20 links within the route. In other time slices, there might be only 8, 12 or 14 links that contain measured travel time data. This has happened due to a combination of the bus scheduling and the natural time variance in which buses reach stops. Across the analysis days, as long as each time slice has the exact same contributing links with measured travel times, the buffer time would be calculable.

For example, to calculate the measured buffer time for the time slice between 12:00 to 12:15 PM, every day of the analysis must have those exact 8 contributing links. If bus 1's arrival at link 8 was delayed by a few minutes, that link would now originate in the 12:15 to 12:30 PM time slice. This would mean that on that day, only 7 contributing links are available in the 12:00 to 12:15 PM time slice and the route travel time is now incomparable to the days where 8 contributing links are available.

Figure 2.2: Hypothetical scenario involving three busses travelling on the same route



For the dataset provided, use of 15 minute time slices resulted in a majority of time slices being inconsistent with the number of contributing links over the 20 weekdays available. This meant that measured buffer time could not be calculated for almost all time slices. This same problem is much less prevalent when using 30 minute time slices, as the amount of overlapped trips for different bus routes within a time slice is greatly increased.

As discussed in Section 2.2.2, these data gaps was solved by using the scheduled bus travel times to fill in inconsistencies, so that every analysis day had the same number of contributing links. With the above example, if one analysis day only had 7 contributing links for the time slice between 12:00 to 12:15 PM, the scheduled travel time for the missing link would be used to bring the number of contributing links up to a consistent 8.

A comparison of the number of travel times that required filling in to prevent an inconsistent number of contributing links is shown in Table 2.2. Thirty minute time slices require a much lower number of 'theoretical' travel times to facilitate the analysis process. Thirty minute time slices are thus preferable to 15 minute time slices in this case study.

Note that in the Gympie Road case study, 30 min data was used as preferred time slice. However, the results based on 15 min data was also provided in Appendix A for reference purpose.

Table 2.2: Percentage of link travel times that required filling for 15-min and 30-min interval

Entries requiring amendment	15-min time slices	30-min time slices
Weekdays in March 2015	18.1%	4.1%
Weekends in March 2015	24.9%	10.0%

Note: Based on data collected from TMR for bus routes 330, 333, 340 and 370

2.3 Step 3: Retrieve Reference Travel Time

The premise of the bus congestion cost framework is that the bus timetable or schedule provides the scheduled bus travel times and arrival times as reference data. Bus travel delay is thus the time difference between the prevailing travel time of a bus on a link and the scheduled travel time (zero if the bus arrives early). Assuming the bus timetable already takes into account recurrent congestion, the resulting bus travel delay mainly reflects non-recurrent congestion delay, or excessive delay, which is consistent with the definition of congestion delay in Luk, Han and Byrne (2016). Note that TMR has been reviewing and updating the bus timetables periodically (e.g. every 6 to 12 months) to incorporate changes to the amount of recurrent congestion present during bus operation.

2.4 Step 4: Determine In-vehicle Delay, Buffer Time and Excessive Passenger Waiting Time

If the measurement time period is from $t = 1, 2, \ldots, T$. 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 $b = 0, 1, \ldots, B(ti)$. Based on the availability of electronic ticketing data, bus congestion delay considers the following three components:

1. *In-bus travel time delay or excessive congestion delay*: it is defined as the prevailing travel time of the bus at time slice t on link i, minus the scheduled bus travel time at time t on the same link. With the available data, the prevailing travel time was estimated as the time difference between the last *go* card transaction times at the upstream and downstream stops of a link. This includes the effect of dwell time, where the bus is stationary while waiting at a stop.

   For simplicity, if the bus arrived earlier than scheduled, the bus delay was treated as zero. The case of a bus not stopping at a bus stop was identified, with travel times adjusted for those links affected.

2. *Buffer time*: used to characterise the reliability of the bus travel times as a function of day-to-day traffic variation and road incidents. Reliability was first considered at the overall route level, as link-level travel time variation was too volatile for meaningful analysis. The measured buffer time (MBT) was determined from the difference between the 95th and 50th percentile bus route travel times at each time slice t. Weekdays and weekends were

considered separately in this percentile calculation, to prevent bus schedule differences from being included as ‘unreliability’.

The measured buffer time could also be disaggregated back to the link level, resulting in an *estimated buffer time* for a bus link. This was achieved through Equation 1, using measured route (MBT_t) and link buffer times (MBT_{ti}). The measured link buffer time was calculated in the same manner as the measured route buffer time, but on a link basis.

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

where

EBT_{ti} = Estimated link buffer time at time *t* on link *i*

MBT_t = Measured route buffer at time *t*

MBT_{ti} = Measured link buffer time at time *t* on link *i*

The final buffer time value was multiplied by an applicability factor, used to adjust for the likelihood that travellers will budget a buffer time for on-time arrival. The reliability applicability factor used was 1.0 according to Luk, Han and Byrne (2016).

3. *Excessive passenger waiting time*: defined as the time difference between a passenger’s *go* card touch-on time and the corresponding scheduled bus arrival time at a stop (or zero if the bus arrives early).

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 (Equation 2)

$$W_{tib} = \sum_{\substack{All\ boarding \\ passengers\ on\ bus\ b \\ at\ time\ t\ and\ stop\ i}} [Passenger\ touch\ on\ times - Scheduled\ bus\ arrival\ times] \quad (2)$$

where

W_{tib} = Passenger waiting time at time *t* on link *i* with bus *b*

2.5 Step 5: Compile Unit Time Costs

As discussed in the methodology report (Luk, Han and Byrne 2016), the followed unit costs of travel time were applied.

