FINAL REPORT

Project Title: R22 Measuring On-Road Congestion Costs for Multi-modal Travel - Case Study 2: Bruce Highway Managed Motorway Project (2014/15 - 2015/16)

Project No: 010580

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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) and buses. 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 took into consideration the reliability cost of travel time. Two case studies, one for bus congestion delay cost estimation and one for freeway before-and-after congestion cost comparison, were also conducted to test the methodology.

This report contains the working process and main findings from Case Study 2: Before-and-after comparison of congestion cost for the Bruce Highway managed motorway project. It evaluates the possible impacts on freeway congestion cost following the installation of a ramp metering system along the Bruce Highway. The congestion cost is defined as the sum of excessive delay cost and travel time reliability cost in the case study.

The case study confirmed that the multi-modal congestion cost methodology is feasible for robust freeway data analysis. By applying the methodology, the ramp metering system installed along the Bruce Highway was confirmed to be highly successful in reducing both excessive delay and reliability costs during the morning peak commute.

The congestion cost reductions identified in the before-and-after comparison are as follows:

- Although the average daily vehicle-kilometre-travelled (VKT) increased by 5% between the before-period and after-period of the study, the daily congestion cost 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.

The report also discusses the limitations of the analysis and proposes possible future work such as reviewing of reference speed thresholds, increasing the sample size for travel time reliability assessment on weekends and considering expanded data sources. A separate report has been produced for Case Study 1: Gympie Road congestion cost case study.

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1 INTRODUCTION

Project R22: Measuring On-Road Congestion Costs for Multi-Modal Travel is funded under the National Asset Centre of Excellence (NACOE) research agreement with additional funding from the Department of Transport and Main Roads (TMR). It aims to enhance the TMR cost-of-congestion estimate, which is based on *Estimating road network congestion and associated costs* (Austroads 2009a) and the national performance indicator (NPI) reporting system (Austroads 2009b, 2016, Walsh, Su & Luk 2008). The TMR cost-of-congestion estimate currently includes four vehicle classes or bins. 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 has produced a methodology for estimating congestion costs associated with multiple road users that includes passenger cars, heavy vehicles (HVs), buses, cyclists and pedestrians in the first year of this project (Luk, Han and Byrne 2016). The second year of work has focused on the refinement of the measurement method and its implementation through two case studies:

- Case Study 1: bus congestion cost estimation for Gympie Road (Han & Byrne, 2016)
- Case Study 2: before-and-after comparison of congestion cost for the Bruce Highway managed motorway project.

This report discusses the data collection, analysis and reporting for Case Study 2. The structure of the report is as follows:

- application of methodology to the estimation of freeway congestion cost (Section 2)
- case study results (Section 3)
- limitations of the research (Section 4)
- conclusions and possible future work (Section 5).

In this report, congestion cost is defined as the sum of excessive delay cost and travel time reliability cost. Other congestion cost components such as environmental costs and vehicle operating costs are not relevant to the travel time reliability measurement and have been discussed in Austroads (2009a) and implemented in TMR cost-of-congestion practices; they were out-of-scope of this case study.

Online classified traffic counts are utilised to replace the previous uniformed percentages of vehicle classes. Traffic counts are classified into four classes or bins according to vehicle length as follows (Austroads 2006):

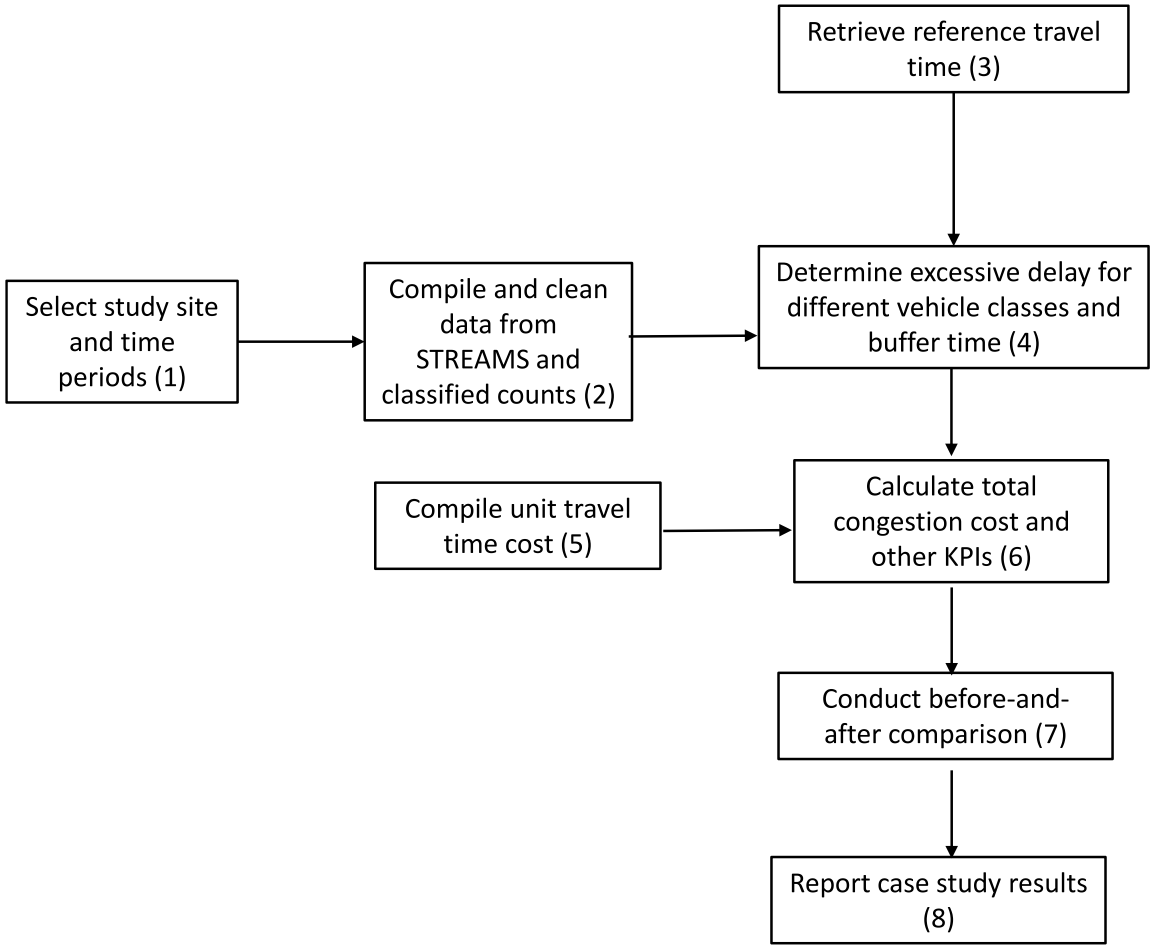
- short vehicles (length < 6 m), this class is further classified into private trips and business trips in the cost estimation
- medium vehicles (6 m ≤ length < 13 m)
- long vehicles (13 m ≤ length < 21 m)
- combination vehicles (length ≥ 21 m).

The focus of this case study is predominantly the application of the congestion costing methodology through the before-and-after analysis. This includes impacts to traffic flow on surrounding ramps and arterials. Extraneous effects of the ramp metering installation are not considered in this study.

2 APPLICATION OF METHDOLOGY TO THE ESTIMATION OF FREEWAY CONGESTION COST

The R22 methodology report (Luk, Han & Byrne 2016) has outlined the framework for estimating freeway congestion cost with multiple vehicle classes. This section discusses an eight-step process that is used to apply the methodology to the current case study: *Before-and-after comparison of congestion cost for the Bruce Highway managed motorway project*. Figure 2.1 shows the procedure followed for the analysis.

Figure 2.1: Methodology for Bruce Highway case study



2.1 Step 1: Select Study Site and Time Periods

TMR (2016a) reported that ramp signals were installed at five on-ramps along the Bruce Highway southbound (city bound) between the Gateway Motorway and Caboolture in 2015, as part of the Bruce Highway managed motorway project. The five on-ramps are at the Dohles Rocks Road, Anzac Avenue, Boundary Road, Deception Bay Road and Uhlmann Road interchanges. The system was activated on 21 September 2015. The ramp signals currently only operate during the morning peak, between 5:45 am to 9:30 am on weekdays.

