

FINAL REPORT

Project Title: R47 Measuring excessive congestion costs for
freeways and arterials by using multiple data sources
— Bruce Highway case study report (2016/17 - Year 1)

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SUMMARY

Project Purpose

The objectives of project R47 are to investigate the feasibility of utilising emerging data sources for excessive congestion cost estimation and also to review and identify alternative methods for defining thresholds for measuring excessive delay for arterial roads. Following the methodology used in project R22 (provide the title here), excessive congestion cost is defined in this report as the sum of excessive delay cost and travel time reliability cost. The excessive travel delay is estimated by comparing prevailing travel times/speeds with reference travel times/ speeds. The travel time reliability (i.e. buffer time) is represented by the difference between the 95th percentile travel time and the 50th percentile travel time. In theory, travel time reliability only applies to the route level and should reflect the day-by-day variations. Two case studies, namely congestion analysis of Bruce Highway and Gympie Road comprise project R47.

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Project Method and Findings

This report documents the methodology and main findings of the Bruce Highway congestion analysis case study. A 24-km section of Bruce Highway was selected as the study site and one month (from 15 February to 13 March 2016) was selected as the study period. Speed or travel time data from inductive loops, probes and Bluetooth were compiled and combined with existing volume and vehicle classification data for the estimation of excessive congestion cost. Selected key performance indicators including route travel time, route buffer time, link travel time, excessive delay cost, travel time reliability cost and total excessive congestion cost were calculated and compared between the three data sources.

For both route and link travel time comparisons, results derived from the three data sources followed very similar patterns. The average weekday route travel time comparison identified that both probe and Bluetooth results were consistently higher (about 9% and 11%) than from inductive loops during peak time (5:00 – 10:00 am). During other times (10:00 am – 5:00 am) the differences were generally small or less significant. Between probe and Bluetooth, the average weekday route travel times were generally more aligned with each other. The inductive loops also showed much lower route buffer time when compared with Bluetooth and probe. However, when using the buffer time index, the results for the three data sources were more aligned with each other. For example, during peak time, the average buffer time indexes for Bluetooth, probes and inductive loops were 1.34, 1.31 and 1.25 respectively.

The excessive delay costs estimated from probe and Bluetooth were generally much higher (55% and 54% higher) than from inductive loops. In absolute cost values (in 2013 dollars), the excessive delay costs estimated from probe and Bluetooth were \$15,559 and \$15,443 higher per weekday than from inductive loops. Similar patterns were identified for the travel time reliability cost comparison. The reliability costs estimated from probe and Bluetooth were \$14,603 and \$15,684 higher per weekday than from inductive loops.

The case study 1 results have confirmed that at both link and route levels, probe and Bluetooth data were generally more sensitive to speed changes and had higher capabilities to pick up congestion delays and travel time

variance. As the inductive loops appeared to consistently underestimate excessive congestion costs during peak time, there might be a need to review or reconsider the reference speed threshold (i.e. 70% of free-flow speed) for the excessive delay estimation when using inductive loops. However, further case studies using different data sources or different study sites should be conducted to validate or generalise the findings from this case study.

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1 INTRODUCTION

Understanding the economic cost of traffic congestion is important for project performance appraisals and investment decision-making. Measuring the cost of traffic congestion is also an essential part of developing the appropriate response strategies for congestion management. The Department of Transport and Main Roads (TMR) cost-of-congestion reporting methodology was based on the ARRB congestion cost model published in Luk, Kazantzidis and Han (2009) and the Austroads national performance indicator (NPI) reporting system (Luk & Kazantzidis 2009; Troutbeck, Su & Luk 2007).

Project R22: *Measuring on-road congestion costs for multi-modal travel* completed in 2015/16 reviewed current TMR cost-of-congestion reporting methodology and further developed an excessive congestion analysis framework for multi-modal road users for TMR. The main outcomes from the project were as follows:

- Developed a framework for excessive congestion cost analysis for multi-modal travel including cars, three heavy vehicle (HV) classes and buses (Luk, Han & Byrne 2016). The framework considered excessive travel delay by comparing prevailing travel times (or speeds) with reference travel times (or reference speeds) and also took into consideration the travel time reliability. Passenger waiting times at a bus stop were also considered in the bus delay cost framework.
- Reviewed available methods of measuring travel time reliability cost. The buffer time method was selected for travel time reliability cost estimation for both buses and general traffic. Buffer time was defined as the difference between the 95th percentile travel time and median travel time of a route for a defined time period, usually one month (Luk, Han & Byrne 2016).
- Conducted two case studies (Han & Byrne 2016, Han et al. 2016) to test and confirm the suitability of the methodology framework. The electronic bus ticket data was used for bus congestion cost for the Gympie Road case study, and the STREAMS and classified counter data were used for the Bruce Highway ramp signalling before-and-after analysis. Both case studies were successful and the results were recognised by TMR stakeholders.

The current project R47 is a continuation of the previous research. The objectives of R47 are:

1. To investigate and develop the method to use emerging data sources such as probe speed data and Bluetooth travel time data for excessive congestion measurement.
2. To review the use of the reference speed method for arterial excessive delay estimation (i.e. using the travel time at the 55% of posted speed limit as the benchmark, above which the travel time is regarded as excessive delay), identify the possible underestimation or overestimation of congestion cost along arterial and side streets and recommend a better alternative if available.

The method to deliver R47 was to conduct two case studies as follows:

- Case study 1: Bruce Highway congestion analysis which aims to investigate the methodology of using volume data from STREAMS and speed or travel time data from three data sources (inductive loops, probes and Bluetooth) to measure the excessive delay cost and travel time reliability cost for freeways. The similarities and differences are also to be compared between the three data sources or technologies.
- Case study 2: Gympie Road congestion analysis which aims to use both inductive loop data and probe data (where available) to test the feasibility of using alternative methods other than reference speed to measure excessive delay for urban arterial roads and side streets.

Two reports have been produced for the above two case studies. This report is for case study 1 and documents the methodology and main findings from the Bruce Highway congestion analysis.

Following the R22 methodology, excessive congestion cost is defined in the report as the sum of excessive travel delay cost and travel time reliability cost. The excessive travel delay is estimated by comparing prevailing travel times/speeds with reference travel times/reference speeds. The travel time reliability (i.e. buffer time) is represented by the difference between the 95th percentile travel time and the 50th percentile travel time. The environmental and vehicle operating costs due to excessive congestion are considered to be out-of-scope of the project.

The structure of the report is as follows:

- Section 1 : Introduction
- Section 2 : Estimating excessive congestion cost for freeways by using three data sources
- Section 3 : Summary of main findings
- Section 4 : Further discussions on relevant data issues.

Appendix A provides a data matching map of the three data sources of the study site and Appendix B lists link lengths of the three data sources. Appendix C to Appendix G provide further details of data analysis results.

A separate report has been prepared for case study 2: Gympie Road congestion analysis.

2 ESTIMATING EXCESSIVE CONGESTION COST FOR FREEWAYS BY USING DIFFERENT DATA SOURCES

2.1 Objectives

The objective of case study 1 is to investigate and compare the outcomes when probe speed data and Bluetooth travel time data are used for excessive congestion cost estimation including excessive delay cost and travel time reliability cost.

The methodology discussed in the R22 case study 2 (Han et al. 2016) is applied to this project. Both excessive delay cost and travel time reliability costs are estimated at link level and aggregated to route level. Three data sources for speed/travel time are considered:

1. inductive loop data: link speed measured by inductive loops from the STREAMS traffic management system
2. Bluetooth data: Bluetooth link travel time sourced and processed by TMR
3. probe data: probe link speed from HERE.

Since the methodology relies on volume data to evaluate congestion cost and network performance, the probe speed data and Bluetooth travel time data need to be blended with STREAMS volume and classified counter data. The inductive loop links, probe links and Bluetooth links are all defined differently in a spatial sense; further details of the study site, data matching and aggregation are explained below.

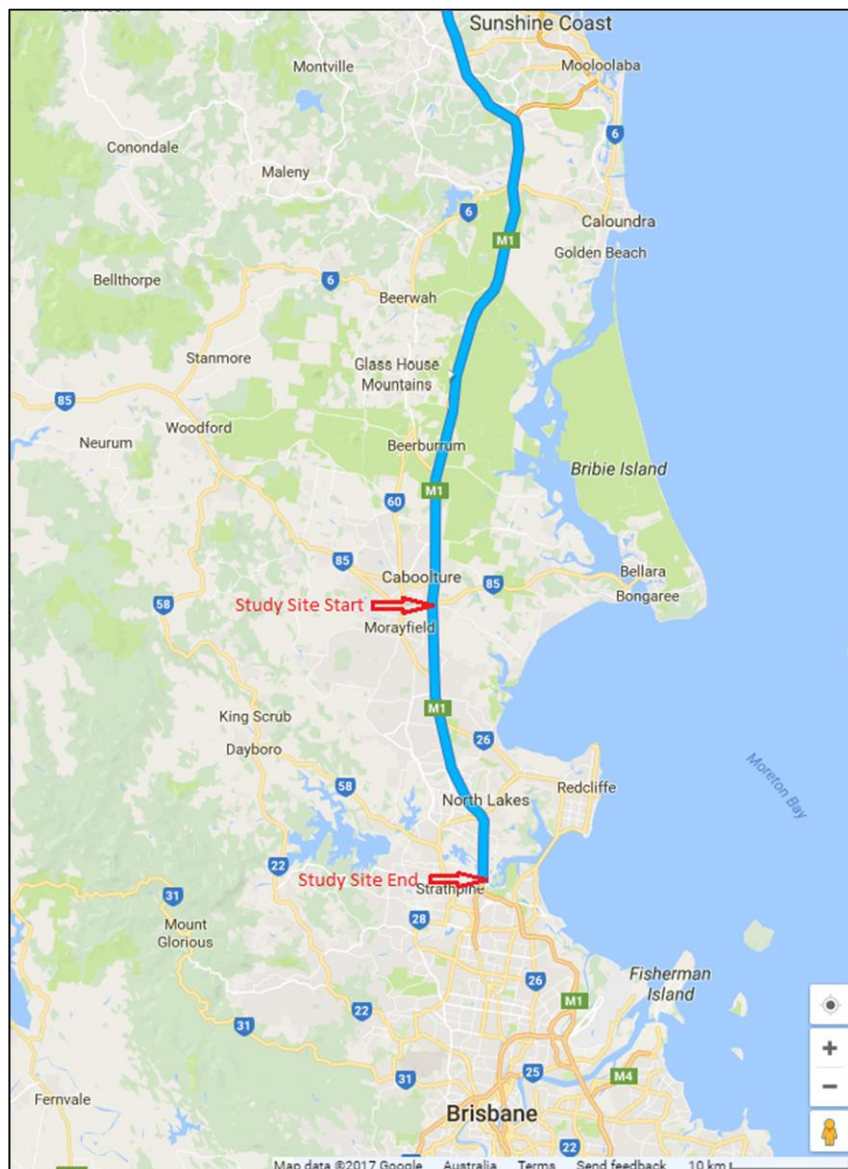
2.2 Study Site and Study Time Period

The study site selected is the same southbound section of Bruce Highway which was used for the R22 case study 2, however, the difference is that inductive loop links 1, 17 and 18 are not included in order to match the inductive loop links with Bluetooth and probe links more accurately.

As shown in Figure 2.1, Bruce Highway connects Brisbane with the north. The study site starts at about 100 m south of Bribie Island Road and finishes at about 200 m south of the South Pine River Bridge, which is 24,227 m long. Figure 2.2 shows the Bruce Highway study site (in smaller scale) including the locations of inductive loop links 1 to 18, the locations of six classified counters and the five on-ramps. The shaded area in Figure 2.2 highlights the study site that is between inductive loop links 2 to 16.