Table 2.3: Unit cost for travel time (in 2013 Australian $)

Road users (urban)	Travel time cost ($/person-h)	Average vehicle occupancy (person/vehicle)	Travel time cost ($/vehicle per hour)
Bus driver	$25.72	1	$25.72
Bus passenger	$14.99	20 (if measured occupancy is not available)	$14.99 (per person) $299.8 (average per bus)

Source: adapted from Transport and Infrastructure Council (2015).

2.6 Step 6: Calculate Total Congestion Cost

In this step, excessive congestion delay cost, passenger waiting time cost and travel time reliability cost are calculated and aggregated, making use of the unit costs compiled in Step 5 and the delay/waiting time/buffer time calculated in Step 4.

The following summarises data required for congestion cost calculation:

- locations of bus stops for references and checking
- scheduled link bus travel times (T_{ti}^{s}) between bus stops for different bus routes on the selected road at time t from bus time tables
- unit travel time costs of the driver (U_d) and each passenger (U_p), which are different
- number of buses at time t on link i (determined from bus departures times at a bus stop)
- bus travel times of each bus b (T_{tib}) on a link identified with a stop (i)
- passenger waiting time (W_{tib}) on each bus b on a link i at time t, given by summing the waiting times of all boarding passengers at the stop identified with link i in that time slice (Equation 3)

$$W_{tib} = \sum_{\substack{All\ boarding \\ passengers\ on\ bus\ b \\ at\ time\ t\ and\ stop\ i}} [Passenger\ touch\ on\ times - Scheduled\ bus\ arrival\ times] \quad (3)$$

- bus occupancies (Ω_{tib}) at time t of each bus (b) on link i
- estimated buffer time (EBT_{ti}) at time t on link i from the link bus travel times.

Table 2.4 shows the framework for bus congestion calculations. A bus link is defined as the distance between two bus stops, with the first bus stop designated as the initial stop or stop zero. The following bus stop is designated as stop no. 1. In other words, for *N* bus links, there will be (*N* + 1) bus stops. Any negative travel delay (i.e. where the bus was ahead of schedule) was treated as zero travel delay (when T_{tib} is equal or higher than T_{ti}).

Table 2.4: Framework for the calculation of congestion delay cost for buses

Time slice *t*	Bus link *i*	Sched. travel time (T^s_{ti})	Bus no. *B(t.i)*	Link pax. waiting time (W_{ti})	Measured buffer time MBT_{ti}	Bus occ. (excl. driver) Ω_{tib}	Driver and passenger link delay cost $ C_{ti}	Route delay cost $ C_t
t = 1	1		1 2 : B(11)	Calculated as: $\sum_{b=1}^{B(11)} W_{11b}$	Calculated from 95th and 50th percentile travel times at t = 1, i = 1 for the estimation of EBT_{ti}	Ω_{111} Ω_{112} : $\Omega_{11B(11)}$	$\sum_{b=1}^{B(11)} [U_d + U_p\Omega_{11b}][T_{11b} - T^s_{11}]$ $+ \sum_{b=1}^{B(11)} U_p[\Omega_{11b}EBT_{11} + W_{11b}]$	
	2		1 2 : B(12)		:	Ω_{121} Ω_{122} : $\Omega_{12B(12)}$	$\sum_{b=1}^{B(12)} [U_d + U_p\Omega_{12b}][T_{12b} - T^s_{12}]$ $+ \sum_{b=1}^{B(12)} U_p[\Omega_{12b}EBT_{12} + W_{12b}]$	$\sum_{i=1}^{N} C_{1i}$
	:	:	:		:	:	As above	
	N	As above						
t = 2	1		1 2 : B(21)		:	Ω_{211} Ω_{212} : $\Omega_{21B(21)}$	$\sum_{b=1}^{B(21)} [U_d + U_p\Omega_{21b}][T_{21b} - T^s_{21}]$ $+ \sum_{b=1}^{B(21)} U_p[\Omega_{21b}EBT_{21} + W_{21b}]$	
	2		1 2 : B(22)		:	Ω_{221} Ω_{222} : $\Omega_{22B(22)}$	$\sum_{b=1}^{B(22)} [U_d + U_p\Omega_{22b}][T_{22b} - T^s_{22}]$ $+ \sum_{b=1}^{B(22)} U_p[\Omega_{22b}EBT_{22} + W_{22b}]$	$\sum_{i=1}^{N} C_{2i}$
	:	:	:		:	:	As above	
	N						As above	
: :	: :	: :	: :		: :	: :	As above	: :
t = T	As above							$\sum_{i=1}^{N} C_{Ti}$
Delay cost of bus drivers and passengers for time period T = $\sum_{t=1}^{T} C_t$								

The bus congestion delay cost at time t and link i (C_{ti}) includes in-vehicle travel delay cost, buffer time cost and passenger waiting time cost. This is calculated using Equation 4.

$$C_{ti} = \sum_{b=1}^{B(ti)} [U_d + U_p\Omega_{tib}][T_{tib} - T^s_{ti}] + \sum_{b=1}^{B(ti)} U_p[\Omega_{tib}EBT_{ti} + W_{tib}] \quad 4$$

The bus congestion delay cost at time t and link i (C_{ti}) includes in-vehicle travel delay cost, buffer time cost and passenger waiting time cost. It is shown in Equation 5.

$$C_{ti} = \sum_{b=1}^{B(ti)} [U_d + U_p\Omega_{tib}][T_{tib} - T_{ti}^{s}] + \sum_{b=1}^{B(ti)} U_p[\Omega_{tib}EBT_{ti} + W_{tib}] \quad (5)$$

The bus congestion delay cost for the whole bus route of N links at time t (C_t) is shown in Equation 6.

$$C_t = \sum_{i=1}^{N} C_{ti} \quad (6)$$

The total bus congestion delay cost for the whole bus road in a measurement time period *T* is given by $\sum_{t=1}^{T} C_t$.