To evaluate the possible impacts on freeway congestion cost following the installation of the ramp metering system, a 30 km segment of the Bruce Highway southbound surrounding the installation zone was selected as the study site. Approximately 5.8 km upstream and 6.0 km downstream of the metered area are included in this zone, extending from Bribie Island Road to Gympie Arterial

Road and the Gateway Motorway respectively. This extra distance was incorporated into the study as the effects of the ramp metering system are likely to propagate far beyond its area of operation.

Study time periods need to represent typical operational conditions. The after-period was selected to give at least three months for system settlement after ramp signals were installed, and it also excluded Christmas, New Year periods and school holidays. The following time periods were therefore selected for before-and-after analysis:

- Monday16 February to 15 Sunday March 2015 (before installation)
- Monday 15 February Sunday to 13 March 2016 (after installation).

Each time period represents a period of four weeks, separated by exactly one year to minimise the impacts of seasonal factors potentially affecting traffic volume and road user behaviour.

2.2 Step 2: Compile and Clean Data from STREAMS and Traffic Counters

The study site was split into 18 distinct national performance indicator (NPI) links, varying between 750 and 4000 m in length. For each of these links during the before-period and after-period, the following data was supplied by TMR in 15-minute segments:

- average link travel time from STREAMS
- link traffic flow from STREAMS.

Classified vehicle counts were also provided from six permanent traffic counting stations within the study site at 15-minute intervals.

2.2.1 Strategies to Apply Classified Vehicle Counts to Road Links

Classified vehicle count data was provided in four classes/bins according to vehicle length as per Austroads (2006):

- short vehicles (length < 6 m), this class is further classified into private trips and business trips in the cost estimation
- medium vehicles (6 m ≤ length < 13 m)
- long vehicles (13 m ≤ length < 21 m)
- combination vehicles (length ≥ 21 m).

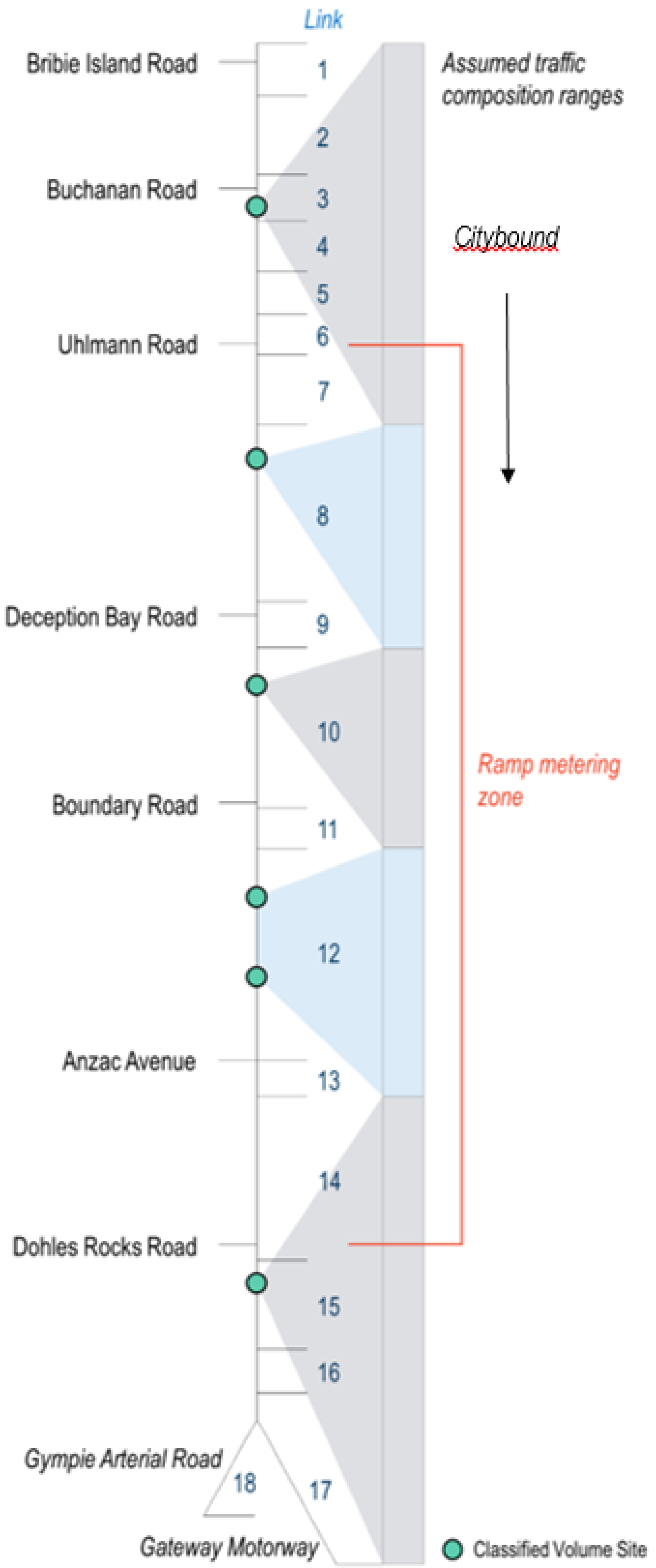
A total of six counting stations were located in the study area, providing the percentage proportion of traffic in each class every 15 minutes. Five of the counting stations were STREAMS detector sites specially configured to detect vehicle length, which other STREAMS detectors could not achieve. Another classified counting site (near Buchanan Road) was also available and configured to classify vehicles by the twelve Austroads vehicle classes, which was aggregated to the above four classes by TMR.

The vehicle classification from the six sites thus originated from two different systems. A comparative analysis of the vehicle class proportions as produced from these two systems was conducted to verify their consistency. It was found that, overall, vehicle class proportions are very similar when comparing the data from the classified counting station and STREAMS sites. Some examples of the analysis results are shown in Appendix B.

There was an insufficient number of classified sites to apply unique classification data to each of the 18 links. However, a scheme was developed to map the traffic composition proportions from a single classifying station to multiple links, depending on likely vehicle movements.

Figure 2.2 shows a diagrammatic representation of the study site, along with the locations of the classified sites and how the traffic composition from these sites were mapped to the 18 individual NPI links.

Figure 2.2: Representation of the Bruce Highway study site and location of key features



Link #	Length (m)
1	997
2	1481
3	849
4	949
5	798
6	764
7	1307
8	3301
9	861
10	2995
11	751
12	3955
13	676
14	3066
15	1662
16	812
17	3123
18	2075

2.2.2 Incident Days

Extreme weather conditions and major incidents have a significant impact on traffic volume and speed, particularly travel time reliability. As this report is focused on facilitating a robust comparison between the before-period and after-period to evaluate ramp metering impacts, days in either period that experienced incidents were excluded from the analysis. This was done to ensure that day-to-day variation in travel times did not adversely bias either time period.

Based on TMR investigation, Table 2.1 lists the incident days that were excluded from the analysis. Four days from the before-period and two days from the after-period were excluded.

Table 2.1: Incident days excluded from analysis

Incident days	Incident	TMR comments
Thursday 19 February 2015	The day before tropical cyclone Marcia. Heavy rain and flood warning	Due to the cyclone warning, the volume was about 4% lower at 5-10 am, compared to the other weekdays.
Friday 20 February 2015 .	The day of tropical cyclone Marcia	The volume was significantly lower, compared to the other weekdays.
Saturday 21 February and Sunday 22 February 2015	The weekend of tropical cyclone Marcia.	Both days showed significantly lower volume and VKT, compared to other weekends.
Monday 24 February 2015	A major incident – four-car crash in southbound lanes at Pine Rivers Bridge on Bruce Highway.	Note that the flow and speed data was not significantly impacted on the day
Friday 4 March 2016	A major incident - crash southbound on the Bruce Highway at 5.38am 400 m south of Dohles Rocks Road caused significant delays across the southern end of the managed motorway and arterial network	Note that both the flow and speed data revealed an obvious impact.
Friday 11 March 2016	Single vehicle rollover on Bruce Highway southbound adjacent to Uhlmann Road southbound	Both the flow and speed data revealed an obvious impact.

2.2.3 Data Cleaning

The data from STREAMS and the classified counting stations was crosschecked by TMR before being applied to the case study – the data was of good quality.

However, during certain time periods, flow and speed data were missing due to electronic disturbances and other errors in communication of data between the vehicle detectors and the STREAMS system. For the before-period, 0.02% of records (11 out of 48,384) were affected. For the after-period, 0.52% of records (253 out of 48,384) were affected.

These entries were replaced using hot-deck imputation. A flow or speed value from the same 15-minute segment of the day, but from exactly one week after or before was used in its place. Due to the small number of replaced speed and flow values, the impact on the calculation results is deemed to be minimal.