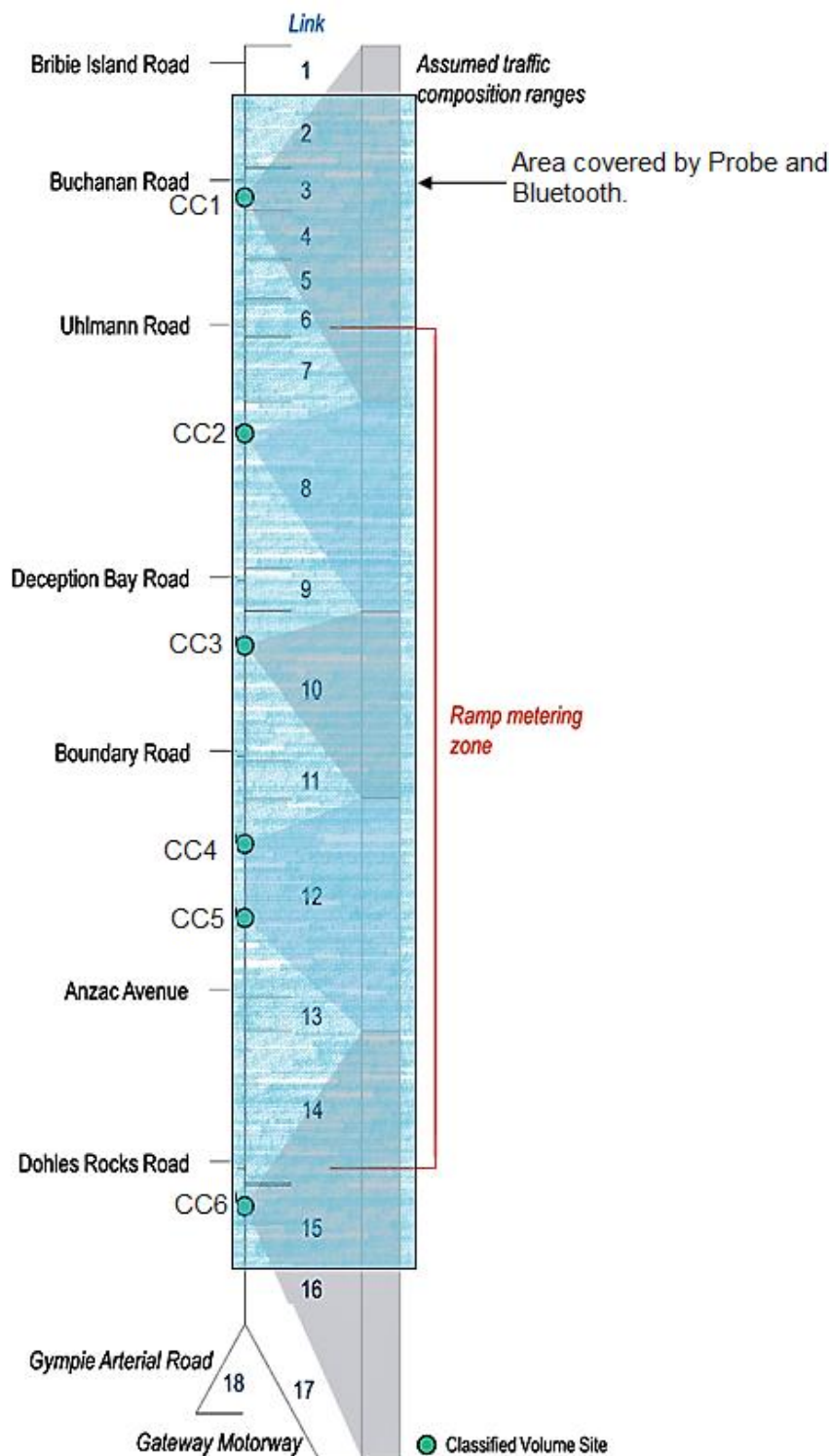
The study time period was chosen to be the same as for the 'after-analysis' in the R22 case study 2, 15 February (Monday) to 13 March (Sunday) 2016. This enabled use of the already available framework and results of inductive loop data from R22 case study 2.

Figure 2.1: Location of Bruce Highway and the site for case study 1



Source: Google Maps (2017), 'Queensland', map data, Google, California, USA.

Figure 2.2: Scope of the Bruce Hwy study site



2.2.1 Incident Days

Extreme weather conditions and major incidents have a significant impact on traffic volume, speed and more significantly, travel time reliability. Based on TMR investigations, no extreme weather

conditions during the study time period were recorded. Table 2.1 lists the two incident days that were excluded from the normal day analysis. Therefore, all weekdays analysed in this report indicate normal weekdays during the study time period.

Table 2.1: Incident days

Incident days	Incident	TMR comments
Friday 4 March 2016	A major incident - crash southbound on the Bruce Highway at 5:38 am 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 occurred on Bruce Highway southbound adjacent to Uhlmann Road southbound.	Both the flow and speed data revealed an obvious impact.

Further, TMR has recognised the importance of the impacts of incidents on congestion cost reporting and would like to investigate if alternative data sources such as probe and Bluetooth have higher or lower capacity to pick up the delays during incidents. Friday 4 March 2016 was therefore selected to conduct an incident-day comparison between the three data sources (Section 2.5.4).

2.3 Data Sources and Data Compiling Process

This section explains how the traffic data from the three sources were compiled in the study:

- inductive loop data (Section 2.3.1)
- probe data (Section 2.3.2)
- Bluetooth data (Section 2.3.2).

2.3.1 Inductive Loop Data

The study site covers 16 distinct inductive loop links, varying between 676 and 3,955 m in length. For each of these links the following data was supplied by TMR in 15-minute intervals for the study period:

- link traffic speed from the STREAMS traffic management platform
- link traffic flow from the STREAMS traffic management platform
- classified vehicle counts from six permanent traffic counting stations.

The data from STREAMS and the classified counting stations were crosschecked by TMR before being applied to the case study, and the data were of good quality. However, during certain time periods, flow and speed data were empty due to electronic disturbances and other errors in communication of data between the vehicle detectors and the STREAMS system, and about 0.5% of the data records were affected. These entries were replaced by flow or speed values from the same 15-minute periods of the weekday, but from exactly one week after or before. Due to the small number of replaced speed and flow values, the impact on the calculation results was deemed to be minimal.

2.3.2 Probe Data

HERE data was retrieved through the HERE software interface, *traffic analytics* (Guthridge 2016) for the study site. The study site (from inductive loop link 2 to link 16) covers 105 probe links. The probe link lengths varied between 16 m and 1,912 m. For each of the links the mean speed was provided in 15-minute intervals.

The data from *traffic analytics* was checked and Table 2.2 shows the percentage of no data cells during daytime (5:00 am – 8:00 pm), other times (8:00 pm – 5:00 am) and all day for both weekdays and weekends (excluding incident days).

Table 2.2: Percentage of 'no data' cells for probe data

	Weekdays			Saturdays			Sundays			Total
	5am-8pm	8pm-5am	All day	5am-8pm	8pm-5am	All day	5am-8pm	8pm-5am	All day	
No data cells	2,110	32,587	34,697	2,327	9,111	11,438	4,708	9,745	14,453	60,588
All available data cells	11,3400	68,040	181,440	25,200	15,120	40,320	25,200	15,120	40,320	26,2080
Percentage	2%	48%	19%	9%	60%	28%	19%	64%	36%	23%

Although in total about 23% of data cells were empty, it was further identified that during daytime (5:00 am - 8:00 pm), 2% of data during weekdays, 9% of data on Saturdays and 19% of data on Sundays were empty. During night-time (8:00 pm - 5:00 am), about 48 – 64 % of data were empty.

Two approaches were tested to fill in those gaps. The first was to replace all the empty cells by the free-flow speed. The second was to use the HERE gap-filling function. In this function, the empty speed is filled by an interpolation between the speeds directly before and after on the same road segment (Guthridge 2016). Both methods were used and no difference was found in the calculation results of travel time and delay at both route level and link level. As most of the replaced speed values are at off-peak time, it is highly likely that the filled values from both methods are free-flow speeds or similar, therefore the impact on the calculation results is deemed to be minimal.

2.3.3 Bluetooth Data

TMR also supplied Bluetooth data for the study site. The study area was covered by eight Bluetooth links and their lengths varied from 1,200 m to 6,800 m. For each Bluetooth link the mean travel time was provided in 5-minute intervals. The Bluetooth data were aggregated to 15-minute intervals by averaging the travel time values from three consecutive 5-minute intervals.

The aggregated data were checked and

Table 2.3 shows the percentage of cells that have no data during day time (5:00 am – 8:00 pm), other times (8:00 pm – 5:00 am) and all day for both weekdays and weekends (excluding incident days).

Table 2.3: Percentage of 'no data' cells for Bluetooth data

	Weekdays			Saturdays			Sundays			Total
	5am-8pm	8pm-5am	All day	5am-8pm	8pm-5am	All day	5am-8pm	8pm-5am	All day	
No data cells	5	1644	1649	0	352	352	10	475	485	2486
All available data cells	8640	5184	13824	1920	1152	3072	1920	1152	3072	19968
Percentage	0.06%	32%	12%	0%	31%	11%	1%	41%	16%	12%

Although in total about 12% of data cells were empty for both weekdays and weekends, it was further found that during daytime (5:00 am – 8:00 pm) including peak periods for both weekdays and weekends less than 1% of Bluetooth cells were empty. During other times (8:00 pm – 5:00 am), about 32% of data on weekdays, 31% of data cells on Saturdays, and 40% of data on Sundays were no data. These empty entries were replaced by the free-flow travel time (defined as travel time at the posted speed limit) for each link. Due to the fact that most of the replaced speed values were at off-peak times, the impact on the congestion calculation results is deemed to be minimal.

2.4 Data Matching and Calculation Methods

The data from all three sources were matched using ArcMap software. The longitude and latitude coordinates for each start and end point for the links of each data source were plotted on the same map and matched accordingly (Appendix A). Table 2.4 shows the link matching results using link numbers from inductive loops as an index.

Table 2.4: Matching inductive loop, probe and Bluetooth links

Inductive loop link number	HERE probe link number covered by the inductive loop link	Bluetooth link number covered by the inductive loop link
Link 2	From link 1 to link 6	Link 1
Link 3	From link 7 to link 11	Link 2
Link 4	From link 12 to link 16	
Link 5	From Link 17 and 18	
Link 6	From link 19 to link 22	
Link 7	From link 23 to link 31	Link 3
Link 8	From link 32 to link 45	Link 4
Link 9	From link 46 to link 52	
Link 10	From link 53 to link 61	
Link 11	From link 62 to link 66	Link 5
Link 12	From link 67 to link 74	
Link 13	From link 75 to link 77	Link 6
Link 14	From link 78 to link 92	Link 6 and Link 7
Link 15	From link 93 to link 98	Link 8
Link 16	From link 99 to link 105	

Note: The highlighted links are the chosen ones for link-level analysis in Section 2.5.3.

The R22 case study 2 report (Han & Byrne 2016) outlined the framework for estimating freeway excessive congestion cost with multiple vehicle classes. This section discusses how this methodology was adapted to account for the different data sources in order to use the volumes and vehicle classified counts for the calculation.

Inductive loops

The inductive loop data were the same as the R22 case study 2 'after data', therefore nothing was changed in the data except withdrawing the first link and the last two links so that it would match the data available for the other two data sources (i.e. probe and Bluetooth) accurately. The calculation method was also the same as the R22 case study 2.

Probes

The probe data provided the mean speed in 15-minute intervals for each of the 105 links. Each inductive loop link can cover 2 to 15 probe links. For the calculation of excessive congestion cost, the volume of the inductive loop link was applied (or repeated) to all probe links that constitute that inductive loop link. For example, traffic volume of inductive loop link 2 was repeated six times to cover probe links 1 to 6 and so on. The same process was used to apply the vehicle classification information to probe links.

Bluetooth

Bluetooth links are much longer than the inductive loop links and most of the Bluetooth links cover at least two inductive loop links. Where a Bluetooth link covers more than one inductive loop link, the volumes from inductive loop links were averaged and used in the congestion cost calculations of that Bluetooth link. For example, the average of traffic volumes of inductive loop links 2 to 6 was used as the volume of Bluetooth link 2.

For the vehicle classification, data from six classification counters were provided in the R22 case study 2 (Han & Byrne 2016). Using their locations, the vehicle classification counters were also matched with the Bluetooth links accordingly (Table 2.5).

Table 2.5: Matching vehicle classification counters for Bluetooth links

Bluetooth link number	Vehicle classification counters
Link 1	CC1
Link 2	CC1
Link 3	CC1
Link 4	CC2
Link 5	CC3
Link 6	CC4
Link 7	CC5
Link 8	CC6

2.5 Results

Applying the R22 methodology (i.e. Han et al. 2016) and the matching processes outlined in Section 2.4, the following key performance indicators (KPIs) were calculated for comparison between inductive loops, Bluetooth and probes:

1. average weekday route travel time
2. route buffer time (monthly) and buffer time index
3. link travel time for selected inductive loop links
4. incident day travel time
5. excessive delay cost at route level
6. reliability cost at route level
7. total excessive congestion cost at route level.

The following four statistical metrics were applied for the comparison of main KPIs (i.e. travel time and buffer time) between inductive loops, probes and Bluetooth:

- percentage difference of means, i.e., difference of mean travel times and buffer times from probe and inductive loop data in % using inductive loop data as reference
- root mean square difference (RMSD), i.e., adjusted average difference in travel times and buffer times from different sources in time units
- R^2 – term, R^2 ranges from 0 to 1. $R^2 = 1$, if the data is able to match perfectly the reference data; $R^2 = 0$ if the compared data have no correlation. R^2 is usually called the correlation coefficient
- test of significance of difference (at the p level of 0.05, i.e. at the 95% confidence level (CL)) using a paired t-test (2-tail). If 'yes', it is 95% certain that the travel time is significantly different from the reference travel time or buffer time.

Note that the weekends were included in the calculation, however, their results were not included in the report. The excessive delays during weekends were generally minimal. The number of weekend days were also too small to be sufficient for buffer time/travel time reliability estimation.

Table 2.6 illustrates the result reporting structure used in this section.