The use of the estimated buffer time term at the link level ensures consistency with a measured route buffer time while maintaining compatibility with occupancy and passenger waiting time data, which naturally exists at the link level.

2.7 Step 7: Report Case Study Results

In this step, congestion cost analysis results are reported including average daily congestion costs by day-of-month and by time-of-day. The congestion costs were reported against the total congestion and each of the three components, excessive congestion delay, passenger waiting time and travel time reliability. The results should also be reported separately for weekdays and weekends prevent the large bus schedule differences between these two times being interpreted as ‘unreliability’.

Detailed data analysis results and discussion on the findings for the Gympie Road case study are provided in Section 3.

3 DATA ANALYSIS RESULTS

Using the methodology and analysis process outlined in Section 2, the following results were obtained for the Gympie Road bus congestion cost case study:

- average congestion cost per day including the delay cost, passenger waiting cost and travel time reliability cost (Section 3.1)
- average daily congestion by day-of-month (Section 3.2)
- typical weekday congestion cost by time-of-day (Section 3.3)
- typical weekend congestion cost by time-of-day (Section 3.4)
- daily route travel time variations by time-of-day (Section 3.5)

Results were derived using 30 minute time slices. For comparison, equivalent results from the 15 minute slice analysis are also provided in Appendix A.

3.1 Average Congestion Cost per Day

Average congestion cost per day was calculated through the aggregation of total congestion cost across all relevant days of the analysis period. Weekends and weekdays were reported separately as the bus timetable differed substantially between these two sets. Table 3.1 shows the summary of average daily congestion costs and total monthly congestion cost for the Gympie Road buses.

Table 3.1: Total cost summary for 20 weekdays and 9 weekend days during the analysis period (in $2013)

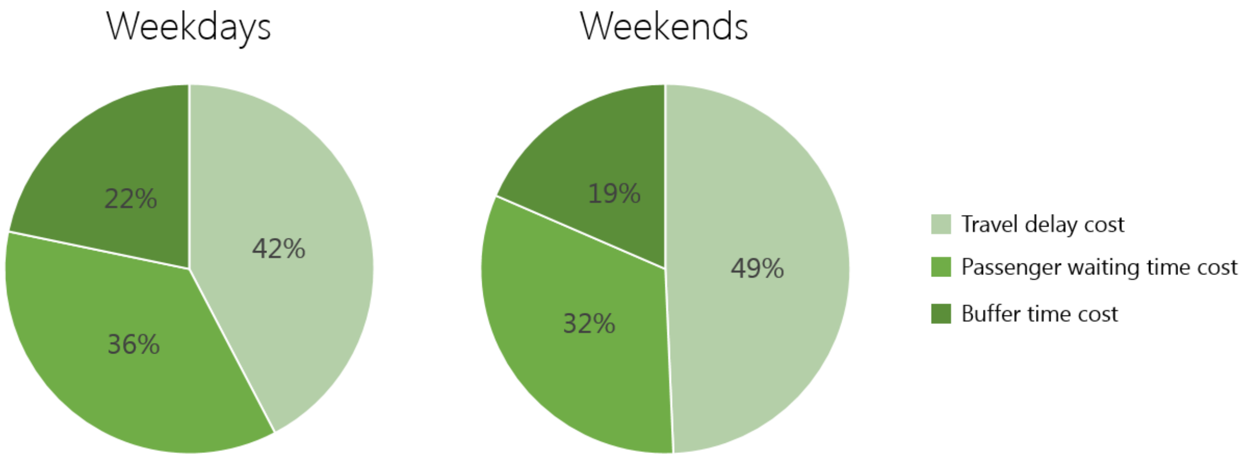
	Weekdays	Weekends
Total Travel Delay Cost	$372,539	$62,622
Total Passenger Waiting Time Cost	$316,315	$40,875
Total Buffer Time Cost	$191,406	$23,499
Total Cost	$880,259	$126,995
Average Travel Delay Cost per Day	$18,627	$6,958
Average Passenger Waiting Time Cost per Day	$15,816	$4,542
Average Buffer Time Cost per Day	$9,570	$2,611
Average Cost per Day	$44,013	$14,111
Number of Distinct Trips[1]	368,110	65,902
Average Travel Delay Cost per Trip	$1.01	$0.95
Average Passenger Waiting Time Cost per Trip	$0.86	$0.62
Average Buffer Time Cost per Trip	$0.52	$0.36
Average Cost per Trip	$2.39	$1.93

[1]One trip is defined as a single passenger boarding a bus then alighting at a later stop.

Table 3.1 shows that the average congestion cost per day was $44,013 for weekdays and $14,111 for weekends. The total congestion cost was $880,259 for weekdays and $126,995 for weekend in March 2015. The difference between the congestion cost per day on weekdays and weekends is expected as the bus frequency and occupancy is much lower on the weekends compared to the weekdays. However, when considering the cost per passenger trip, the difference between weekdays and weekends is relatively small.