2.3 Step 3: Retrieve Reference Travel Time

As proposed in Luk, Han and Byrne (2016), reference travel time for the Bruce Highway case study was estimated based on an assumed 70% of the posted speed limit. The speed limit along this portion of the Bruce Highway is 100 km/h, the reference travel time was therefore estimated at 70 km/h.

2.4 Step 4: Compile Unit Time Costs

Table 2.2 outlines the unit travel time costs for the four vehicle classes.

Table 2.2: Unit cost of travel time (in 2013 Australian dollars)

Vehicle class	Road users (urban)	Travel time cost ($/person per hour)	Average vehicle occupancy (person/ vehicle)	Travel time cost ($/vehicle per hour)	Freight travel time cost ($/vehicle per hour)	Applicability factor for reliability estimation
Short vehicles	Car private	$14.99	1.6	$23.98	n. a.	0.6
Short vehicles	Car business	$48.63	1.4	$68.02	n. a.	1.0
Medium vehicles	Medium HV	$25.72	1.3	$33.44	$4.15	1.0
Long vehicles	Articulated HV	$26.81	1.0	$26.81	$39.01	1.0
Combination vehicles	B-double HV	$27.20	1.0	$27.20	$64.91	1.0

Source: Vehicle class sourced from Austroads (2006). Unit cost sourced from Transport and Infrastructure Council (2015). Applicability factor sourced from Wang (2014).

The short vehicle class was split into private and business use, as unit travel time costs are quite different in the case of these two uses. The traditional method of differentiating between these trip types has been to apply a single assumed private/business split ratio (e.g. 80:20) to vehicle counts.

For this case study, TMR's Transport System Management team provided a more detailed private/business trip split matrix encompassing all 15-minute time intervals for typical weekdays and weekends. The trip split matrix was sourced from the *South East Queensland Household Travel Survey* (2009-12 combined survey) and weighted to 2011 values (TMR 2016b). This allowed the split to change according to time and day of the week. Thus, although only four vehicle classes were measured by the classifying stations, five vehicle classes were used to estimate congestion cost.

2.5 Step 5: Determine Excessive Delay Cost, Buffer Time Cost and Total Congestion Cost

Using the speed and flow data, as well as derived traffic compositions from each link, the excessive travel delay cost, reliability cost and total congestion cost was calculated for each 15-minute time slice on every link for the before-and-after periods.

The input data for a time slice (t) of 15 minutes on the freeway link (i) include the following:

- length of link i
- reference speeds v_{rij} for link i (i=1 to N) and vehicle class j (j = 1 to 5)
- unit costs of vehicle travel times by vehicle class U_j
- applicability factors for the costing of the reliability of travel times by vehicle classes A_j
- traffic counts q_{tij} of vehicle class j at road link i in time slice t

- measured speed v_{tij} at time t on link i for vehicle class j.

Table 2.3 shows a framework for the calculation of excessive travel delay cost (*COT*) for a freeway route of N links (i = 1, … , N) for the time period t = 1 to T, where T is the period of measurement. At a time slice of 15 minutes, T = 96 for a whole-day measurement period and T = 8 for a peak-period measurement of two hours. In this case study, N=18.

For a route of N links, the number of detector stations is N+1. The initial station is designated as station zero.

A similar framework for the calculation of the link reliability cost (*COR*) is shown in Table 2.4, where BT_{tij} is the buffer time at time slice t, link i and vehicle class j.

Table 2.3: Calculation of link delay costs for five vehicle classes

Time slice t	Link. i	Length L_i km	Vehicle class j	Flow $q_{t,i,j}$	Ref. speed v^r_{ij}	Unit cost U_j	Link travel delay cost for veh class j \$ COT_{tij}	Link delay cost for all veh COT_{ti}
$t = 1$	1		1				$U_1 q_{111}[\frac{L_1}{v_{111}} - \frac{L_1}{v^r_{11}}]$	
			2				$U_2 q_{112}[\frac{L_1}{v_{112}} - \frac{L_1}{v^r_{12}}]$	
			3				$U_3 q_{113}[\frac{L_1}{v_{113}} - \frac{L_1}{v^r_{13}}]$	$\sum_{j=1}^{5} COT_{11j}$
			4				$U_4 q_{114}[\frac{L_1}{v_{114}} - \frac{L_1}{v^r_{14}}]$	
			5				$U_5 q_{115}[\frac{L_1}{v_{115}} - \frac{L_1}{v^r_{15}}]$	
	2		1				$U_1 q_{121}[\frac{L_1}{v_{122}} - \frac{L_1}{v^r_{22}}]$	
			2				$U_2 q_{122}[\frac{L_1}{v_{122}} - \frac{L_1}{v^r_{22}}]$	
			3				$U_3 q_{123}[\frac{L_1}{v_{123}} - \frac{L_1}{v^r_{23}}]$	$\sum_{j=1}^{5} COT_{12j}$
			4				$U_4 q_{124}[\frac{L_1}{v_{124}} - \frac{L_1}{v^r_{24}}]$	
			5				$U_5 q_{125}[\frac{L_1}{v_{125}} - \frac{L_1}{v^r_{25}}]$	
	:							:
	N		1				As above	$\sum_{j=1}^{5} COT_{1Nj}$
			:					
			5					
$t = 2$	1		1 : 5				As above	$\sum_{j=1}^{5} COT_{21j}$
	2		1 : 5				As above	$\sum_{j=1}^{5} COT_{22j}$
	:		:				:	:
	N		1				As above	
			:					
			5					
: :	: :	: :	: :	: :	: :	: :	: :	: :
$t = T$	As above							As above

Note: Only the speeds below threshold values are used for delay calculation.

Table 2.4: Calculation of link reliability costs for four vehicle classes

Time slice t	Link i	Length L_i km	Vehicle class j	Measured buffer time $MBT_{t,i,j}$ (Note)	Reliability app. factor A_j	Unit cost U_j	Reliability cost ($) for veh class j COR_{tij}	Link reliab. cost for all veh classes $ COR_{ti}
t = 1	1		1	Calculated from 95th and 50th percentile travel times at t = 1, i = 1 for j = 1 to 5	0.6		$U_1 MBT_{111} A_1$	$\sum_{j=1}^{5} COR_{11j}$
			2		1.0		$U_2 MBT_{112} A_2$	
			3		1.0		$U_3 MBT_{113} A_3$	
			4		1.0		$U_4 MBT_{114} A_4$	
			5		1.0		$U_5 MBT_{115} A_5$	
	2		1	As above for link 2	0.6		$U_1 MBT_{121} A_1$	$\sum_{j=1}^{5} COR_{12j}$
			2		1.0		$U_2 MBT_{122} A_2$	
			3		1.0		$U_3 MBT_{123} A_3$	
			4		1.0		$U_4 MBT_{124} A_4$	
			5		1.0		$U_5 MBT_{125} A_5$	
	:			:			:	:
	N		1		0.6		As above	$\sum_{j=1}^{5} COR_{1Nj}$
			2		1.0			
			3		1.0			
			4		1.0			
			5		1.0			
t = 2	1		1 2 3 4 5				As above	$\sum_{j=1}^{5} COR_{21j}$
	2		1 2 3 4 5				As above	$\sum_{j=1}^{5} COR_{22j}$
	:		:				:	:
	N		1				As above	
			2					
			3					
			4					
			5					
: :	: :	: :	: :	: :	: :	: :	: :	: :
t = T	As above							As above

Note: The measured link buffer time (MBT) cost may not have a physical meaning; the purpose of calculating link MBT is to disaggregate the route MBT to individual links properly so that a total congestion cost at link level could be calculated and reported. The details are explained in Luk, Han and Byrne (2016).

The *total delay* cost at time *t* and link *i* and for vehicle class *j* (TD_{tij}) is the sum of travel delay cost (COT_{tij}) and reliability cost (COR_{tij}). From these basic cost elements, various levels of cost aggregation can be carried out. Some examples of aggregation are as follows:

- The *link* delay cost including reliability cost for time *t*, link *i* and vehicle class *j* (Equation 1)

$$TD_{tij} = COT_{tij} + COR_{tij} \quad (1)$$

- The *route* delay cost including reliability cost for vehicle class *j* at time *t* Equation 2)

$$TD_{tj} = \sum_{i=1}^{N} TD_{tij} \quad (2)$$

- The *delay* cost including reliability cost in time period *T* for vehicle class *j* (Equation 3)

$$TD_j = \sum_{t=1}^{T} TD_{tj} \quad (3)$$

- The *total* delay cost including reliability cost in time period *T* for all vehicle classes (Equation 4)

$$TD = \sum_{j=1}^{4} \sum_{t=1}^{T} TD_{tj} = \sum_{j=1}^{4} TD_j \quad (4)$$

Delay costs are generally analysed at the link level to identify more accurately where congestion occurs to facilitate network operations on freeways and arterials. In the case of reliability costs, the variation of travel times should be analysed at the route level and the measured *route buffer time* at time *t* (MBT_t) is determined from a route travel time distribution. The route travel time is simply the sum of measured link travel times on that route at time *t*.