Table 2.6: Result reporting structure in Section 2.5

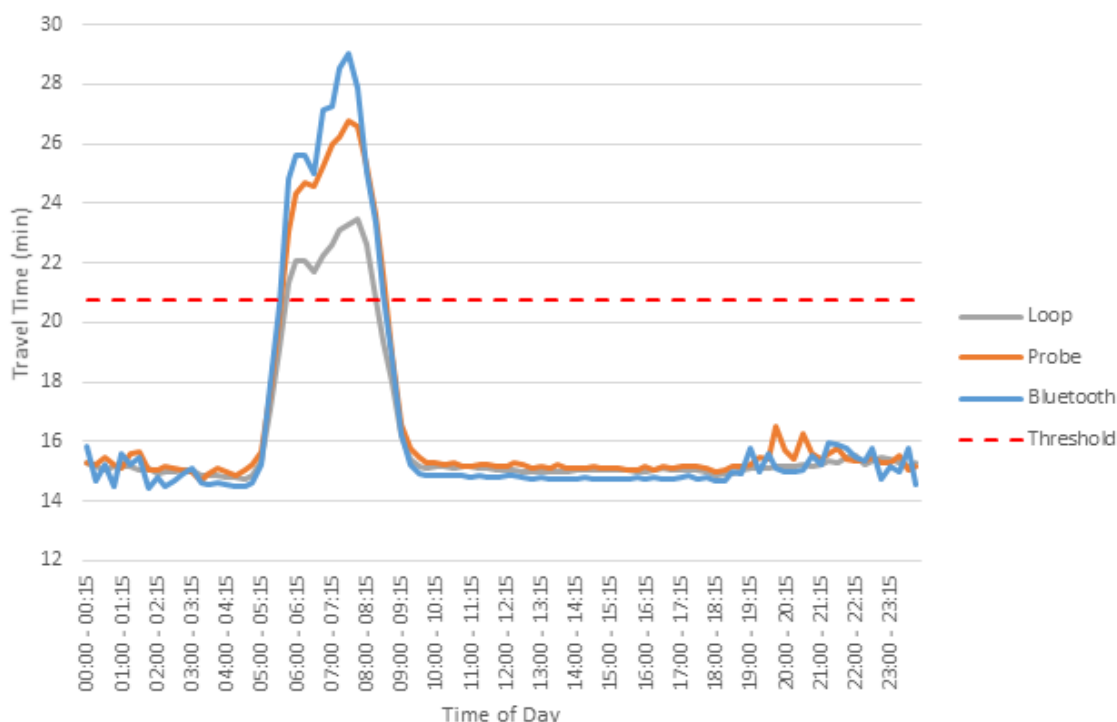
KPIs	Section reference	Result comparison and reporting methods					
		% difference of mean	RMSD	R^2	Significance test at 95% CL (Y/N)	Time series plotting	Summary of findings
Average weekday route travel time	2.5.1	√	√	√	√	√	√
Route buffer time (monthly)	2.5.2	√	√	√	√	√	√
Buffer time index	2.5.2	√	√	√	√	√	√
Link travel time for loop links 9, 16, 14, 15	2.5.3	√	√	√	√	√	√

KPIs	Section reference	Result comparison and reporting methods					
		% difference of mean	RMSD	R ²	Significance test at 95% CL (Y/N)	Time series plotting	Summary of findings
Incident day travel time (route and loop links 14, 15)	2.5.4	√	√	√	√	√	√
Excessive delay cost at route level	2.5.5	√				√	√
Reliability cost at route level	2.5.6	√				√	√
Total excessive congestion cost at route level	2.5.7	√				√	√

2.5.1 Average Weekday Route Travel Time

Figure 2.3 shows the average weekday route travel time in 15-minute intervals for all three data sources. It shows that the travel times generated from the three data sources followed a similar pattern across the whole day, while both Bluetooth and probe data showed higher travel times than inductive loops during peak times (5:00 – 10:00 am). The results of Bluetooth and probe data appeared to be more aligned with each other across the whole day. Route travel times during off-peak periods between inductive loops and other data sources are more aligned with each other, with inductive loop data showing less volatility, particularly after 7:30 pm.

Figure 2.3: Average weekday route travel times from three data sources



Note: The red dashed line indicates the 70% free-flow travel time as the threshold for calculating excessive delay.

Table 2.7 and Table 2.8 show the percentage differences for average probe and Bluetooth weekday route travel times compared to the inductive loop data, for peak (5:00 – 10:00 am) and

other times (10:00 – 5:00 am) respectively. The last column of the two tables also shows the percentage difference between average Bluetooth and probe travel time for reference. Further statistical tests were conducted for the route travel time comparisons during peak, other times and all day. Table 2.9 shows the four statistical metrics for these comparisons.

Table 2.7: Day-of-week average route travel time (in minutes) comparison during peak time (5:00 am – 10:00am)

	Inductive loops	Probe	Bluetooth	% Difference between probe and inductive loops	% Difference between Bluetooth and inductive loops	% Difference between Bluetooth and probe
Monday	22.48	25.15	26.31	12%	17%	5%
Tuesday	19.37	21.00	21.53	8%	11%	2%
Wednesday	19.65	21.54	22.03	10%	12%	2%
Thursday	19.15	20.98	21.23	10%	11%	1%
Friday	16.95	17.75	17.61	5%	4%	-1%
Average weekdays	19.52	21.28	21.74	9%	11%	2%

Table 2.8: Day-of-week average route travel time (in minutes) comparison during other times (10:00 am – 5:00 am)

	Inductive loops	Probe	Bluetooth	% Difference between probe and inductive loops	% Difference between Bluetooth and inductive loops	% Difference between Bluetooth and probe
Monday	15.08	15.13	14.74	0%	-2%	-3%
Tuesday	15.06	15.19	15.10	1%	0%	-1%
Wednesday	15.15	15.42	15.09	2%	0%	-2%
Thursday	15.10	15.31	14.88	1%	-1%	-3%
Friday	15.01	15.08	14.89	0%	-1%	-1%
Average weekdays	15.08	15.23	14.94	1%	-1%	-1%

Table 2.9: Statistical metrics for route travel time comparison

Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Between probe and inductive loops	Peak	9%	2.22	0.99	YES
	Other times	1%	0.28	0.26	YES
	All day	3%	1.04	0.99	YES
Between Bluetooth and inductive loops	Peak	11%	3.12	0.98	YES
	Other times	-1%	0.34	0.08	YES
	All day	1%	1.46	0.98	YES
Between Bluetooth and probe	Peak	2%	1.11	0.99	YES
	Other times	-2%	0.46	0.11	YES
	All day	-1%	0.65	0.98	NO

On average, the route travel times derived from probe and Bluetooth data were 9% and 11% higher than from inductive loops during peak time (5:00 – 10:00 am). During other times (10:00 – 5:00 am), probe travel time was 1% higher and Bluetooth travel time was 1% lower than that of

inductive loops. All these differences were statistically significant, which indicated that they were systematic differences.

The route travel times derived from Bluetooth data were 2% higher during peak time and 2% lower during other times than from probe data. These differences were also statistically significant, which indicated that Bluetooth travel times were consistently aligned with probe travel times.

Between Bluetooth and inductive loops, the differences during peak times and other times were statistically significant, however there was no statistically significant difference for the all-day comparison, which indicated that it was unclear if there was a systematic difference across the whole day. Expressed another way, it made more sense to compare the results for peak time and other times separately, rather than across all day.

Further comparisons of route travel times for an average weekday (Thursday) and a typical weekday (Thursday, 25 February 2016) were also conducted and the results are shown in Appendix C and Appendix D. The results showed that when compared with inductive loops, both Bluetooth and probe were consistently higher in travel time values, and more sensitive to speed changes during peak time.

Summary

Results derived from the three data sources followed very similar patterns for average weekday route travel time. Both probe and Bluetooth results were consistently higher (about 9% and 11%) than from inductive loops during peak time (5:00 – 10:00 am), and the differences were statistically significant. During other times (10:00 am – 5:00 am) the differences were generally small or less significant. At late night (after 7:30 pm) both Bluetooth and probe travel times showed more volatility and less consistent patterns, when compared to inductive loop data. It is unclear if this was because of the volatile nature of vehicle speed during that time period, or because of the limited sample sizes and gap-fillings of probe and Bluetooth data during low-volume conditions.

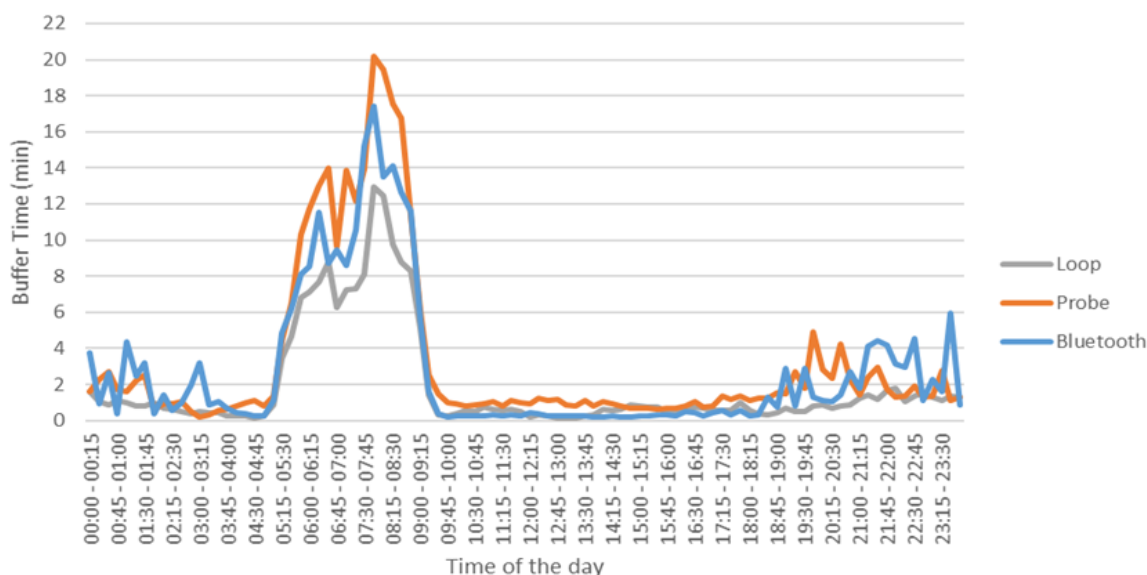
Between probe and Bluetooth, the average weekday route travel times were generally aligned well, with no statistically significant differences or only small differences during both peak and other times.

2.5.2 Average Weekday Route Buffer Time

Buffer time is the difference between 95th percentile and 50th percentile travel time in the whole study month and it indicates the variance in travel times day-by-day. The higher the buffer time, the higher the day-by-day differences would be. For each of the 15-minutes intervals, buffer time remains consistent in different weekdays in the study month.

Figure 2.4 shows the average weekday route buffer time comparison in minutes for the three data sources in 15-minute intervals. For peak time (5:00 am – 10:00 am), the buffer time of probes was the highest and the buffer time of inductive loops was the lowest. During other times (10:00 am – 5:00 am) the buffer time of probes remained as the highest until 9:00 pm, and the buffer time of Bluetooth became the highest afterwards until early morning; the buffer time of inductive loops was generally the lowest.

Figure 2.4: Average weekday route buffer time



Further statistical tests (Table 2.10) identified that probe buffer time was much higher than inductive loop buffer time (62% higher during peak time and 92% higher during other times) and these differences were statistically significant; Bluetooth buffer time was also much higher than inductive loop buffer time (33% higher during peak time and 75% higher during other times) and these differences were also statistically significant. Note that these percentage differences of means appeared to be very high, however these differences were much smaller in absolute time values. Between Bluetooth and probes, the differences appeared to be smaller or less significant.

Table 2.10: Statistical test metrics for buffer time comparison

Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Between probe and inductive loops	Peak	62%	4.72	0.96	YES
	Other times	92%	1.01	0.13	YES
	All day	71%	2.33	0.96	YES
Between Bluetooth and inductive loops	Peak	33%	2.85	0.90	YES
	Other times	75%	1.27	0.41	YES
	All day	46%	1.72	0.90	YES
Between Bluetooth and probe	Peak	-18%	2.77	0.89	YES
	Other times	-9%	1.30	0.14	NO
	All day	-15%	1.72	0.88	YES

As discussed in Luk, Han and Byrne (2016), road agencies also report the buffer time by using a buffer time index, which is expressed by a ratio of the 95th percentile travel time and the 50th percentile travel time. The buffer time index represents the percentage share of additional travel time that a traveller has to leave earlier than on average in order to arrive on time in 95% of the cases. The buffer time indexes were also calculated and compared as shown in Figure 2.5 and Table 2.11. The comparison shows that buffer time indexes (when compared with buffer time) for the three technologies were better aligned with each other and their differences were generally

small. During the morning peak 5:00 – 10:00 am, the average buffer time indexes for Bluetooth, probe and inductive loops were 1.34, 1.31 and 1.25 respectively.

Figure 2.5: Average weekday route buffer time indexes

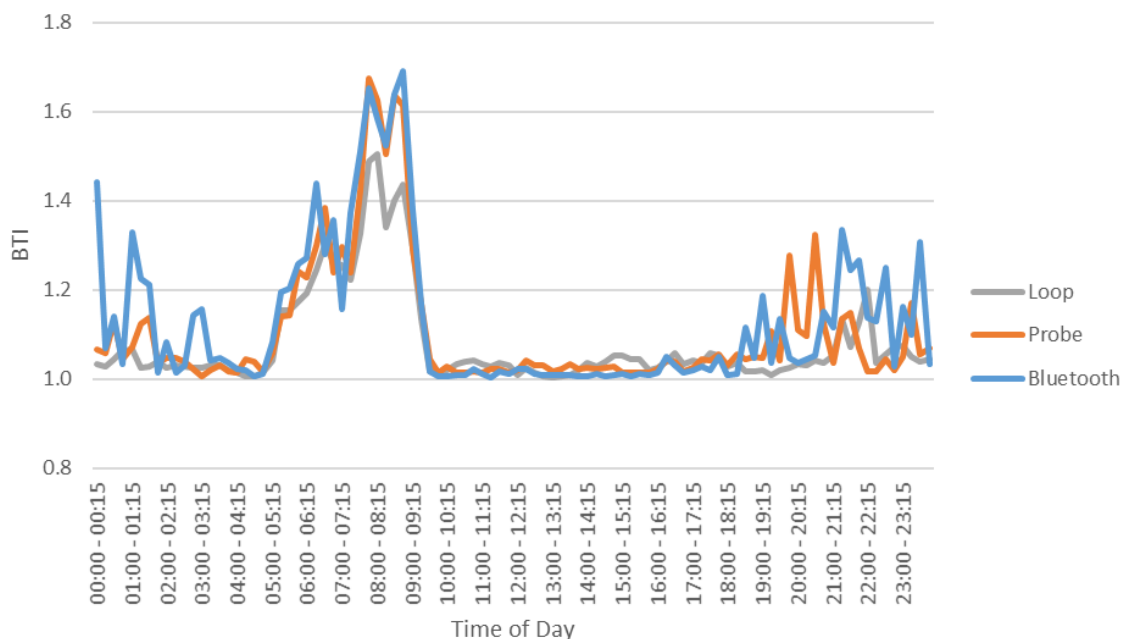


Table 2.11: Statistical metrics of route buffer time index comparison

Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Between probe and inductive loops	Peak	5%	0.10	0.94	YES
	Other times	1%	0.06	0.01	YES
	All day	2%	0.07	0.83	YES
Between Bluetooth and inductive loops	Peak	7%	0.13	0.87	YES
	Other times	3%	0.09	0.16	YES
	All day	4%	0.10	0.74	YES
Between Bluetooth and probe	Peak	2%	0.08	0.88	NO
	Other times	2%	0.10	0.09	NO
	All day	2%	0.09	0.71	YES

Summary

For peak time (5:00 – 10:00 am) the buffer time of probe data was the highest and buffer time of inductive loop data was the lowest. During other times (10:00 am – 5:00 am) the buffer time of probes remained as the highest until 9:00 pm, and the buffer time of Bluetooth data became the highest afterwards until early morning; the buffer time of inductive loops was generally the lowest. The buffer time differences between those three datasets were generally large and statistically

significant. However, when comparing the buffer time indexes, the results for the three data sources were more aligned with each other and their differences were generally small. During peak time, the average buffer time indexes estimated from Bluetooth, probes and inductive loops were 1.34, 1.31 and 1.25 respectively.