Travel delay cost was the largest contributor to total congestion cost, followed by passenger waiting time cost. Buffer time cost was consistently the lowest contributor to congestion cost. Proportions are shown in Figure 3.1.

Figure 3.1: Average weekday and weekend congestion cost proportions

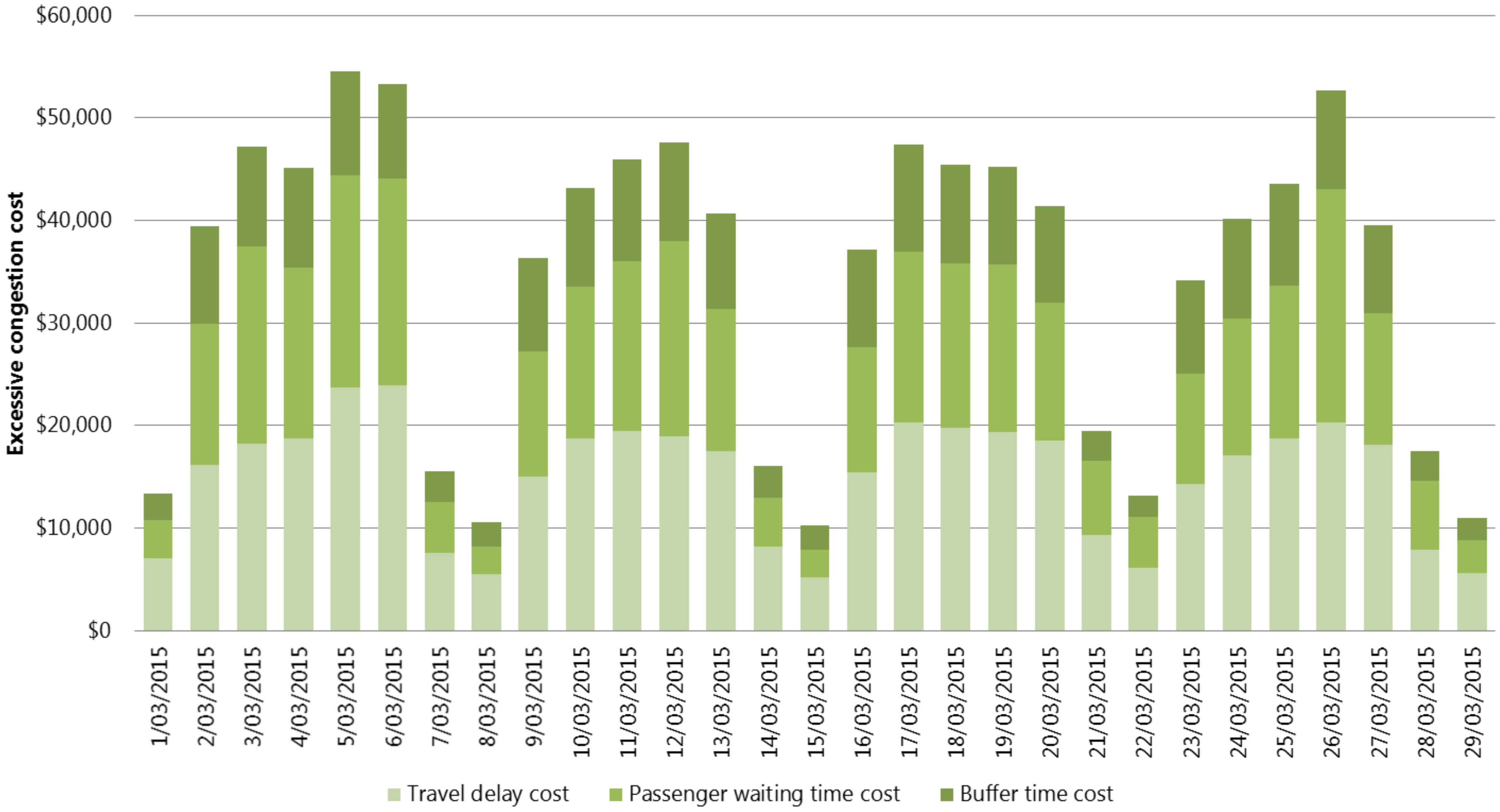


3.2 Daily Congestion Cost by Day-of-month

Figure 3.2 shows a profile of the total congestion for each day over the analysis period, including its underlying components. The variation in congestion throughout the week can be identified, with consistently low congestion costs on the weekends.

A comparison between average congestion costs per day derived from 15 minute and 30 minute time slices is shown in Appendix A.2.