Note that route buffer time determined from the route travel time distribution will be different from the sum of all link buffer times (*MBT*) determined from link travel times. Therefore the link *estimated buffer time* (EBT_{tij}) is introduced as shown in Equation 5.

$$EBT_{tij} = MBT_t \times \frac{MBT_{tij}}{\sum_{i=1}^{N} MBT_{tij}} \quad (5)$$

This approach assumes that the link with a larger measured buffer time receives a larger proportion of the route buffer time, with the sum of estimated link buffer times equal to the measured route buffer time. By replacing MBT_{tij} with EBT_{tij} in Table 2.4 the results from the table should be consistent with a route buffer time obtained from route travel times.

The route reliability cost at time *t* for vehicle class *j* (COR_{tj}) can also be directly calculated, shown in Equation 6

$$COR_{tj} = MBT_{tj} \times A_j \times U_j = \sum_{i=1}^{N} EBT_{tij} \times A_j \times U_j \quad (6)$$

Again, the route delay cost including variability of travel times at time t for vehicle class j is the sum of route travel time cost COT_{tj} and route reliability cost COR_{tj}.

2.6 Step 6: Conduct Before-and-After Comparisons

Two types of before-and-after comparisons were conducted for the Bruce Highway case study:

- **A general comparison of the congestion costs**

The excessive delay cost, buffer time cost and the total congestion cost were compared for the whole before-period and after-period. Twenty-four hour data on non-incident weekdays was used for this analysis.

- **Impact of ramp signals**

  The excessive delay cost, buffer time cost and total congestion cost experienced during the effective ramp metering times were compared. Data between 5 am to 10 am on non-incident weekdays was analysed.

2.7 Step 7: Report Case Study Results

The results of the before-and-after comparisons were processed and collated in Section 3 of this report.

3 CASE STUDY RESULTS

Using the methodology and analysis processes outlined in Section 2, the following results were obtained:

- Before-and-after comparison of vehicle-kilometres travelled (VKT)
- Before-and-after comparison of average congestion cost for weekdays
- Before-and-after comparison of average congestion cost per VKT for weekdays
- Before-and-after comparison of average weekday congestion cost by time-of-day
- Before-and-after comparison of congestion cost for all study days.

The above items were calculated for both 24-hour day and for the effective ramp metering time during the morning peak (between 5 am to 10am) where relevant.

All cost values in both Case Study 1 (Han and Byrne 2016) and Case Study 2 (this report) and unit time costs are in 2013 Australian dollar values ($2013) for consistency.

3.1 Before-and-After Comparison of VKT

VKT provides a standard metric for determining the total amount of traffic that passed through the study site for both the before-period and after-period. This was calculated using the flow data from STREAMS and the link lengths provided by TMR for each 15-minute time slice. Table 3.1 shows the average VKT for each day of the week for both time periods across the whole study site, including the percentage difference.

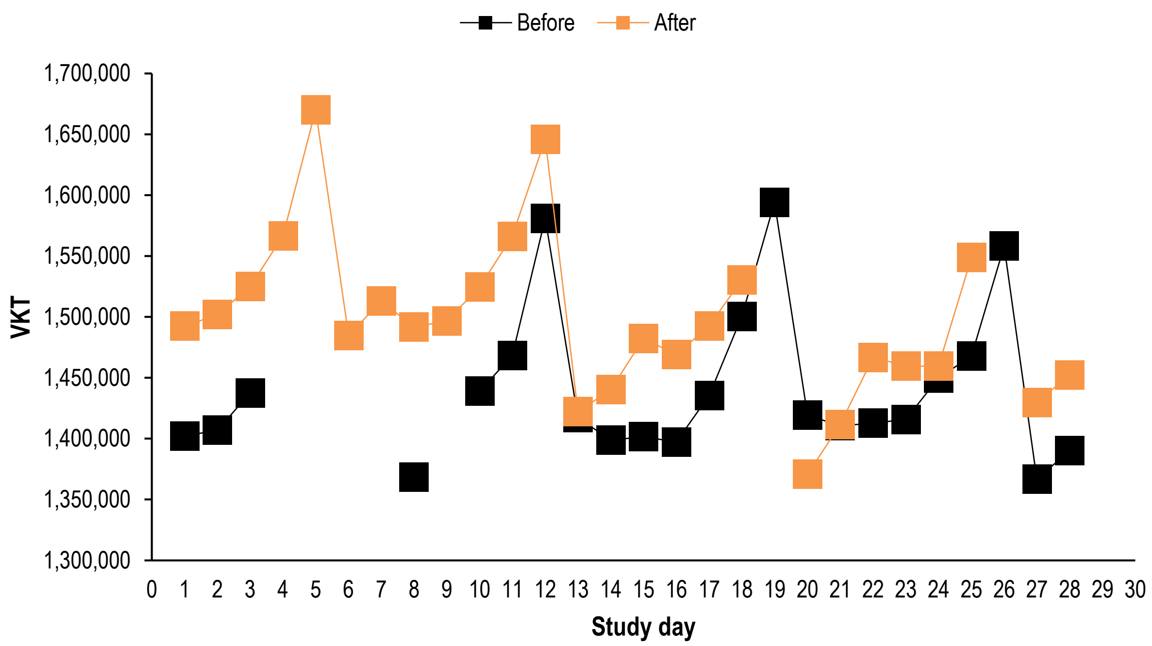
Table 3.1: Day-of-week average VKT comparison

Day	VKT		Percentage difference
	Before-period	After-period	
Monday	1,396,242	1,483,349	6%
Tuesday	1,406,651	1,481,900	5%
Wednesday	1,440,524	1,500,427	4%
Thursday	1,478,842	1,553,119	5%
Friday	1,577,739	1,658,076	4%
Saturday	1,401,143	1,426,876	1%
Sunday	1,399,828	1,454,398	3%
Average weekdays	1,460,000	1,535,374	5%

As incident days had been excluded from the analysis, the number of each weekday may not be the same between the before-period and the after-period. To ensure that average VKT values were not biased, weighted averaging for each of the weekdays was used to ensure that fair comparison was made between the before-periods and after-periods.

Overall, VKT increased by an average of 5% for weekdays from February/March 2015 to February/March 2016, which is consistent with expected traffic growth for the Bruce Highway over one year. Figure 3.1 shows the daily variation in the VKT over the four weeks (28 days) of both before and after periods. Gaps in the chart are for the days removed due to incidents (see Section 2.2.2).

Figure 3.1: Burwood Highway study site daily VKT for the before-period and after-period



3.2 Before-and-After Comparison of Average Congestion Cost per Weekday

Average congestion cost per day was calculated through aggregation of total congestion cost across all relevant days of the analysis period. Weekends (Saturday and Sunday) were not included in the comparison as the sample size was too small to produce statistically meaningful values, plus the congestion costs due to excessive delay were generally very small over the weekend.

Table 3.2 summarises the before-and-after comparison results of average daily congestion cost. All cost values in Project R22 are in $2013 for consistency.

Table 3.2: Before-and-after comparisons of average daily congestion cost for weekdays ($2013)

		Before	After	Difference
Effective ramp metering time	Excessive delay cost	$59,408	$36,014	-39%
	Reliability cost	$40,021	$37,102	-7%
	Total cost	$99,429	$73,115	-26%
Other times	Excessive delay cost	$133	$127	-4%
	Reliability cost	$3,707	$6,558	77%
	Total cost	$3,840	$6,685	74%
Total congestion cost	Excessive delay cost	$59,541	$36,141	-39%
	Reliability cost	$43,728	$43,659	0%
	Total cost	$103,269	$79,800	-23%

Despite the increases of 5% in average traffic volumes on weekdays, the cost of congestion following the installation of ramp metering was reduced. The average cost of congestion on a weekday in the 2015 study period was $103,269, while in 2016 it was $79,800, representing a cost saving of 23%. A bulk of these cost savings originates from less excessive delay cost, from $59,541 to $36141, representing a 39% reduction. The travel time reliability cost was also reduced marginally from $43,728 to $43,659.