2.5.3 Link Travel Time

The link-level analysis aims to compare the pattern or behaviour of speed/travel time generated from probes and inductive loops at a higher resolution, and with more details. This needs to be understood as the excessive congestion costs are calculated at the link level.

Two short inductive loop links (9 and 16) and two long links (14 and 15) with good-quality data were chosen. Link 9 and link 14 are before ramps and links 15 and 16 are after ramps. As shown in Table 2.4, inductive loop links 9 and 16 cover seven probe links, inductive loops link 14 covers 15 probe links and inductive loops link 15 covers 6 probe links. Two methods were tested for the processing of probe data:

- Method 1 – aggregate/add the travel time of each probe link that constitutes that inductive loop link to get the inductive loop link travel time. This is consistent with the route travel time aggregation method in Section 2.5.1.
- Method 2 – average all the probe speeds of all probe links that constitute that inductive loop link to get the link travel time. This is consistent with current HERE probe data process.

Note that in theory, method 2 only works with short links and is not applicable with very long links or links with higher volatile speed values. The reason is that for long links (e.g. longer than 1,000 m) the speed differences could be very large; by averaging probe speeds for such a long link, the higher and lower speeds could offset each other and result in a more harmonised travel time with no or less peaks, which will lose the benefits of probe data's high resolution. On the other hand, method 1 of aggregating the travel times works for both short and long links.

For link 14, Bluetooth data were also covered in the comparison as link 14 is long and covers two Bluetooth links.

Figure 2.6 to Figure 2.9 show the travel time comparison for the four selected links. The link travel times derived from the loops were compared with link travel times derived from Bluetooth and from probe by using method 1 and method 2 respectively. A threshold travel time line is also presented in these graphs to indicate the 70% free-flow speed travel time, as a reference for excessive delay estimation.

For all four links, the travel times derived from inductive loops were generally lower or less volatile than from probes, which indicated a consistent pattern with the route-level comparison in Section 2.5.1. Further findings were:

- For loop link 9 (861 m), travel times derived from loops, probe method 1 and probe method 2 were closely aligned with each other across the whole day; the only exception was that probe method 1 picked up a small peak at 8:30 pm, while both loops and probe method 2 did not.
- For loop link 16 (812 m), travel times derived from loops, probe method 1 and probe method 2 were also aligned well; however, probe method 1 was more sensitive to speed changes and showed higher travel times and more congestion delay peaks during peak time, when compared with loops and probe method 2.

- For loop link 14 (3,066 m), peak-time travel times derived from Bluetooth and probe method 1 were consistently higher than from inductive loops; probe method 2 was less sensitive than method 1 and failed to pick up a few morning peaks between 6:15 – 9:00 am, which confirms that probe method 2 does not work well for long links.
- For loop link 15 (1,662 m), both probe method 1 and method 2 showed consistently higher travel times than from inductive loops, and method 1 was again more sensitive to speed changes.

Figure 2.6: Inductive loop link 9 (861 m in length) travel time

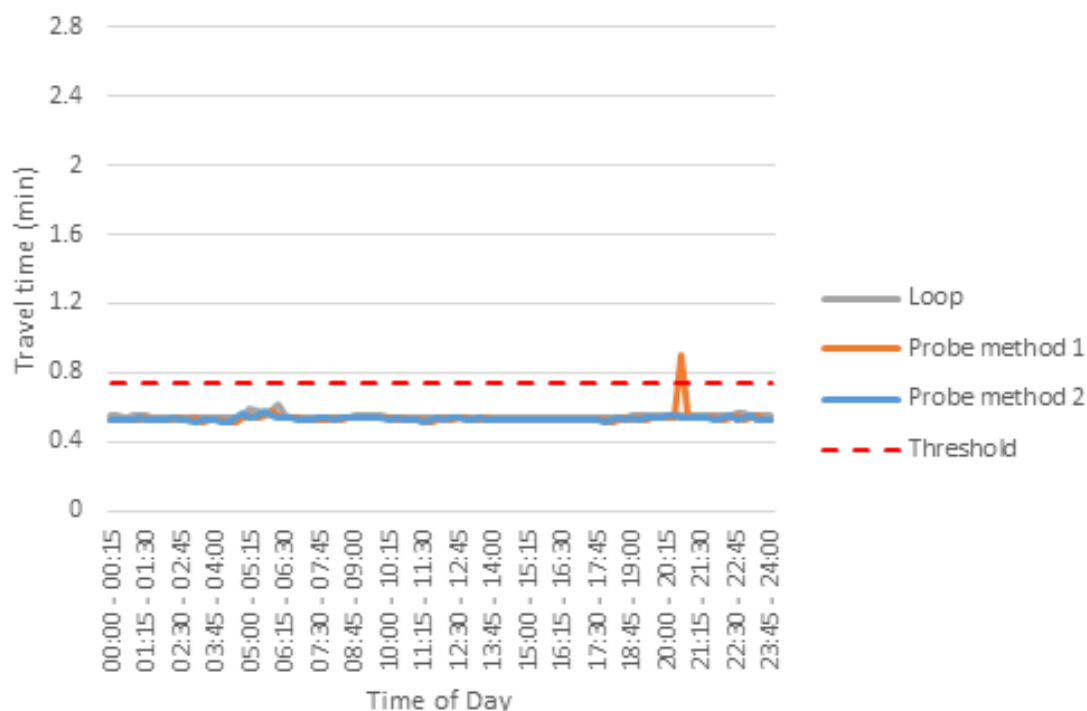


Figure 2.7: Inductive loop link 16 (812 m in length) travel time

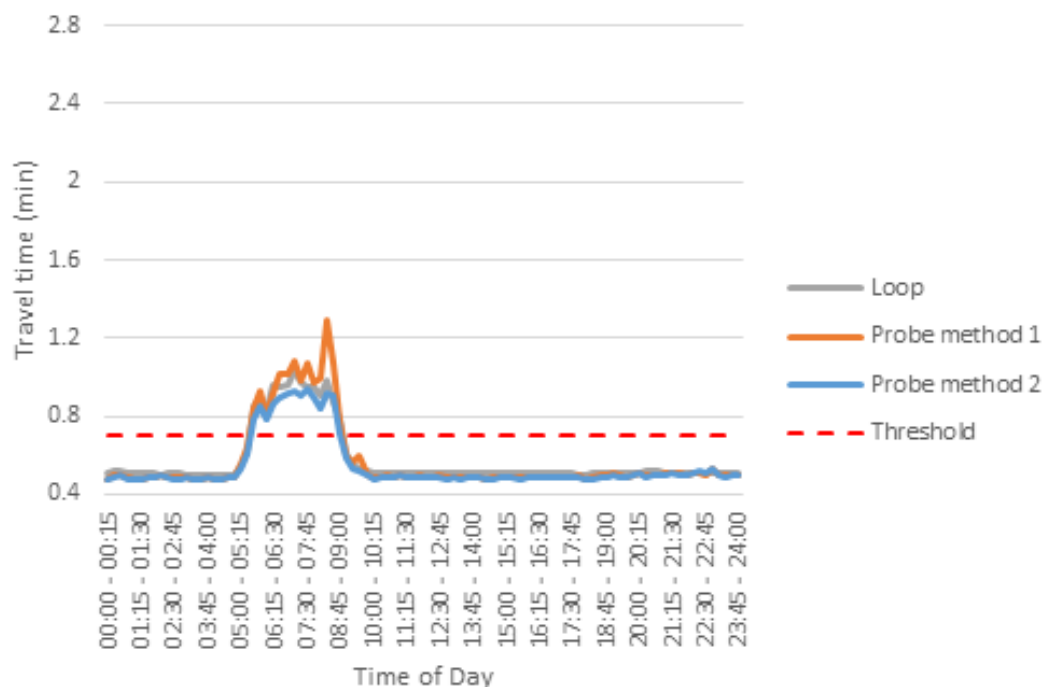


Figure 2.8: Link 14 (3,066 m in length) travel time

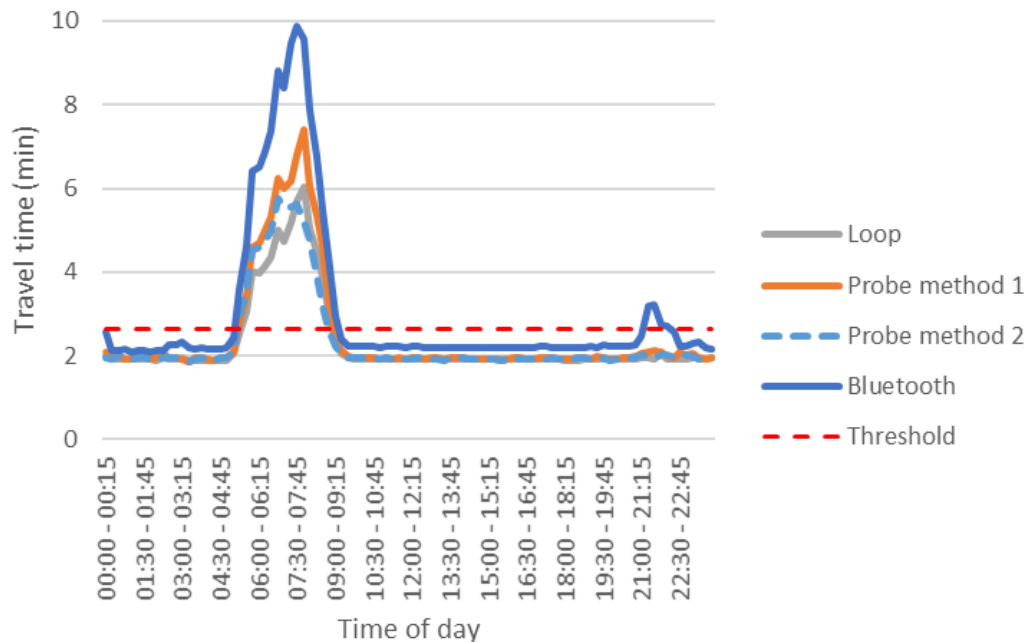
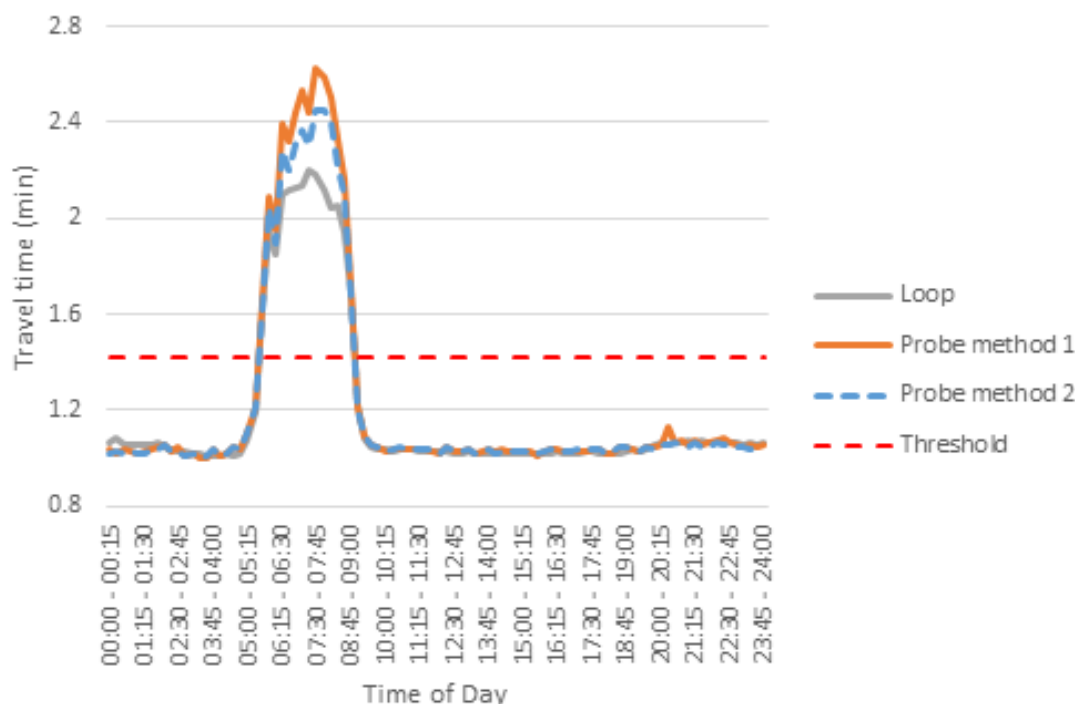


Figure 2.9: Link 15 (1,662 m in length) travel time



The same statistical tests were conducted and Table 2.12 shows the comparison between loops and probe method 1. As probe method 2 does not always work for longer links or links that have higher volatility of speed values, it is not recommended that method 2 is applied for further link-level analysis. Table 2.13 shows the comparison between Bluetooth and inductive loops for link 14 as Bluetooth data is only available for link 14.