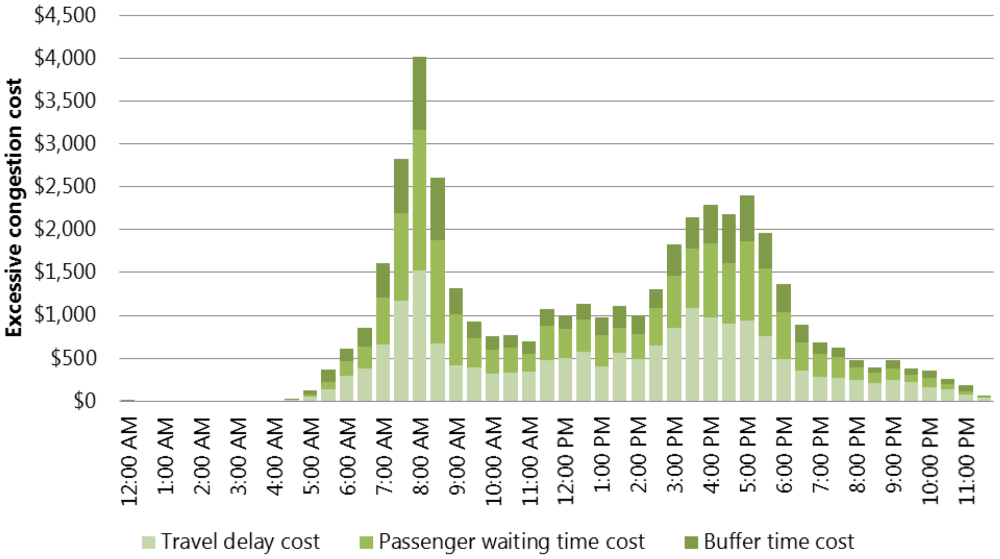
Figure 3.2: Profile of daily congestion cost in March 2015



3.3 Typical Weekday Performance by Time-of-day

Figure 3.3 shows the average congestion cost profile in a 24-hour time period for weekdays, derived using 30 minute time slices. Two clear peaks can be identified, corresponding to morning and afternoon peak travel times.

Figure 3.3: Average congestion cost by time-of-day on weekdays

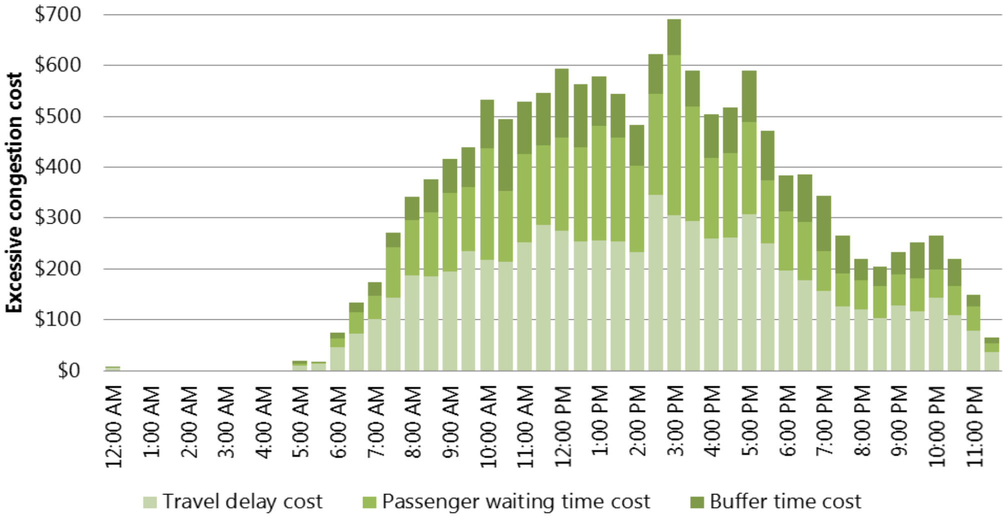


A chart showing the output as calculated from 15 minute time slices is shown in Appendix A.3 for reference.

3.4 Typical Weekend Performance by Time-of-day

Figure 3.4 shows the average congestion cost profile in a 24-hour time period for weekends, derived using 30 minute time slices.

Figure 3.4: Average congestion cost by time-of-day on weekends



Unlike the weekday chart as shown in Figure 3.3, the peaks are harder to discern, with local maximums occurring at mid-morning, mid-afternoon and late-evening.

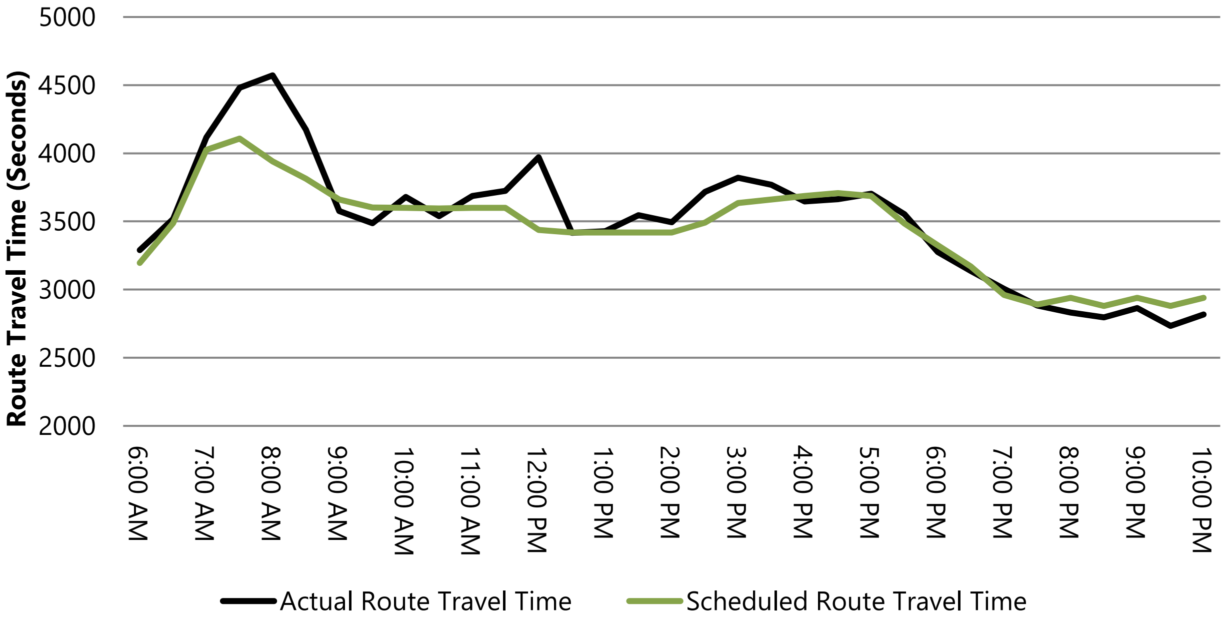
A chart showing the output as calculated from 15 minute time slices is shown in Appendix A.3 for reference.