Due to the very minimal excessive delay experienced during off-peak time for both the before-period and the after-period, the major cost saving was achieved during morning peak when ramp metering is operating. During the morning peak, the average congestion cost was reduced from $99,429 to $73,115, representing a 26% cost reduction. Again the most significant cost saving originates from excessive delay cost, which was decreased from $59,408 to $36,014, indicating a 39% reduction. The travel time reliability cost was also reduced by 7% from $40,021 to $37,102.

Reliability cost increased by 77% outside the ramp metering operating times, but it should be noted that this represents a cost increase of only $2851, which is insignificant when compared to the overall cost saving from $103,269 to $79,800.

3.3 Before-and-After Comparison of Average Congestion cost per 1000 VKT for Weekdays

In addition to average congestion cost, average congestion cost per 1000 VKT was also calculated. This indicator normalised congestion cost by VKT and it mitigates the effects of increased traffic volumes between the before-period and after-period. Table 3.3 summarises these results. Again all cost values in Project R22 are in $2013 for consistency.

Table 3.3: Average congestion cost per 1000 VKT for weekdays ($2013)

		Before	After	Difference
Effective ramp metering time	Excessive delay cost	$113.10	$65.29	-42%
	Reliability cost	$75.89	$67.05	-12%
	Total cost	$188.99	$132.35	-30%
Other times	Excessive delay cost	$0.15	$0.13	-9%
	Reliability cost	$3.98	$6.68	68%
	Total cost	$4.12	$6.81	65%
Total across day	Excessive delay cost	$19.60	$12.13	-38%
	Reliability cost	$19.80	$19.27	-3%
	Total cost	$39.40	$31.40	-20%

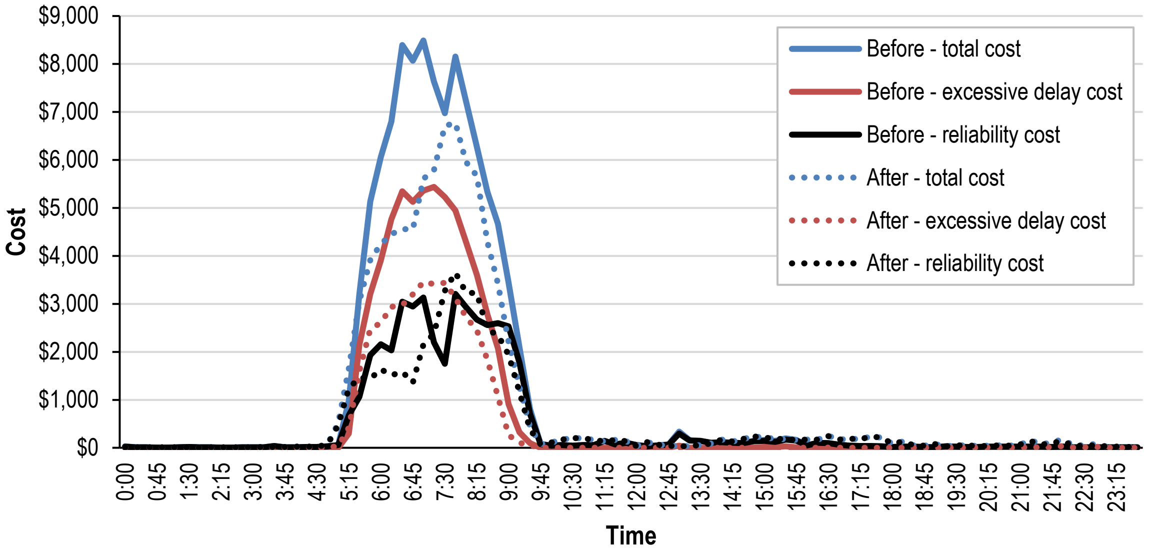
After normalising by VKT, total congestion cost (both peak and off-peak) was reduced by 20%, from $39.40 in the before-period to $31.40 in the after-period. Excessive congestion cost per 1000 VKT was reduced by 38% and from $19.60 to $12.13. Reliability cost per 1000 VKT demonstrated a marginal decrease of 3%.

A majority of congestion cost saving was due to less excessive delays being experienced during the morning peak when ramp metering was activated. During the morning peak, reduction of total congestion, excessive delay and reliability cost per 1000 VKT were 30%, 42% and 12% respectively.

3.4 Before-and-After Comparison of Average Weekday Congestion Cost by Time-of-Day

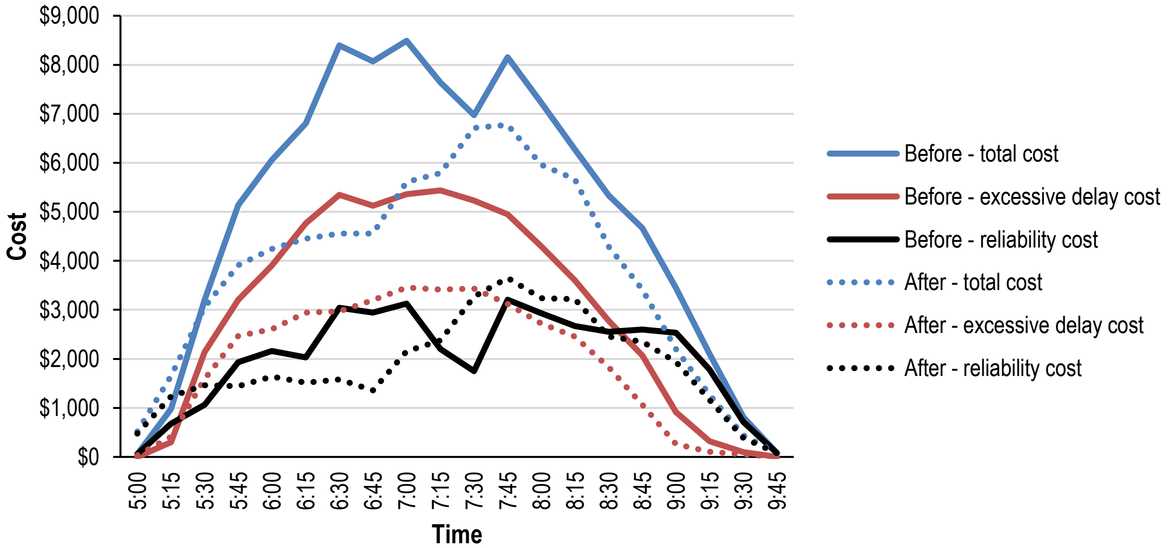
Figure 3.2 shows the average congestion costs by time-of-day for weekdays for the before-period and after-period. As expected, a clear spike in congestion cost was experienced during the morning peak as commuters travel inbound, with little congestion encountered at any other time of the day.

Figure 3.2: Average weekday costs by time-of-day ($2013)



Comparison between the costs including the excessive congestion cost, reliability cost and total congestion cost for the before-period and after-period confirm observations made in previous sections. Costs following the installation of the ramp metering sites are generally lower than those before installation, particularly in morning peak periods. Figure 3.3 shows the costs of the morning peak period only, for clarity.

Figure 3.3: Average weekday cost by time of day for the morning peak period ($2013)



3.5 Before-and-After Comparison of Congestion Cost for All Study Days

Figure 3.4 shows the profile of total congestion for each day of the before-period and after-period of analysis. It also includes weekend values. As expected, congestion was consistently very low on weekends, with little if any excessive delay experienced. Gaps in the charts are the specific days excluded due to incidents.

Figure 3.5 shows the same profile; however, only accounts for the congestion costs incurred during the effective ramp metering times on weekday mornings (5 am – 10 am). The after-period results show noticeably lower congestion costs consistently across the entire study period, for the whole day as well as during the morning peak period when ramp metering is active.

Appendix A contains a full breakdown of the congestion cost for each day of the before-period and after-period.