It was found that for the two shorter links (9 and 16), the percentage differences of mean travel times between probe and inductive loop data were quite small for peak, other times and all day. The differences during peak time were larger than during other times, and these differences were generally statistically significant.

For longer links (14 and 15) the percentage differences in mean travel times for the three technologies at peak times were much higher than for the shorter links. For link 14 during peak time, the probe travel time was 17% higher and Bluetooth travel time was 56% higher than loop travel time. For link 15, the probe travel time was 11% higher than loop travel time. These differences were also statistically significant. During other times, the differences were generally small or less consistent.

Table 2.12: Statistical metrics for probe (method 1) and inductive loop comparison

Link number	Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Link 9	Average weekday	Peak	-3%	0.02	0.67	YES
		Other Times	-2%	0.15	0.09	NO
		All Day	-2%	0.040	0.06	YES
Link 16	Average weekday	Peak	6%	0.10	0.87	YES
		Other Times	-3%	0.02	0.15	YES

		All Day	0%	0.05	0.96	NO
Link 14	Average weekday	Peak	17%	0.78	1.00	YES
		Other Times	2%	0.06	0.30	YES
		All Day	7%	0.36	1.00	YES
Link 15	Average weekday	Peak	11%	0.25	0.98	YES
		Other Times	0%	0.02	0.38	NO
		All Day	3%	0.11	0.99	YES

Table 2.13: Statistical metrics for Bluetooth and inductive loop comparison (link 14 only)

Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Link 14 average weekday	Peak	56%	2.52	0.98	YES
	Other Times	17%	0.38	0.26	YES
	All day	31%	1.20	0.98	YES

Summary

For the two shorter links 9 and 16 (shorter than 1,000 m), the percentage differences in mean travel times between probe and inductive loop data were generally small for peak, other times and all day. However, the differences during peak time were relatively larger than during other times, and these differences were generally statistically significant.

For the two longer links 14 and 15 (longer than 1,000 m), the percentage differences in mean travel times for three technologies at peak times were much higher than for the shorter links. For link 14 during peak time, the probe travel time was 17% higher and Bluetooth travel time was 56% higher than loop travel time. For link 15, the probe travel time was 11% higher than loop travel time. These differences were also statistically significant. During other times, the differences were generally small or less consistent.

Probe and Bluetooth data were more sensitive to speed changes and generally showed higher travel times during peak time, which was also identified from the route travel time comparison.

2.5.4 Incident Day Travel Time

As mentioned in Section 2.2.1, TMR has recognised the importance of the impacts of incidents on the congestion cost reporting process and would like to investigate if alternative data sources such as probes and Bluetooth would have a higher capacity to pick up the delays during incidents. On Friday 4 March 2016, a major incident, a crash at 5:38 am at 400 m south of Dohles Rocks Road (southbound) caused significant delays across the southern end of the managed motorway and arterial network. The day was then selected to conduct a comparison between the three data sources. Travel times of both the route and (loop) links 14 and 15 where the incident occurred were compared. For Bluetooth data, links 6 and 7 and a small part of link 8 (loop links 14 and 15) were the locations where the incident occurred.

Figure 2.10 shows the route travel time comparison between loops, probes and Bluetooth on the incident day. Route travel times from loops and probes were aligned quite well for both peak and other times, however Bluetooth did not pick up a peak of the delay between 5:15 and 7:15 am but was able to pick up another higher peak between 8:15 to 10:15 am.

The Bluetooth data on the incident were investigated further. It was found that soon after the incident occurred, the immediate upstream section of Bruce Highway was closed and traffic was re-routed. As a result, insufficient sample size limited Bluetooth to return any statistically sound data. Also, TMR has a filtering rule applied to Bluetooth data processing in which any speed measured slower than 5 km/h will be discarded to minimise noise in the data. In this situation, free-flow speed was assumed and used to fill the gaps and that caused significant underestimation of route and link travel times.

Probe data were slightly more sensitive to speed changes than loop data and picked up a few extra peaks between 6:30 and 9:15 am. The statistical metrics in Table 2.14 further confirm that travel time differences between probes and loops were either small or not statistically significant for peak, other times and all day. However, the travel time differences between Bluetooth and the other two data sources were quite large and statistically significant during peak time.

Figure 2.10: Incident day route travel time

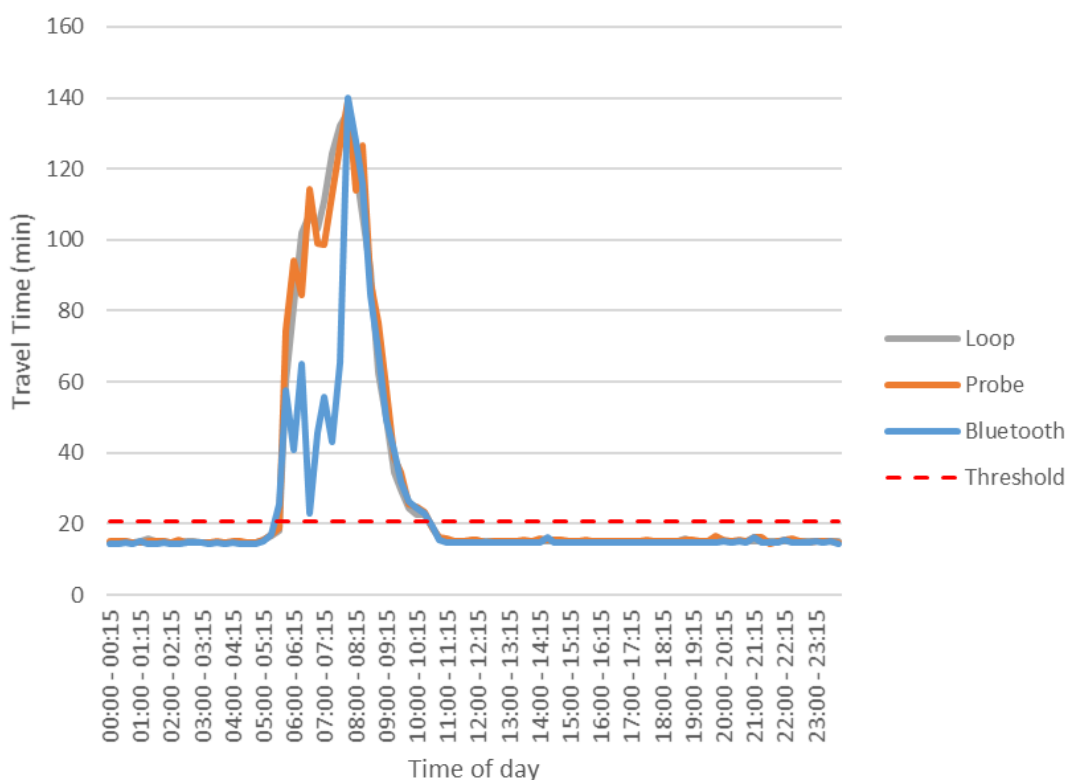


Table 2.14: Statistical metrics for incident day route travel time comparison

Category	Time of comparison	% difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Probe - inductive loops	Peak	2%	9.54	0.95	NO
	Other times	1%	0.48	0.93	YES
	All day	2%	4.38	0.98	NO
Bluetooth - inductive loops	Peak	-25%	37.34	0.44	YES
	Other times	-1%	0.44	0.95	YES
	All day	-15%	17.05	0.73	YES
Bluetooth - probe	Peak	-27%	35.81	0.22	YES

	Other times	-3%	0.58	0.57	YES
	All day	-16%	16.35	0.63	YES

Figure 2.11 and Figure 2.12 show the travel time comparison for inductive loop links 14 and 15. For link 14, three data sources were compared. For link 15, only probe and loop data were compared as the Bluetooth link was much longer than the loop link at the location. Table 2.15 and Table 2.16 present the statistical metrics for the link level comparison. The main findings are:

- For link 14, probe and loop travel times were aligned well with each other, with probe data showing more sensitivity to speed changes. Bluetooth failed to pick up the delay between 5:30 am and 7:45 am. After 7:45 am Bluetooth picked up some of the delay but was not as sensitive as the probe data.
- For link 15, probe travel time was much higher and much more volatile than from loops. It appeared that the loops failed to identify some delays between 5:30 – 9:00 am.

To assess the performance of Bluetooth data during the morning peak of the incident day, further analysis of Bluetooth data at the link level are provided in Appendix E. Appendix E also compares the Bluetooth link travel time between a normal Friday and the Friday of the incident. It was identified that the large amount of 'no data' cells (15 – 40%) during the morning peak for Bluetooth links 5, 6 and 7 on the incident day was likely the key reason why Bluetooth failed to pick up part of the delay between 5:15 – 7:15 am. As mentioned previously, the sample size issue (due to re-routing after the incident) and the TMR Bluetooth data filter were regarded as the main reasons of the Bluetooth performance on the day.

Figure 2.11: Incident day link 14 (3,066 m in length) travel time

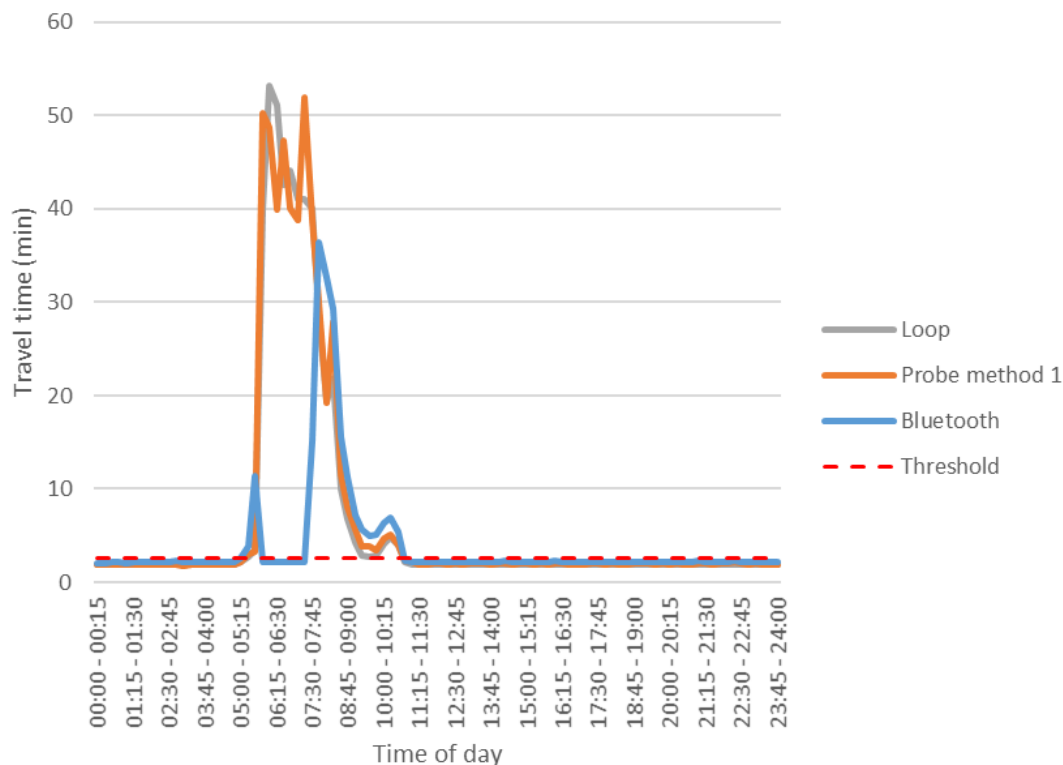


Figure 2.12: Incident day link 15 (1,662 m in length) travel time

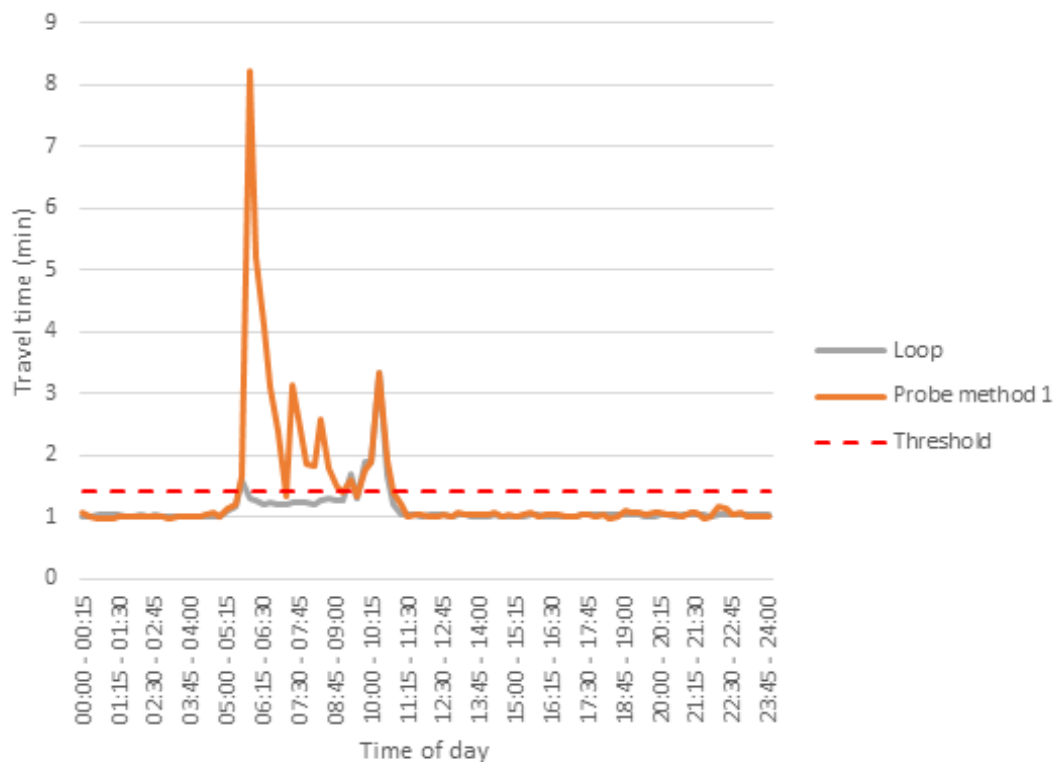


Table 2.15: Statistical metrics for incident day link 14 travel time comparison

Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Probe (method 1) – inductive loops	Peak	3.7%	4.79	0.94	NO
	Other times	2.8%	0.11	0.98	YES
	All day	1.7%	2.19	0.97	NO
Bluetooth – inductive loops	Peak	-57%	14.16	0.02	YES
	Other times	17%	1.32	0.99	YES
	All day	-39%	6.57	0.08	YES

Table 2.16: Statistical metrics for incident day link 15 travel time comparison

Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Probe (method 1) – inductive loops	Peak	89%	2.05	0.01	YES
	Other times	2%	0.05	0.97	YES
	All day	23%	0.94	0.17	YES

Summary

Route travel times from loops and probes were generally aligned quite well for both peak and other times. Probe data were more sensitive to speed changes and were able to pick up more delays at both link and route levels.