3.5 Discussion on Bus Route Travel Time Variation

The methodology report (Luk, Han and Byrne 2016) explained the definition of excessive congestion delay and Figure 2.4 in Luk, Han and Byrne (2016) illustrated an example of the calculation of congestion delay by using a reference speed in the freeway scenario. For buses, the reference route travel time is the scheduled travel time and it is not a constant value as is the case for freeways. Variation in average route travel time across 20 weekdays, for route 330 (Citybound) is shown in Figure 3.5.

It shows that the scheduled travel time already takes into account the recurrent congestion along the route and it already has two peaks. Excessive congestion costs arise when the actual route travel time exceeds the scheduled route travel time.

Figure 3.5: Average route travel time for route 330 (citybound) with 30 minute time slices



3.6 Summary of Main Findings

The Gympie Road case study successfully tested the bus congestion cost methodology that was developed in Luk, Han and Byrne (2016). The bus congestion cost was calculated as the sum of in-bus travel delay cost, passenger waiting time cost and travel time reliability cost.

The data analysis yielded reasonable congestion cost values that closely followed expected commuting patterns. Average total congestion cost per weekday was found to be $44,013, while the cost was $14,111 for weekends. Additionally, analysis of daily variation in congestion cost showed this consistent pattern of low congestion cost for weekends and high congestion cost for weekdays explicitly.

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.

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. The congestion costs profile during a typical weekend day showed much less distinguished peaks with local maximums occurring at mid-morning, mid-afternoon and late-evening.

4 LIMITATIONS OF THE RESEARCH AND FUTURE WORKS

The Gympie Road case study confirmed that the bus congestion cost methodology developed in first-year of R22 is feasible for the *go* card data analysis. It should be noted that the limitations or the scope of work in this case study are as follows:

- The congestion cost analysis in this case study does not take into account recurrent congestion since the bus timetables are used as reference. Assuming that bus timetables have been reviewed and updated and considered recurrent congestions, and therefore the delay cost estimated in this report is mainly excessive congestion delay.
- The congestion cost in this report and in R22 project is limited to congestion delay cost, the environmental cost, additional vehicle operating cost and cost of operating additional buses due to congestion are all out-of-the scope of the project.
- The spreadsheet developed in this project is suitable for the process of *go* card transaction data, which is based on passenger touch-on and touch-off records. If bus travel time is measured by different methods such as automatic vehicle location GPS tracking and if Timing Points data is available to identify instances where a bus stopped at a timing point in order to adjust running time (this is unable to be captured using just *go* card data), the data analysis process will need to be redesigned. However, the framework discussed in Section 2 should still be valid.
- The 30 minute time interval was selected as a proper time resolution of data process after sensitivity comparison of data gaps in 15 minute and 30 minute data. However, if the method is applied to a different bus route with less or more frequent bus schedule times, sensitivity analysis might need to be conducted again to select a proper time interval.
- To fill in data gaps, theoretical travel time values based on bus schedules were used to fill in the missed link travel time values. With a busy bus route, only a small amount of links may require assumed values. However, with a quiet bus route, it may be necessary to fill in many links so that the method will function. Thus, this method is more suitable for busier bus routes where the need to assume travel times will be low.
- There are various methods to estimate travel time reliability cost. In this report the buffer time method was used based on findings from the literature review. It would be helpful if different methods such as reliability cost ratio method could be tested and compared with more research evidence and data is available in this area.

This project is a pilot to test the methodology and it is suggested to consider the followed research works in a future stage:

- Run the congestion delay cost calculation to estimate the excessive congestion costs of private traffic on Gympie Road. This will allow comparisons of the congestion cost between private traffic and public transport. Appendix B demonstrates an example of comparing the bus congestion costs calculated in this report and congestion costs along Gympie Road as determined through STREAMS data.
- Consider to aggregate the congestion delay cost of buses into the total congestion cost estimation for the future project appraisals.
- Review bus vehicle operating cost and emissions equations in relation to the cost of congestion to further enhance the congestion impact analysis of buses.