Figure 3.4: Total daily congestion cost comparison ($2013, 24-hour data including weekends)

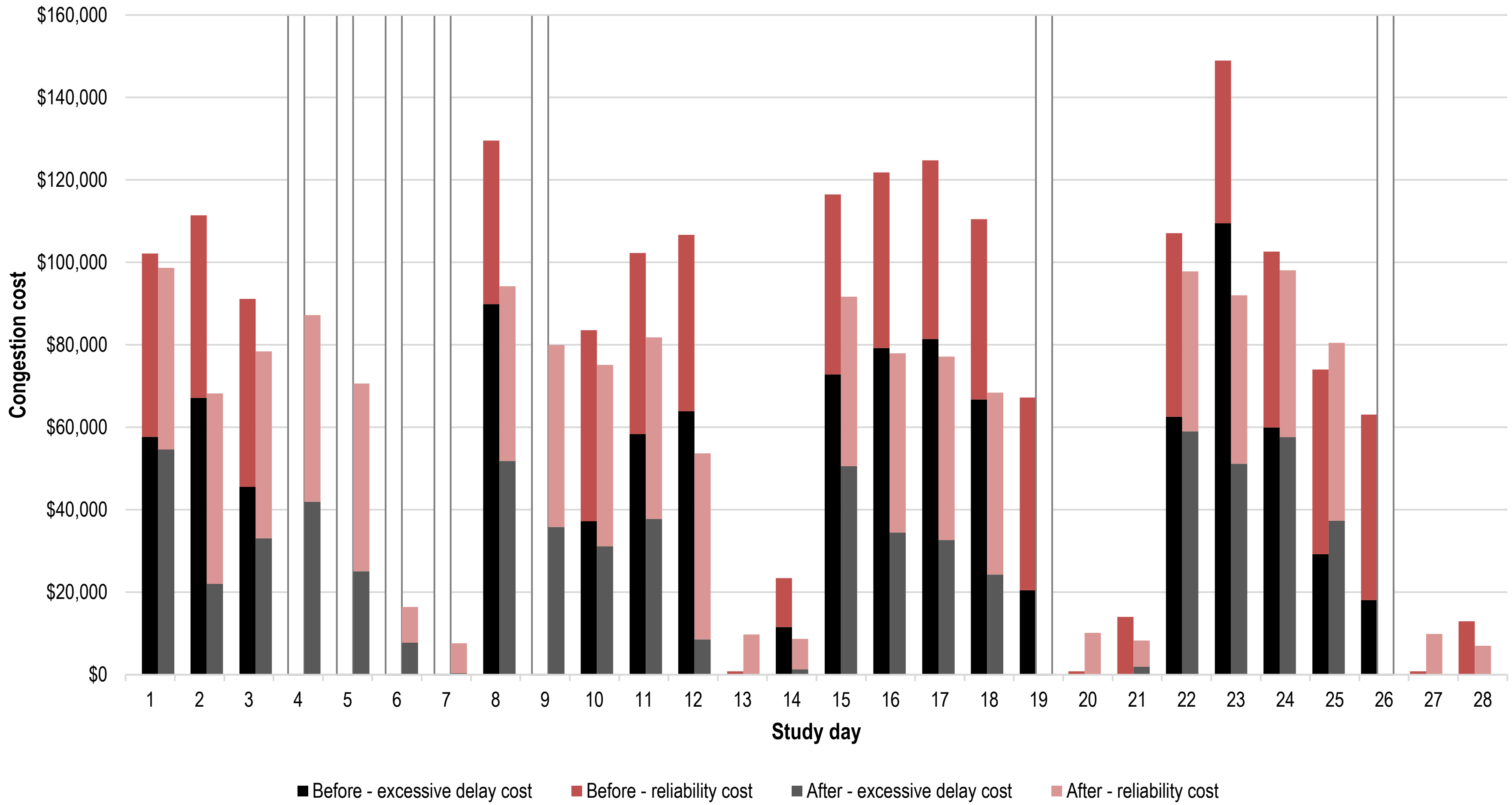
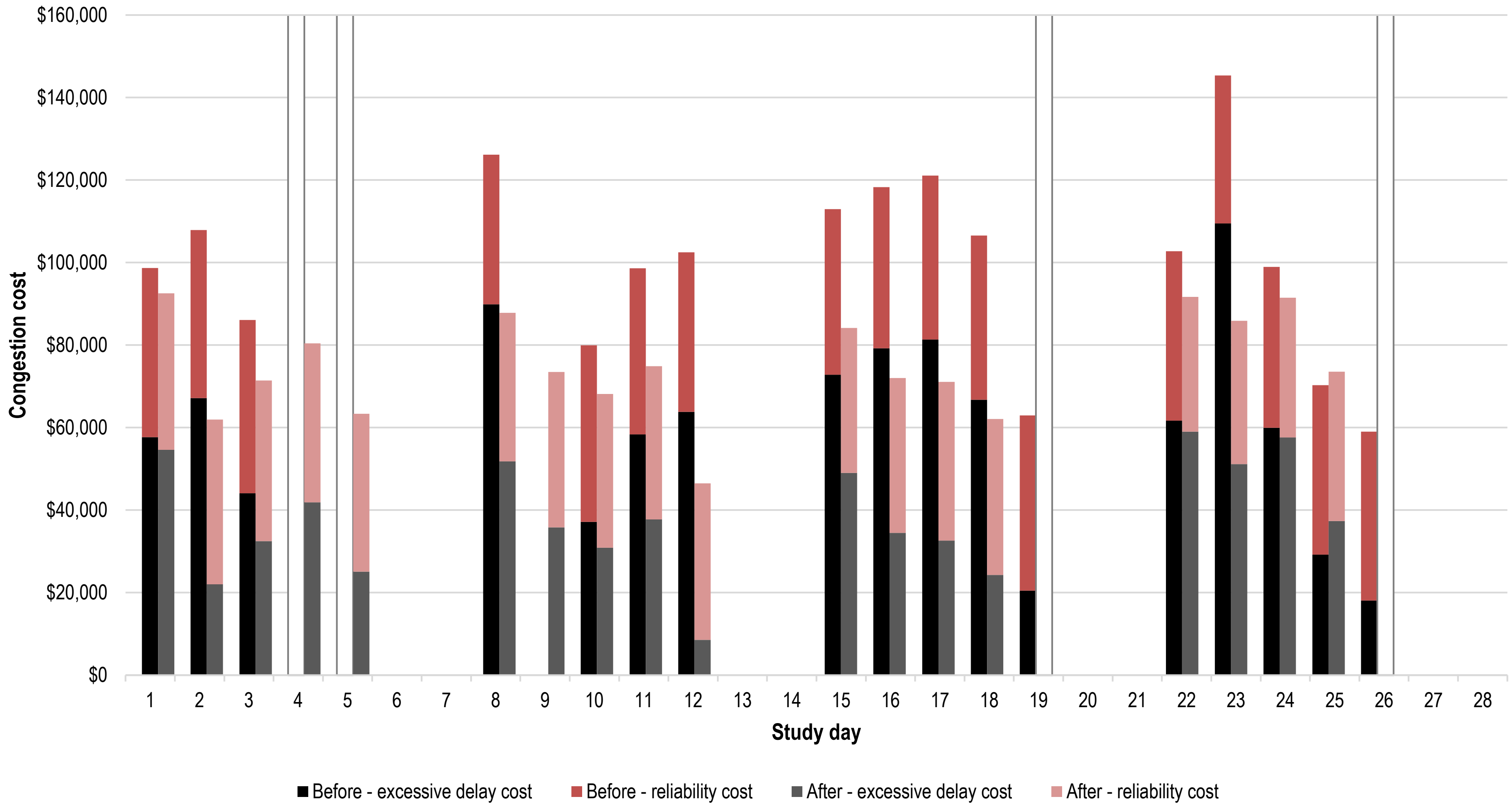


Figure 3.5: Total daily congestion cost comparison ($2013, 5am – 10 am weekday morning peak only)



4 LIMITATIONS OF THE RESEARCH

The Bruce Highway case study has proven a successful implementation of the congestion costing methodology developed by Luk, Han and Byrne (2016)as implemented with a combination of STREAMS data and classified counts. The limitations of the research are listed below.

- For this project, a combination of data from STREAMS and classified vehicle counters was used to estimate flow and travel speeds along the corridor. This data could be enhanced in future works with more data sources, such as probe data, which could potentially facilitate a higher resolution and coverage of travel time/speed analysis.
- The travel time reliability calculations require a sufficient sample size to produce a statistically significant result from percentile calculations. The study period of one month provided sufficient data for weekday analysis; however, there were not enough weekend days within a month to provide stable weekend travel reliability results free from the excessive variation caused by small sample sizes. This issue was compounded when incident days occurred on weekends and were thus excluded, further shrinking the amount of data available for weekend congestion cost analysis.
- As there were only six classified vehicle counters to cover the 18 distinct links across the study site, the traffic composition had to be extrapolated based on assumed vehicle access and egress movements on the highway. If more classified counting stations were available, the resolution of traffic composition data used to calculate congestion costs would have been improved, thus providing more accurate results.
- The reference speed assumed for the entire study was 70% of the posted speed limit. It has been discussed that the current methodology for calculating the costs of excessive congestion may result in a systematic underestimation of excessive congestion costs experienced by users on slow speed road networks (for instance, those urban networks that rely predominately on lower posted speed arterials rather than those networks that rely on higher posted speed motorways). Further research would be required on how to apply the reference speed methodology adequately to reflect congestion cost outcomes for different type of networks.