However, Bluetooth failed to pick up part of the delays at both route and link levels around the incident locations. Further investigation of the Bluetooth links on the incident day identified that the abnormally large amount of no-data cells during peak time for a few Bluetooth links (5, 6 and 7) where the incident occurred appeared to be the main reason why Bluetooth failed.

2.5.5 Excessive Delay Cost

Figure 2.13 shows the average daily excessive delay cost for the study site in 15-minute intervals. It shows that the results derived from the three datasets followed the same pattern, with inductive loop data showing less volatility and being consistently lower than the other two datasets during peak time.

Table 2.17 shows the average daily excessive delay cost for day-of-week and also compares percentage differences between results from probes, Bluetooth and inductive loops. The excessive delay costs estimated based on probe data were generally much higher than from inductive loops (between 40% – 63% and on average 55% higher during weekdays). The excessive delay costs estimated based on Bluetooth data were also much higher than from inductive loops (between 43% – 68% and on average 54% higher during weekdays). However, the results for probes and Bluetooth were much closer (between -5% and 4% and on average there was no difference during weekdays). In absolute values, the excessive delay costs estimated from probe and Bluetooth data were \$15,559 and \$15,443 higher per day than from inductive loop data.

The differences in excessive delay costs between Bluetooth and loops, and between probe and loops were much larger than the differences in the travel time comparison in Section 2.5.1; this was mainly due to the use of a threshold value (i.e. 70% free-flow speed travel time) in the excessive delay calculation (the red dotted line in Figure 2.3).

Figure 2.13: Average weekday excessive delay cost

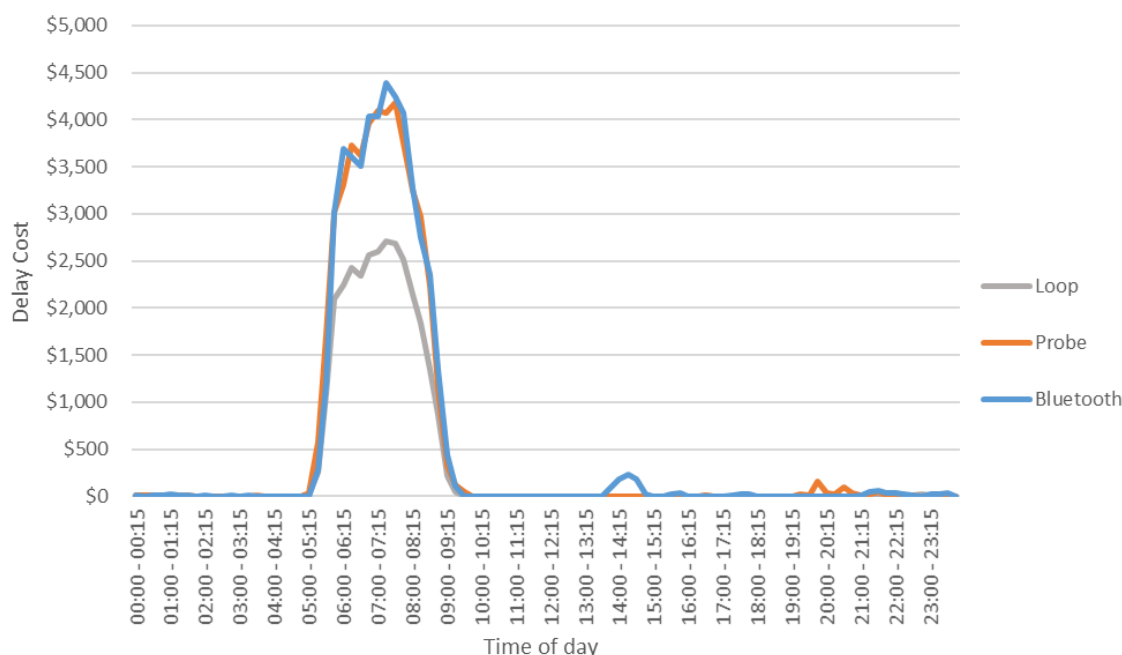


Table 2.17: Day-of-week excessive delay cost (\$2013)

Day	Inductive loops	Probe	Bluetooth	% Difference between probe and inductive loops	% Difference between Bluetooth and inductive loops	% Difference between Bluetooth and probe
Monday	\$43,325	\$65,291	\$67,014	51%	55%	3%
Tuesday	\$28,414	\$42,488	\$44,004	50%	55%	4%
Wednesday	\$29,930	\$48,035	\$47,372	60%	58%	-1%
Thursday	\$27,415	\$44,701	\$42,338	63%	54%	-5%
Friday	\$12,995	\$19,359	\$18,564	49%	43%	-4%
Average weekday	\$28,416	\$43,975	\$43,858	55%	54%	0%

Note that although all the volume data come from the same source, there were some slight differences or some overlaps in link lengths during the data matching process. Therefore, VKT values aggregated for different data links showed minor differences. Appendix G shows the VKT calculated for the three datasets. The excessive delay costs normalised by VKT were also calculated to take account of the impact of these differences.

Table 2.18 shows the normalised average daily excessive delay costs and the differences between the three data sources. After normalisation, the differences between probe and inductive loop results were very similar (changed from 55% to 54%), however the differences between Bluetooth and inductive loop results and between Bluetooth and probe results became larger (from 54% to 63% and from 0% to 6%). These changes were within expectation as the VKT values estimated for inductive loops and probe links were almost the same with only minor differences, however the

VKT values estimated for Bluetooth showed slightly greater differences from the other two datasets (Appendix G).

Table 2.18: Normalised day-of-week excessive delay cost (\$2013)

Day	Inductive loops	Probe	Bluetooth	% Difference between probe and inductive loops	% Difference between Bluetooth and inductive loops	% Difference between Bluetooth and probe
Monday	\$0.0341	\$0.0511	\$0.0555	50%	63%	9%
Tuesday	\$0.0225	\$0.0334	\$0.0367	48%	63%	10%
Wednesday	\$0.0235	\$0.0373	\$0.0391	59%	67%	5%
Thursday	\$0.0206	\$0.0333	\$0.0336	62%	63%	0.8%
Friday	\$0.0091	\$0.0135	\$0.0138	48%	51%	2%
Average weekday	\$0.0220	\$0.0337	\$0.0357	54%	63%	6%

Summary

The excessive delay costs estimated from probe data were generally much higher than from inductive loops (between 40% – 63% and on average 55% higher during weekdays). The excessive delay costs estimated from Bluetooth data were also much higher than from inductive loops (between 43% – 68% and on average 54% higher during weekdays). However, the results for probe and Bluetooth were much closer (between -5% and 4% and on average there was no difference during weekdays).

Note that when estimating excessive delay cost values, the differences (percentage difference of means) between probe/Bluetooth and inductive loops became much larger than the travel time comparison, which was within expectation. This was mainly due to the use of a threshold speed in the excessive delay calculation.

In absolute cost values, the excessive delay costs estimated from probe and Bluetooth data were \$15,559 and \$15,443 higher per weekday than from inductive loop data.

2.5.6 Travel Time Reliability Cost

As mentioned in Section 2.5.2, for each data source, the buffer time remains consistent in every weekday of the study month for each 15-minute interval, and the differences in travel time reliability costs between different weekdays came from the variations in volumes.

Figure 2.14 shows the average daily travel time reliability costs for the study site in 15-minute intervals. It shows that the results derived from the three datasets followed similar patterns across the day, with inductive loop data showing less volatility and being consistently lower than the other two datasets during peak time. The reliability costs also followed a very similar pattern to the route buffer times, as expected.

Table 2.19 shows the average reliability costs for day-of-week and the differences between the three data sources. It was found that the reliability costs estimated from Bluetooth were much higher than from inductive loops (between 40% – 41% and on average 40% higher). The reliability costs estimated from probe data were also much higher than from inductive loops (between 37% – 38% and on average 37% higher). However, the results for Bluetooth and probe were much closer (1% – 3% and in average 2%). In absolute values, the reliability costs estimated from Bluetooth and probe data were \$15,684 and \$14,603 higher per day than from inductive loop data.

Figure 2.14: Average weekday travel time reliability cost

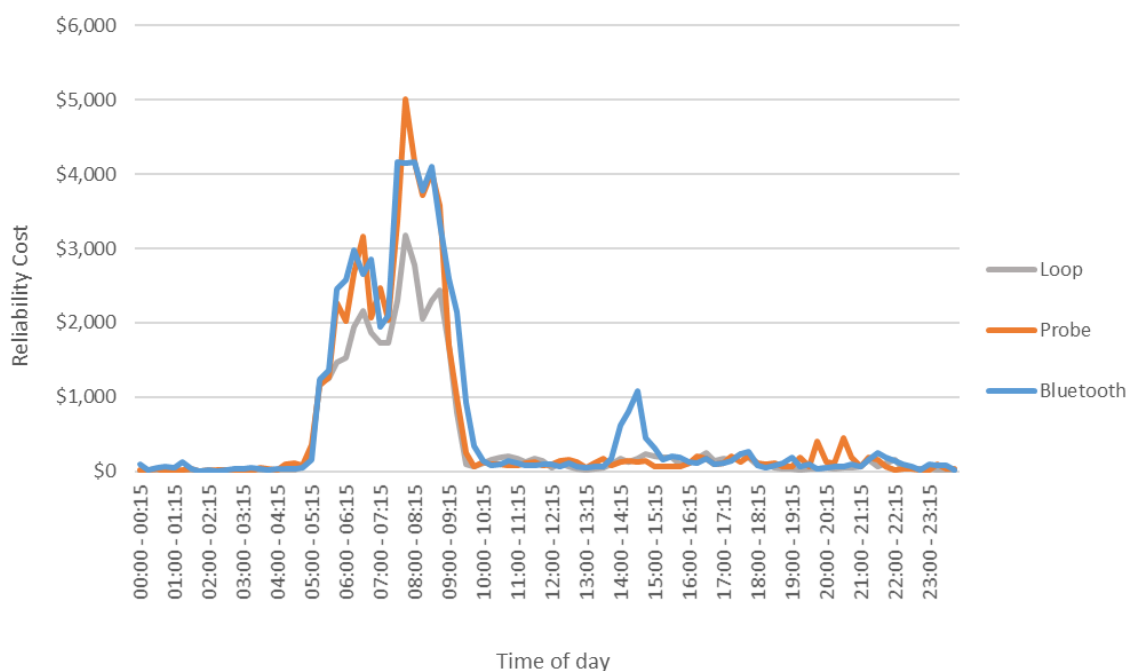


Table 2.19: Day-of-week travel time reliability cost (\$2013)

Day	Inductive loops	Probe	Bluetooth	% Difference between probe and inductive loops	% Difference between Bluetooth and inductive loops	% Difference between Bluetooth and probe
Monday	\$37,446	\$51,166	\$52,670	37%	41%	3%
Tuesday	\$39,091	\$53,714	\$54,619	37%	40%	2%
Wednesday	\$38,924	\$53,503	\$55,008	37%	41%	3%
Thursday	\$39,722	\$54,511	\$55,652	37%	40%	2%
Friday	\$40,225	\$55,529	\$55,879	38%	39%	1%
Average weekdays	\$39,082	\$53,685	\$54,766	37%	40%	2%

Table 2.20 shows the normalised average reliability costs for day-of-week and the differences between the three data sources. It was found that after normalisation, the differences between probe and inductive loop results were still the same (37%), however the differences between Bluetooth and inductive loops and between Bluetooth and probe became larger (from 40% to 48% and from 2% to 8%). Again, these changes were expected given the minor differences in VKT values as shown in Appendix G.