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APPENDIX A COMPARISON OF RESULTS FOR 15 MIN AND 30 MIN

A.1 Average Congestion Cost per Day

Table A 1: Total cost summary for 20 weekdays during the analysis period (in $2013)

	15 minute Time Slices	30 minute Time Slices
Total Travel Delay Cost	$372,539	$372,539
Total Passenger Waiting Time Cost	$316,315	$316,315
Total Buffer Time Cost	$186,240	$191,406
Total Cost	$875,093	$880,259
Average Travel Delay Cost per Day	$18,627	$18,627
Average Passenger Waiting Time Cost per Day	$15,816	$15,816
Average Buffer Time Cost per Day	$9,312	$9,570
Average Cost per Day	$43,755	$44,013

Table A 2: Total cost summary for 9 weekend days during the analysis period (in $2013)

	15 minute Time Slices	30 minute Time Slices
Total Travel Delay Cost	$62,622	$62,622
Total Passenger Waiting Time Cost	$40,875	$40,875
Total Buffer Time Cost	$25,802	$23,499
Total Cost	$129,298	$126,995
Average Travel Delay Cost per Day	$6,958	$6,958
Average Passenger Waiting Time Cost per Day	$4,542	$4,542
Average Buffer Time Cost per Day	$2,867	$2,611
Average Cost per Day	$14,366	$14,111

It should be noted that when comparing 15 minute and 30 minute time slices, only the buffer time cost will differ due to the way in which percentiles are aggregated across the time periods. Travel delay cost and passenger waiting time cost are both independent of this process and are unaffected by time slice size.

A.2 Actual Congestion Cost per Day

Table A 3: Daily congestion cost as calculated with 15 minute time slices (in $2013)

Date	Travel Delay Cost	Passenger Waiting Time Cost	Buffer Time Cost (15 min)	Buffer Time Cost (30 min)
01/03/2015, Sunday	$7,081	$3,684	$2,834	$2,658
02/03/2015, Monday	$16,148	$13,749	$9,216	$9,567
03/03/2015, Tuesday	$18,203	$19,253	$9,545	$9,718
04/03/2015, Wednesday	$18,798	$16,629	$9,342	$9,689
05/03/2015, Thursday	$23,724	$20,725	$9,752	$10,063
06/03/2015, Friday	$23,911	$20,180	$9,124	$9,253
07/03/2015, Saturday	$7,578	$4,969	$3,186	$2,966
08/03/2015, Sunday	$5,542	$2,684	$2,624	$2,316
09/03/2015, Monday	$15,040	$12,245	$8,895	$9,085
10/03/2015, Tuesday	$18,755	$14,821	$9,306	$9,564
11/03/2015, Wednesday	$19,488	$16,494	$9,561	$9,969
12/03/2015, Thursday	$18,991	$18,966	$9,339	$9,679
13/03/2015, Friday	$17,508	$13,871	$8,999	$9,291
14/03/2015, Saturday	$8,176	$4,816	$3,358	$3,033
15/03/2015, Sunday	$5,214	$2,651	$2,714	$2,383
16/03/2015, Monday	$15,423	$12,241	$9,264	$9,467
17/03/2015, Tuesday	$20,263	$16,712	$9,916	$10,486
18/03/2015, Wednesday	$19,755	$16,031	$9,505	$9,681
19/03/2015, Thursday	$19,349	$16,360	$9,456	$9,564
20/03/2015, Friday	$18,547	$13,439	$9,114	$9,461
21/03/2015, Saturday	$9,379	$7,193	$3,187	$2,934
22/03/2015, Sunday	$6,151	$4,945	$2,356	$2,124
23/03/2015, Monday	$14,355	$10,738	$8,870	$9,115
24/03/2015, Tuesday	$17,126	$13,326	$9,452	$9,710
25/03/2015, Wednesday	$18,752	$14,930	$9,636	$9,858
26/03/2015, Thursday	$20,291	$22,780	$9,520	$9,567
27/03/2015, Friday	$18,110	$12,824	$8,426	$8,615
28/03/2015, Saturday	$7,910	$6,662	$3,240	$2,987
29/03/2015, Sunday	$5,592	$3,270	$2,302	$2,098

A.3 Performance by Time of Day (15 Minute Time Slices)

Figure A 1: Average congestion cost by time of day on weekdays using 15 minute time slices