5 CONCLUSIONS AND FUTURE WORK

The Bruce Highway case study confirmed that the multi-model congestion cost methodology framework developed in the first year of R22 was feasible for the freeways/motorway analysis by using data from STREAMS and classified counts. The congestion cost is defined as the sum of excessive delay cost and travel time reliability cost in the case study.

The case study evaluated the possible impacts on freeway congestion cost following the installation of a ramp metering system along the Bruce Highway. The case study revealed that although the average daily VKT increased by 5%, the cost of congestion following the installation of ramp metering was reduced significantly. If using $2013 values, the average cost of congestion on a weekday in the 2015 study period was $103,269, while in 2016 it was $79,800, representing a cost saving of 23%. A bulk of these cost savings originates from less excessive delay cost, from $59,541 to $36141, representing a 39% reduction.

For a typical weekday, the congestion cost reduction mainly came from the morning peak when ramp metering is operating. During the morning peak, the average congestion cost was reduced from $99,429 to $73,115, representing a 26% cost reduction. Again the most significant cost saving originates from excessive delay cost, which decreased from $59,408 to $36,014, indicating a 39% reduction. The travel time reliability cost was also reduced by 7%, from $40,021 to $37,102.

When normalising by VKT, 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 1000 VKT were 30%, 42% and 12% respectively during morning peak.

Given that these improvements have occurred in the presence of a significant increase in traffic volumes, the positive changes can likely be attributed to the installation of the ramp metering system between the before-period and after-period. The amount of congestion has been markedly reduced as a result, with improvements seen in both travel time and travel reliability across the study site along the Bruce Highway.

It is suggested the following be considered in the next stage of the project:

- Conduct a sensitivity study by applying possible reference speed/threshold options and using the current available data collected from R22 case studies and in the TMR congestion cost reporting system. Further information would be required to analyse the impact of different speed thresholds on congestion cost estimation for the network.
- Review the available probe data sets and identify the suitability and applicability of probe data for the congestion cost estimation. Case studies on the use of probe speed data for excessive congestion cost estimation on the same study site might be conducted if required data is available.
- When more data is available, a more robust investigation into the accuracy of the STREAMS vehicle classification estimates should be conducted in relation to the results produced from dedicated classified counting stations across the network.

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APPENDIX A DAILY CONGESTION COSTS

Table A 1: Daily congestion cost for the before-period

Date	Excessive delay Cost	Reliability cost
Monday, 16 February 2015	$57,682	$44,459
Tuesday, 17 February 2015	$67,186	$44,212
Wednesday, 18 February 2015	$45,556	$45,622
Thursday, 19 February 2015	-	-
Friday, 20 February 2015	-	-
Saturday, 21 February 2015	-	-
Sunday, 22 February 2015	-	-
Monday, 23 February 2015	$89,865	$39,695
Tuesday, 24 February 2015	-	-
Wednesday, 25 February 2015	$37,218	$46,353
Thursday, 26 February 2015	$58,378	$43,937
Friday, 27 February 2015	$63,884	$42,777
Saturday, 28 February 2015	$0	$828
Sunday, 1 March 2015	$11,568	$11,859
Monday, 2 March 2015	$72,830	$43,659
Tuesday, 3 March 2015	$79,229	$42,613
Wednesday, 4 March 2015	$81,396	$43,385
Thursday, 5 March 2015	$66,762	$43,720
Friday, 6 March 2015	$20,499	$46,704
Saturday, 7 March 2015	$0	$825
Sunday, 8 March 2015	$0	$14,041
Monday, 9 March 2015	$62,587	$44,517
Tuesday, 10 March 2015	$109,507	$39,449
Wednesday, 11 March 2015	$59,985	$42,666
Thursday, 12 March 2015	$29,212	$44,802
Friday, 13 March 2015	$18,115	$44,946
Saturday, 14 March 2015	$0	$802
Sunday, 15 March 2015	$0	$12,969

Table A 2: Daily congestion cost for the after-period

Date	Excessive delay Cost	Reliability cost
Monday, 15 February 2016	$54,592	$44,122
Tuesday, 16 February 2016	$22,046	$46,152
Wednesday, 17 February 2016	$33,087	$45,310
Thursday, 18 February 2016	$41,979	$45,252
Friday, 19 February 2016	$25,066	$45,590
Saturday, 20 February 2016	$7,762	$8,661
Sunday, 21 February 2016	$335	$7,319
Monday, 22 February 2016	$51,852	$42,374
Tuesday, 23 February 2016	$35,847	$44,095
Wednesday, 24 February 2016	$31,151	$43,993
Thursday, 25 February 2016	$37,783	$44,052
Friday, 26 February 2016	$8,588	$45,086
Saturday, 27 February 2016	$0	$9,779
Sunday, 28 February 2016	$1,275	$7,394
Monday, 29 February 2016	$50,554	$41,155
Tuesday, 1 March 2016	$34,507	$43,470
Wednesday, 2 March 2016	$32,667	$44,466
Thursday, 3 March 2016	$24,316	$44,129
Friday, 4 March 2016	-	-
Saturday, 5 March 2016	$0	$10,142
Sunday, 6 March 2016	$1,932	$6,373
Monday, 7 March 2016	$59,037	$38,764
Tuesday, 8 March 2016	$51,131	$40,924
Wednesday, 9 March 2016	$57,642	$40,428
Thursday, 10 March 2016	$37,327	$43,146
Friday, 11 March 2016	-	-
Saturday, 12 March 2016	$0	$9,919
Sunday, 13 March 2016	$40	$7,002

Table A 3: Daily congestion cost for the before-period (5am – 10 am weekday morning peak only)

Date	Excessive delay Cost	Reliability cost
Monday, 16 February 2015	$57,674	$41,039
Tuesday, 17 February 2015	$67,186	$40,697
Wednesday, 18 February 2015	$44,088	$42,003
Thursday, 19 February 2015	-	-
Friday, 20 February 2015	-	-
Saturday, 21 February 2015	-	-
Sunday, 22 February 2015	-	-
Monday, 23 February 2015	$89,862	$36,281
Tuesday, 24 February 2015	-	-
Wednesday, 25 February 2015	$37,185	$42,762
Thursday, 26 February 2015	$58,378	$40,231
Friday, 27 February 2015	$63,817	$38,658
Saturday, 28 February 2015	-	-
Sunday, 1 March 2015	-	-
Monday, 2 March 2015	$72,813	$40,164
Tuesday, 3 March 2015	$79,229	$39,080
Wednesday, 4 March 2015	$81,346	$39,719
Thursday, 5 March 2015	$66,727	$39,819
Friday, 6 March 2015	$20,485	$42,491
Saturday, 7 March 2015	-	-
Sunday, 8 March 2015	-	-
Monday, 9 March 2015	$61,680	$41,075
Tuesday, 10 March 2015	$109,507	$35,869
Wednesday, 11 March 2015	$59,975	$38,953
Thursday, 12 March 2015	$29,212	$41,090
Friday, 13 March 2015	$18,115	$40,887
Saturday, 14 March 2015	-	-
Sunday, 15 March 2015	-	-

Table A 4: Daily congestion cost for the after-period (5am – 10 am weekday morning peak only)