Table 2.20: Normalised day-of-week travel time reliability cost (\$2013)

Day	Inductive loops	Probe	Bluetooth	% Difference between probe and inductive loops	% Difference between Bluetooth and inductive loops	% Difference between Bluetooth and probe
Monday	\$0.0295	\$0.0400	\$0.0436	36%	48%	9%
Tuesday	\$0.0308	\$0.0421	\$0.0455	37%	48%	8%
Wednesday	\$0.0303	\$0.0414	\$0.0451	37%	49%	9%

Thursday	\$0.0299	\$0.0407	\$0.0441	36%	48%	8%
Friday	\$0.0283	\$0.0389	\$0.0413	37%	46%	6%
Average weekdays	\$0.0298	\$0.0406	\$0.0439	37%	48%	8%

Summary

The travel time reliability costs estimated from Bluetooth were generally much higher than from inductive loops (between 40% – 41% and on average 40% higher). The reliability costs estimated from probe data were also much higher than from inductive loops (between 37% – 38% and on average 37% higher). However, the results for Bluetooth and probe were much closer (1% – 3% and on average 2%).

In absolute values, the reliability costs estimated from Bluetooth and probe data were \$15,684 and \$14,603 higher per day than from inductive loop data.

2.5.7 Total Excessive Congestion Cost

Total excessive congestion cost is the sum of excessive delay cost and travel time reliability cost. Figure 2.15 shows the average total excessive congestion costs for the three data sources for weekdays. As expected, a clear spike in congestion costs was experienced during the morning peak as more commuters travelled inbound, with little congestion encountered at any other time of the day. As expected, the total excessive congestion costs estimated from Bluetooth and probes were much higher (46% and 45% higher) than from inductive loop data for an average weekday. However, the differences between the total excessive congestion costs estimated from Bluetooth and probes were very small (1%).

Table 2.21 shows the total excessive congestion costs and the differences between the three data sources.

Table 2.22 shows the normalised average excessive congestion costs and the differences. It was found that after normalisation, the differences between probes and inductive loops were still very similar (from 45% to 44%), however the differences between Bluetooth and inductive loops and between Bluetooth and probes became larger (from 46% to 54% and from 1% to 7%).

Figure 2.16 shows the profile of excessive congestion costs for the three data sources on each day of the study time period (for detailed data see Appendix F). It also includes weekend values for reference although weekend results are not discussed in this report. As expected, excessive congestion cost was consistently low on weekends, with little if any excessive delay cost and some small reliability cost experienced.

Regardless of which data collection methods were considered in estimating the costs, travel time reliability costs were higher than excessive delay costs on most days except Mondays during the study month (Figure 2.16 and Appendix F). Note that in this case study, the average weekday travel time was estimated by averaging 18 weekdays of data (18 samples); however, the average weekday buffer time was estimated by using only one monthly distribution (one sample). If using a longer study time period for example 2- 3 months, the behaviour of buffer time and travel time reliability costs could be much different. It should be noted that TMR had commented that buffer time estimation should always exclude public holidays and days with incidents.

Figure 2.15: Average weekday total excessive congestion cost

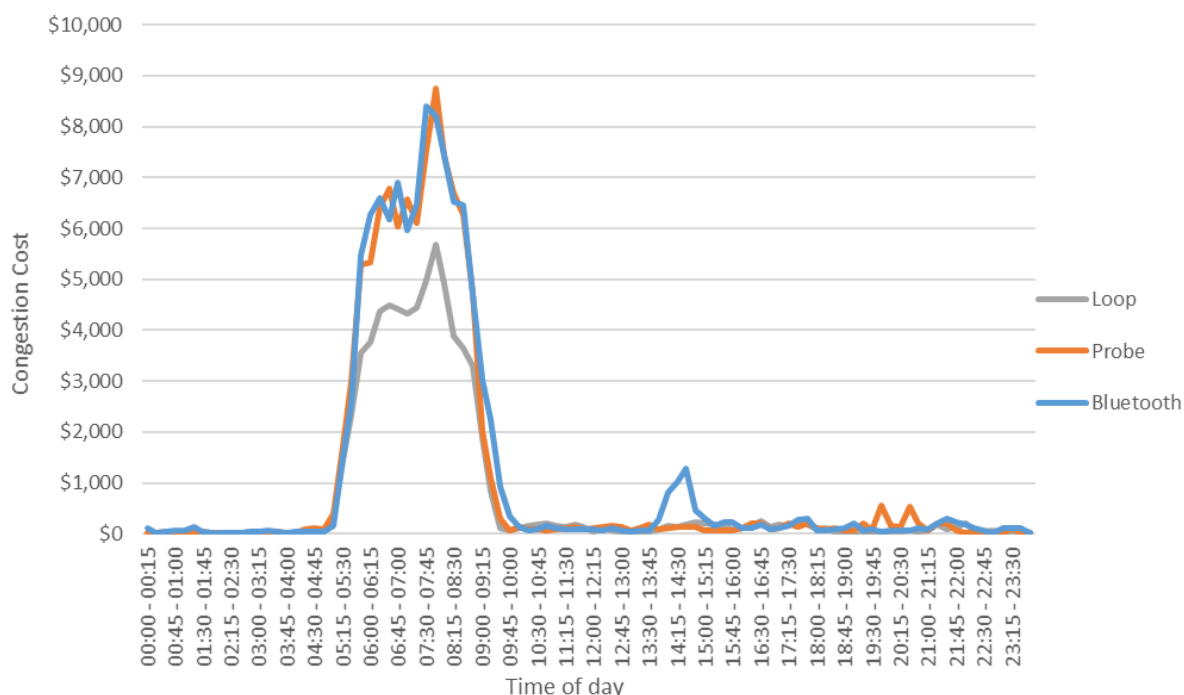


Table 2.21: Day-of-week total cost of excessive congestion (\$2013)

Day	Inductive loops	Probe	Bluetooth	% Difference between probe and inductive loops	% Difference between Bluetooth and inductive loops	% Difference between Bluetooth and probe
Monday	\$80,771	\$116,457	\$119,684	44%	48%	3%
Tuesday	\$67,505	\$96,202	\$98,623	43%	46%	3%
Wednesday	\$68,854	\$101,539	\$102,380	47%	49%	1%
Thursday	\$67,137	\$99,213	\$97,991	48%	46%	-1%
Friday	\$53,220	\$74,888	\$74,443	41%	40%	-1%
Average weekdays	\$67,497	\$97,660	\$98,624	45%	46%	1%

Table 2.22: Normalised day-of-week total cost of excessive congestion (\$2013)

Day	Inductive loops	Probe	Bluetooth	% Difference between probe and inductive loops	% Difference between Bluetooth and inductive loops	% Difference between Bluetooth and probe
Monday	\$0.06	\$0.09	\$0.10	43%	56%	9%
Tuesday	\$0.05	\$0.08	\$0.08	42%	54%	9%
Wednesday	\$0.05	\$0.08	\$0.08	46%	56%	7%
Thursday	\$0.05	\$0.07	\$0.08	47%	54%	5%
Friday	\$0.04	\$0.05	\$0.06	40%	47%	5%
Saturday	\$0.01	\$0.01	\$0.02	50%	84%	23%
Sunday	\$0.00	\$0.01	\$0.01	32%	19%	-10%

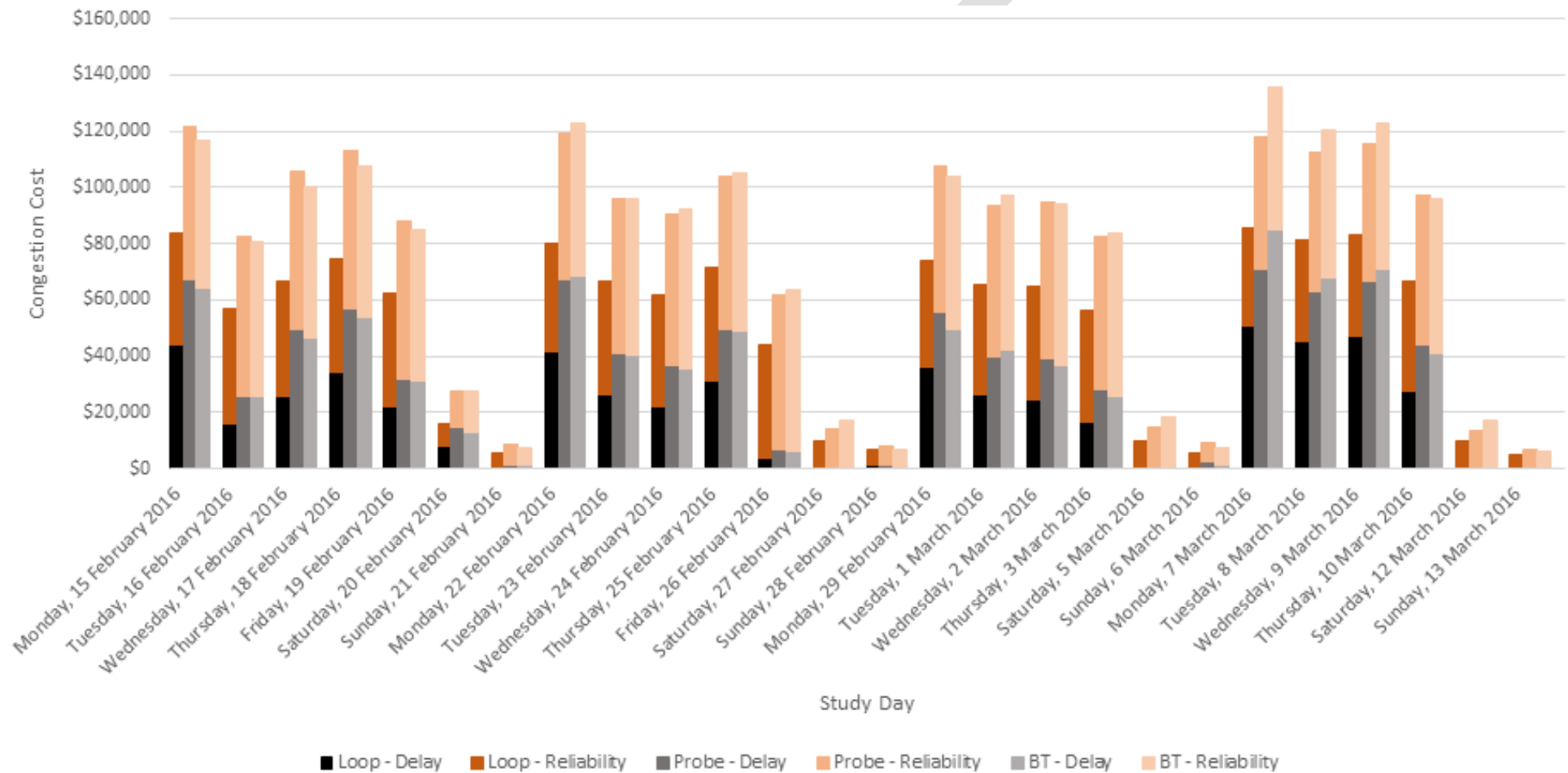
Average weekdays	\$0.0517	\$0.074 4	\$0.0769	44%	54%	7%
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Summary

As expected, the total excessive congestion costs estimated from Bluetooth and probes were much higher (46% and 45% higher on average on weekdays) than from inductive loops. However, the differences between the total excessive congestion costs estimated from Bluetooth and probes were very small (1%).

Regardless of which data collection methods were considered in estimating the costs, travel time reliability costs were higher than excessive delay costs on most days except Mondays in the study month.

Figure 2.16: Daily excessive congestion cost for the study period (\$2013)



3 SUMMARY OF MAIN FINDINGS

The key findings are summarised as follows:

1. The excessive congestion cost methodology developed in project R22 has been successfully applied to multiple data sources which are inductive loop, probe speed and Bluetooth travel time data.
2. For both weekday route and link travel time comparisons, results derived from the three data sources followed very similar patterns. The route travel time comparison identified that both probe and Bluetooth results were consistently higher (about 9% and 11%) than from inductive loops during peak time (5:00 – 10:00 am). The differences were statistically significant indicating that there were systematic differences between probe and inductive loops, and between Bluetooth and inductive loops. During other times (10:00 am – 5:00 am) the differences were generally small or less significant. At night-times (after 7:30 pm) both Bluetooth and probe travel times showed more volatility and less consistent patterns, when compared to inductive loop data. It is unclear if this was because of the volatile nature of vehicle speeds during that time period, or because of the limited sample sizes and gap-fillings of probe and Bluetooth data during low-volume conditions.
3. Between probe and Bluetooth, the average weekday route travel times were generally aligned well, with no statistically significant differences or only small differences during both peak and other times.
4. The weekday route buffer time comparison showed that for peak time (5:00 – 10:00 am) the buffer time of probe data was the highest and the buffer time of inductive loop data was the lowest. During other times (10:00 am – 5:00 am) the buffer time of probes was the highest until 9:00 pm, and the buffer time of Bluetooth was the highest afterwards until early morning; the buffer time of inductive loops was generally the lowest. The buffer time differences between those three datasets were generally large and statistically significant. However, when comparing the buffer time indexes, the results for the three data sources were more aligned with each other and their differences were generally small. During peak time, the average buffer time indexes estimated from Bluetooth, probes and inductive loops were 1.34, 1.31 and 1.25 respectively.
5. The comparison of weekday link travel times for a few selected links showed that probe and Bluetooth data were more sensitive to speed changes and showed higher travel times during peak time, which was also identified from the route travel time comparison. For shorter links, the travel time differences between probes and loops were generally smaller; for longer links, the travel time differences between probes and loops were generally larger, particularly during peak times.
6. An analysis of the day of the incident found that route travel times from loops and probes were generally aligned quite well for both peak and other times, and that probe data were more sensitive to speed changes and were able to pick up more delays at both link and route level. However, Bluetooth failed to pick up part of the delays at both route and link levels around the incident locations. Further investigation of all Bluetooth links on the day identified that the abnormally large amount of no- data cells during peak time for a few Bluetooth links (5, 6 and 7) where the incident occurred appeared to be the main reason why Bluetooth failed on the day.
7. The excessive delay costs estimated from probe data were generally much higher than from inductive loops (between 40% – 63% and on average 55% higher during weekdays). The excessive delay costs estimated from Bluetooth data were also much higher than from inductive loops (between 43% – 68% and on average 54% higher during weekdays).