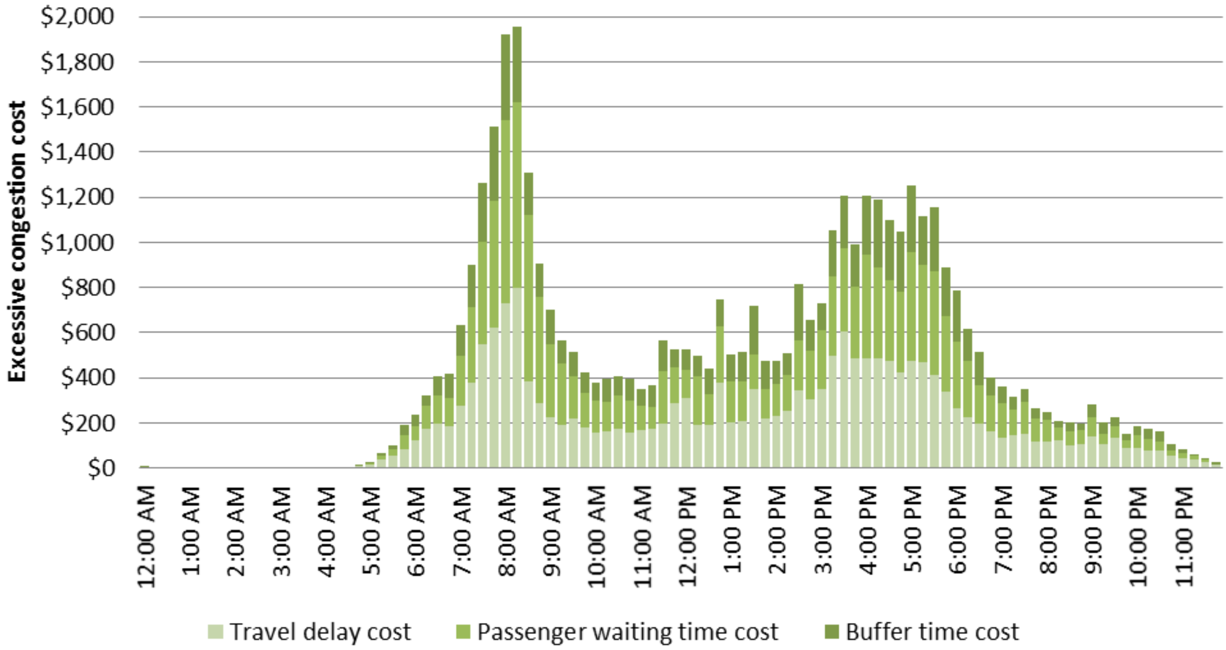
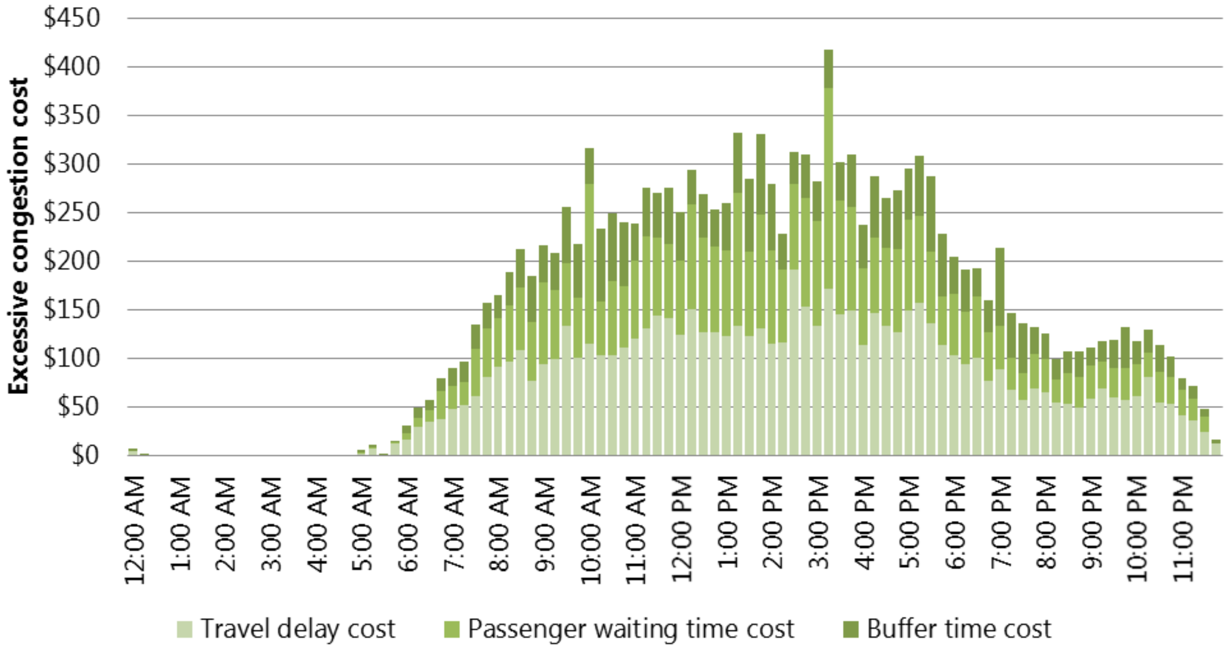


Figure A 2: Average congestion cost by time of day on weekends using 15 minute time slices



APPENDIX B COMPARISON TO GENERAL TRAFFIC

The cost of excessive congestion experienced by general traffic was available from STREAMS on a select part of Gympie Road. By comparing the full cost of congestion experienced by general traffic to the cost of congestion experienced by buses as outlined in this report, the validity of the bus congestion costs can be evaluated.

The STREAMS congestion costs encompassed the area between the intersection of Gympie Road and Graham Road southbound until Gympie Road transitions into Lutwyche Road. The study site used in this case study for buses was larger than this, so to facilitate a fair comparison only the bus links that fell within the STREAMS area were used to calculated excessive delay costs for buses.

Table B 4: Comparison of bus and general traffic excessive delay costs

	Bus	Traffic
Average Weekday Cost	$7,586 (5.2%)	$147,000
Average Weekend Cost	$2,647 (2.9%)	$90,000

Table B 4 shows that the congestion experienced by bus passengers constitute approximately 3-5% of actual traffic cost. This represents a reasonable proportion of the costs as would be expected for the volume of buses that travel along Gympie Road.

It should be noted however, that certain limitations exist in making a comparison of this nature. The excessive delay cost for buses is calculated from the difference between the scheduled bus travel time and the actual bus travel time. However, for general traffic the excessive delay cost is calculated from the difference between a reference travel time and the actual travel time of vehicles. This reference travel time is generated based on vehicles travelling at a set proportion of the speed limit, such as 70%. The two methods of calculating costs are fundamentally different, meaning that comparisons are only indicative of the actual proportion of congestion cost that buses experience as part of the general traffic flow.

Additionally, under the STREAMS cost calculation buses are counted as rigid trucks. This fails to account for the passenger movements that occur within the bus system, slightly distorting the congestion costs. A more thorough analysis will need to take this error in vehicle classification into account to arrive at more precise economic cost values.