Date	Excessive delay Cost	Reliability cost
Monday, 15 February 2016	$54,592	$37,968
Tuesday, 16 February 2016	$22,046	$39,890
Wednesday, 17 February 2016	$32,500	$38,907
Thursday, 18 February 2016	$41,882	$38,510
Friday, 19 February 2016	$25,065	$38,271
Saturday, 20 February 2016	-	-
Sunday, 21 February 2016	-	-
Monday, 22 February 2016	$51,852	$35,994
Tuesday, 23 February 2016	$35,847	$37,676
Wednesday, 24 February 2016	$30,895	$37,282
Thursday, 25 February 2016	$37,752	$37,158
Friday, 26 February 2016	$8,582	$37,918
Saturday, 27 February 2016	-	-
Sunday, 28 February 2016	-	-
Monday, 29 February 2016	$49,053	$35,091
Tuesday, 1 March 2016	$34,507	$37,535
Wednesday, 2 March 2016	$32,639	$38,459
Thursday, 3 March 2016	$24,311	$37,764
Friday, 4 March 2016	-	-
Saturday, 5 March 2016	-	-
Sunday, 6 March 2016	-	-
Monday, 7 March 2016	$59,037	$32,623
Tuesday, 8 March 2016	$51,131	$34,732
Wednesday, 9 March 2016	$57,618	$33,850
Thursday, 10 March 2016	$37,324	$36,215
Friday, 11 March 2016	-	-
Saturday, 12 March 2016	-	-
Sunday, 13 March 2016	-	-

Table A 5: Daily congestion cost for the before-period (outside morning peak on weekdays)

Date	Excessive delay Cost	Reliability cost
Monday, 16 February 2015	$8	$3,420
Tuesday, 17 February 2015	$0	$3,514
Wednesday, 18 February 2015	$1,468	$3,620
Thursday, 19 February 2015	-	-
Friday, 20 February 2015	-	-
Saturday, 21 February 2015	-	-
Sunday, 22 February 2015	-	-
Monday, 23 February 2015	$3	$3,414
Tuesday, 24 February 2015	-	-
Wednesday, 25 February 2015	$33	$3,591
Thursday, 26 February 2015	$0	$3,706
Friday, 27 February 2015	$67	$4,119
Saturday, 28 February 2015	-	-
Sunday, 1 March 2015	-	-
Monday, 2 March 2015	$17	$3,495
Tuesday, 3 March 2015	$0	$3,533
Wednesday, 4 March 2015	$50	$3,666
Thursday, 5 March 2015	$35	$3,902
Friday, 6 March 2015	$15	$4,213
Saturday, 7 March 2015	-	-
Sunday, 8 March 2015	-	-
Monday, 9 March 2015	$908	$3,442
Tuesday, 10 March 2015	$0	$3,580
Wednesday, 11 March 2015	$10	$3,712
Thursday, 12 March 2015	$0	$3,712
Friday, 13 March 2015	$0	$4,059
Saturday, 14 March 2015	-	-
Sunday, 15 March 2015	-	-

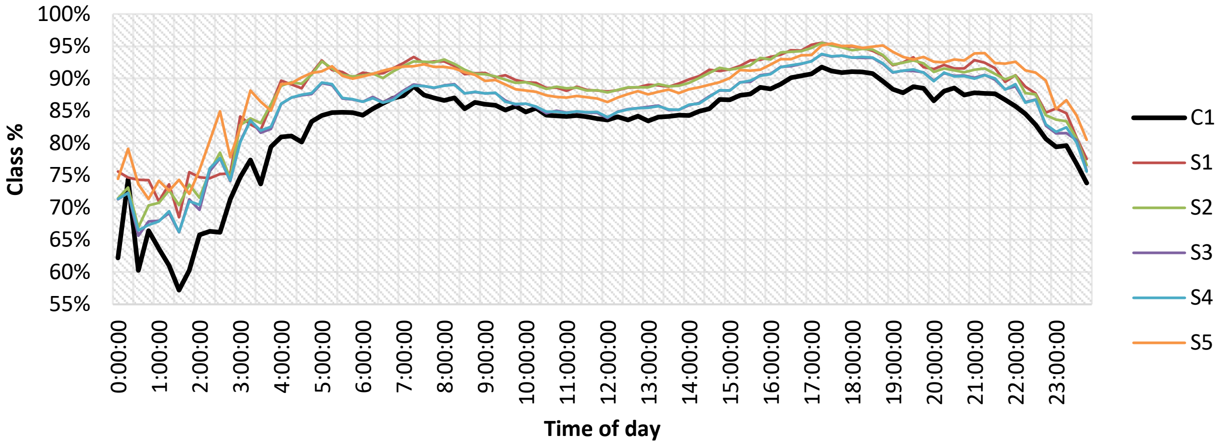
Table A 6: Daily congestion cost for the after-period (outside morning peak on weekdays)

Date	Excessive delay Cost	Reliability cost
Monday, 15 February 2016	$0	$6,154
Tuesday, 16 February 2016	$0	$6,263
Wednesday, 17 February 2016	$586	$6,404
Thursday, 18 February 2016	$97	$6,741
Friday, 19 February 2016	$0	$7,318
Saturday, 20 February 2016	-	-
Sunday, 21 February 2016	-	-
Monday, 22 February 2016	$0	$6,380
Tuesday, 23 February 2016	$0	$6,419
Wednesday, 24 February 2016	$256	$6,710
Thursday, 25 February 2016	$31	$6,893
Friday, 26 February 2016	$6	$7,169
Saturday, 27 February 2016	-	-
Sunday, 28 February 2016	-	-
Monday, 29 February 2016	$1,502	$6,064
Tuesday, 1 March 2016	$0	$5,936
Wednesday, 2 March 2016	$27	$6,007
Thursday, 3 March 2016	$4	$6,365
Friday, 4 March 2016	-	-
Saturday, 5 March 2016	-	-
Sunday, 6 March 2016	-	-
Monday, 7 March 2016	$0	$6,141
Tuesday, 8 March 2016	$0	$6,193
Wednesday, 9 March 2016	$25	$6,578
Thursday, 10 March 2016	$3	$6,932
Friday, 11 March 2016	-	-
Saturday, 12 March 2016	-	-
Sunday, 13 March 2016	-	-

APPENDIX B CLASSIFIED COUNTER COMPARISON

As shown in Figure 2.2, the data used to determine the proportion of each vehicle class travelling along the Bruce Highway was collected from six classified counting stations within the study area. The northernmost station used was a dedicated vehicle speed and classified counting station, with the other five being STREAMS detector sites.

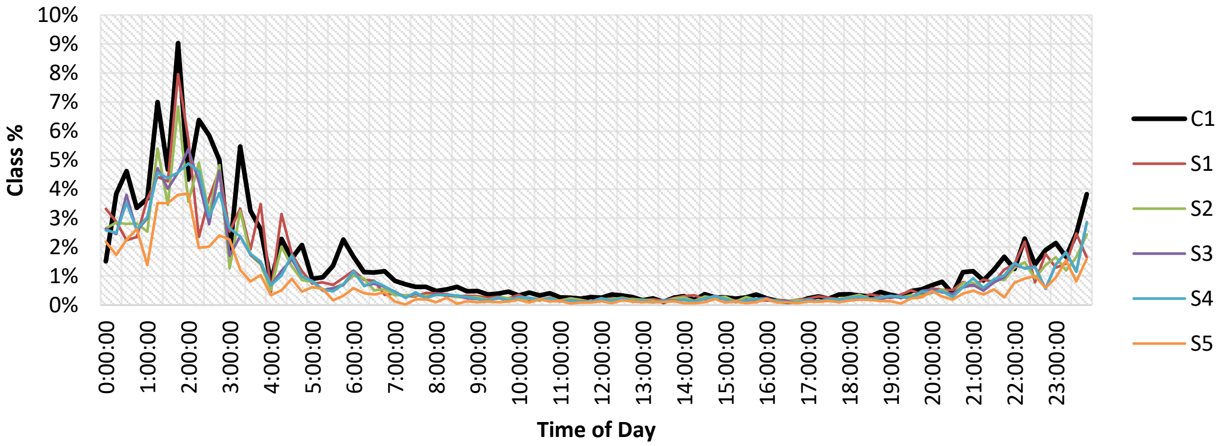
Figure B 1: Proportion of short vehicles passing through the classified counting stations on a weekday (before-period)



C – Dedicated classified counting station
S – STREAMS detector site

Figure B 1 shows the proportion of short vehicles (i.e. passenger cars, the vehicle class with the largest volume) passing through each of the stations on a typical weekday during the before-period. It confirms that the overall pattern of class proportion is very similar between the dedicated classifying stations and the STREAMS detector sites.

Figure B 2: Proportion of combination vehicles passing through the classified counting stations on a weekend day (before-period)



C – Dedicated classified counting station
S – STREAMS detector site

Figure B 2 shows the same results with the combination vehicle class on a typical weekend day of the before-period.

Similar analysis was conducted for every vehicle class and the STREAMS detector site data followed a very similar profile to that produced from the dedicated classified counting station.

These patterns lend confidence to the accuracy of the STREAMS detector site data, as well as the validity of combining the data produced by both these systems for the case study.