However, results for probe and Bluetooth were much closer (between -5% and 4% and on average there was no difference during weekdays). Note that when estimating excessive delay cost values, the differences (percentage difference of means) between probe/Bluetooth and inductive loops became much larger than the travel time comparison, which was within expectations. This was mainly due to the use of a threshold speed in the excessive delay calculation. In absolute cost values, the excessive delay costs estimated from probe and Bluetooth data were \$15,559 and \$15,443 higher per weekday than from inductive loop data.

8. Similar patterns were identified for travel time reliability costs. The reliability costs estimated from Bluetooth were generally much higher than from inductive loops (between 40% – 41% and on average 37% higher). The excessive delay costs estimated from probe data were also much higher than from inductive loops (between 37% – 38% and on average 40% higher). However, the results for probe and Bluetooth were much closer (1% – 3% and on average 2%). In absolute values, the reliability costs estimated from probe and Bluetooth data were \$14,603 and \$15,684 higher per weekday than from inductive loop data.
9. As expected, the total excessive congestion costs estimated from Bluetooth and probes were much higher (46% and 45% higher on average weekday) than from inductive loop data. However, the differences in total excessive congestion costs estimated from Bluetooth and probes were very small (1%). Regardless of which data collection methods were considered in estimating the costs, travel time reliability costs were higher than excessive delay costs on most days except Mondays during the study month. TMR should be aware that the variability in travel time experienced on this section of Bruce Highway has cost the community more than the excessive delays.

4 FURTHER CONSIDERATIONS

Further considerations arising from case study 1 results include:

- The nature of data from the three sources – inductive loops, probe and Bluetooth – are different. The probe and Bluetooth link data come from the average of all data samples within a link, and the samples could be distributed randomly along the link. Inductive loop speed comes from the freeway detector stations, which are located at fixed locations along the freeway, therefore the speed derived from inductive loops is based on a spot speed at certain location (s) within the inductive loop link. On the other hand, probe and Bluetooth derive the link speed based on the space-mean speed method which might be more capable of capturing the volatility of speed/travel times. The case study results have confirmed that at both link and route levels, probe and Bluetooth data generally had a higher capability to pick up speed changes and excessive delays.
- Probe links are generally much shorter, ranging from 16 m to 1,912 m, therefore probe data could be more sensitive to the speed changes at higher resolution. Other studies conducted by using probe data from Eastlink (Melbourne), Perth and Roads and Maritime Services (Espada & Bennett 2016) have also confirmed that one of the key benefits of using probe data was the high resolution and sensitivity to speed changes that helps to identify bottlenecks more accurately.
- Although Bluetooth links are generally much longer than inductive loop links, this case study showed that Bluetooth data could also have a higher capability to pick up travel time/speed changes and excessive delays.
- Based on the results from this study, the inductive loops appeared to consistently underestimate travel time, buffer time, excessive delay cost and reliability cost when compared to both Bluetooth and probe. For example, for each weekday at the study site, the inductive loops could underestimate excessive congestion costs by \$15 – 16 k, and also underestimate travel time reliability costs by \$16 – 17 k. There might be a chance to review or reconsider the threshold (i.e. 70% of free-flow speed) for the excessive delay estimation when using inductive loop data. However, further case studies using different data sources or different study sites should be conducted to validate the findings from this study.

It was also identified that limitations and some issues in using probe data and Bluetooth data for excessive congestion cost estimation may include:

- Limited samples during off-peak or low-volume periods may have impact on the accuracy and reliability of the travel time and buffer time estimation, although excessive delay in this report was mainly concerned with peak times.
- The sample sizes are generally unknown to the users. For probes, a 'confidence level' parameter is given to indicate the range of sample sizes for each time interval, however, HERE reported that the relationships between probe link length and sample size levels are not linear and have no consistent pattern.
- Only speed and travel time data are available, and the data still need to be blended with other data sources such as STREAMS/SCATS volume information in order to estimate and report congestion costs and other KPIs.

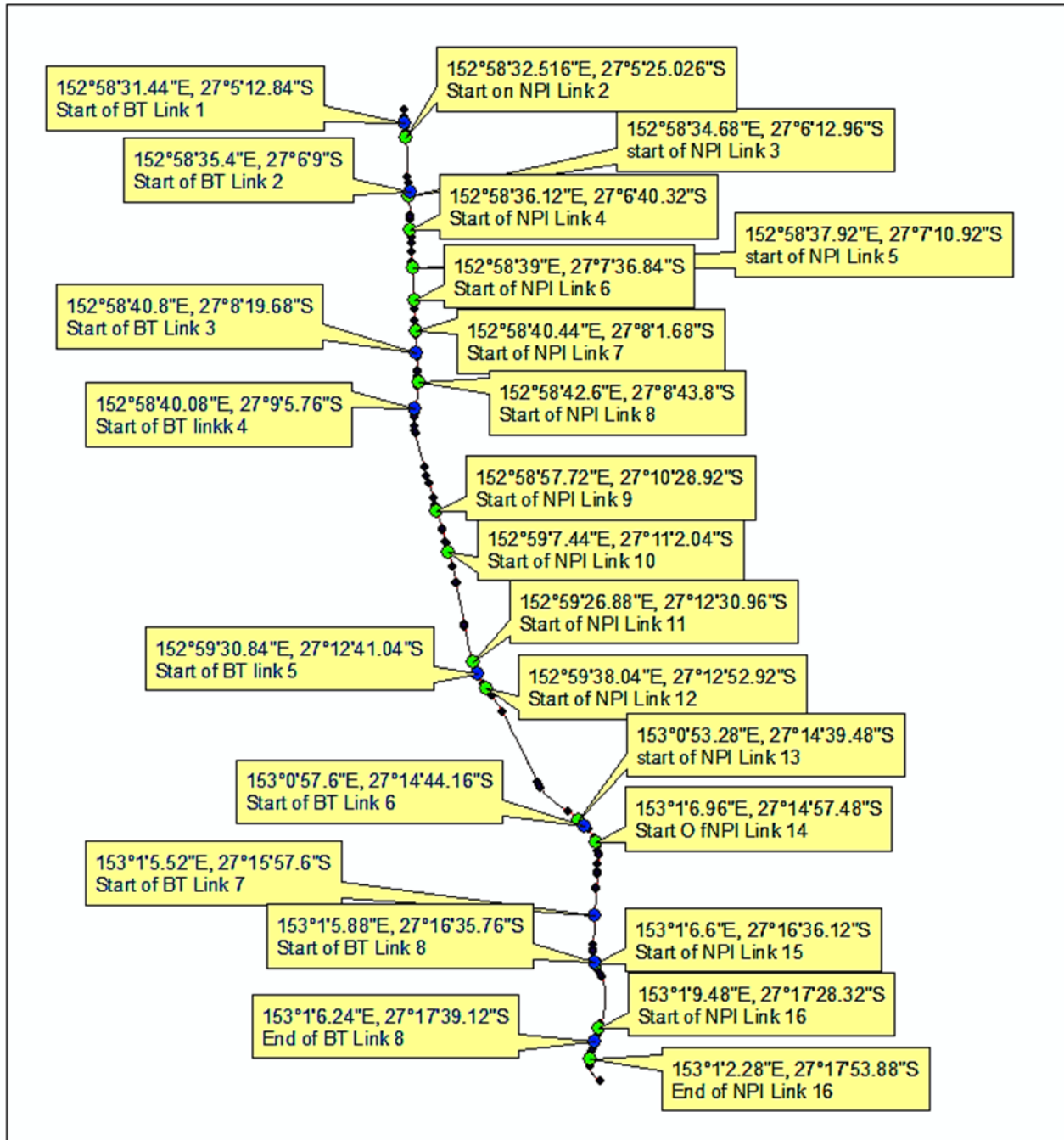
- When estimating loop link travel times by using probe data, two methods were tested. Method 1 is to aggregate or add the travel times of all probe links that constitute that inductive loop link to get the inductive loop link travel time. Method 1 is consistent with the route travel time aggregation method. Method 2 is to average all the probe speeds of all probe links that constitute that inductive loop link to get the link travel time. Method 2 is consistent with the current HERE probe process of calculating link travel time. As expected, method 2 was less sensitive to speed changes and could fail in picking up the excessive delays especially for longer links, therefore method 2 was not recommended for longer links.
- On the day that involved a severe crash, Bluetooth was unable to pick up the speed of stationary or diverted traffic during road closure due to the high number of no-data cells on the day. The main reasons were insufficient sample size due to the road closure and re-routing after the incident and the TMR filtering rule (discarding any reading < 5 km/h to minimise noise in the data). This resulted in the underestimation of excessive delay during the critical period after the incident.

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APPENDIX A DATA MATCHING MAP

Figure A 1: ArcMap snapshot showing the start and end of each of the links for the different data sources



APPENDIX B LINK LENGTH OF THE THREE DATA SOURCES

Table B 1: Inductive loop link length

Link number (note 1)	Link name	Link length (m)
2	Bruce Hwy SB between Bruce Hwy On Ramp 5 & Buchanan Rd Off Ramp	1481
3	Bruce Hwy SB between Buchanan Rd Off Ramp 2 & Bruce Hwy On Ramp	849
4	Bruce Hwy, Bruce Hwy On Ramp 14, Bh Sb Bp Off Ramp SB between Bruce Hwy Bruce Hwy On Ramp 14 & Bh Sb	949
5	Bh Sb Bp Off Ramp, Bh Sb Bp On Ramp SB between Bh Sb Bp Off Ramp & Bh Sb Bp On Ramp	798
6	Bh Sb Bp On Ramp, Bruce Hwy, Uhlmann Rd Off Ramp 2 SB between Bh Sb Bp On Ramp & Bruce Hwy Uhlmann R	764
7	Bruce Hwy SB between Uhlmann Rd Off Ramp 2 & Bruce Hwy On Ramp	1307
8	Bruce Hwy SB between Bruce Hwy On Ramp & Deception Bay Rd Off Ramp	3301
9	Bruce Hwy SB between Deception Bay Rd Off Ramp & Bruce Hwy On Ramp 2	861
10	Bruce Hwy SB between Bruce Hwy On Ramp 2 & Bruce Hwy Boundary Sb Off Ramp	2995
11	Bruce Hwy SEB between Bruce Hwy Boundary Sb Off Ramp & Bruce Hwy Boundary Sb On Ramp	751
12	Bruce Hwy SEB between Bruce Hwy Boundary Sb On Ramp & Anzac Ave Off Ramp	3955
13	Bruce Hwy SEB between Anzac Ave Off Ramp & Bruce Hwy On Ramp Bruce Hwy 3	676
14	Bruce Hwy On Ramp, Bruce Hwy 3, Bruce Hwy, Bruce Hwy On Ramp 7 SB between Bruce Hwy On Ramp Bruce Hwy	3066
15	Bruce Hwy SB between Bruce Hwy On Ramp 7 & Pine River Sb - North Coast District/metro District Bound	1662
16	Bruce Hwy SB between Pine River Sb - North Coast District/metro District Boundary & Pine Rivers Bridge?	812

Note 1: Link 1 was excluded for matching purpose.

Table B 2: Probe link length

Link number	Link name	Link length (m)
1	842214565T	40
2	868470953T	937
3	868470952T	136
4	1464592381T	165
5	1464592380T	104
6	767146173T	79
7	778473268T	468
8	1464939194T	21
9	1464939193T	18
10	820977323T	78
11	820977322T	274
12	811762931T	180

Link number	Link name	Link length (m)
13	851414257T	115
14	851414256T	234
15	921052431T	265
16	921052430T	91
17	1464772535T	141
18	1464772534T	657
19	1464591555T	292
20	778396784T	277
21	868555308T	155
22	868555307T	100
23	832988841T	54
24	1464934737T	55
25	1464934735T	448
26	778516049T	35
27	921050866T	89
28	921050865T	312
29	820977327T	41
30	820977326T	119
31	832988848T	109
32	832988847T	147
33	828663839T	653
34	778396812T	53
35	778396814T	48
36	778396813T	223
37	130835863T	108
38	130835862T	67
39	930791855T	885
40	930791854T	210
41	921050868T	217
42	921050867T	380
43	1464775479T	155
44	833097962T	102
45	766859496T	50
46	778396796T	453
47	778396795T	21
48	778396798T	30
49	821044650T	304
50	821044649T	42
51	130835811T	131

Link number	Link name	Link length (m)
52	833097961T	108
53	1074685468T	352
54	1074685471T	419
55	1074685470T	19
56	1464775476T	1010
57	796211561T	60
58	796211563T	21
59	796211562T	17
60	833007430T	796
61	833007429T	128
62	778516026T	306
63	778516025T	22
64	778516028T	24
65	820977319T	227
66	820977318T	97
67	130835754T	122
68	833007426T	113
69	921052429T	480
70	1085675678T	1912
71	833093257T	71
72	833093256T	103
73	767134177T	863
74	130835758T	274
75	1464802010T	361
76	1464802009T	253
77	1464802008T	90
78	1464802007T	104
79	821380431T	19
80	821380430T	114
81	1125601775T	61
82	1125601774T	50
83	833093244T	224
84	1125601777T	190
85	1125601776T	72
86	807425264T	332
87	778396811T	26
88	1132210319T	657
89	1132210318T	716
90	833008696T	111

Link number	Link name	Link length (m)
91	736384928T	75
92	736384927T	326
93	833008703T	146
94	1128830828T	120
95	1129359514T	97
96	1129359513T	1,178
97	1464632037T	31
98	1464632036T	81
99	792653723T	207
100	792653722T	176
101	792653721T	74
102	792653720T	60
103	773246051T	16
104	130838651T	90
105	801204906T	354

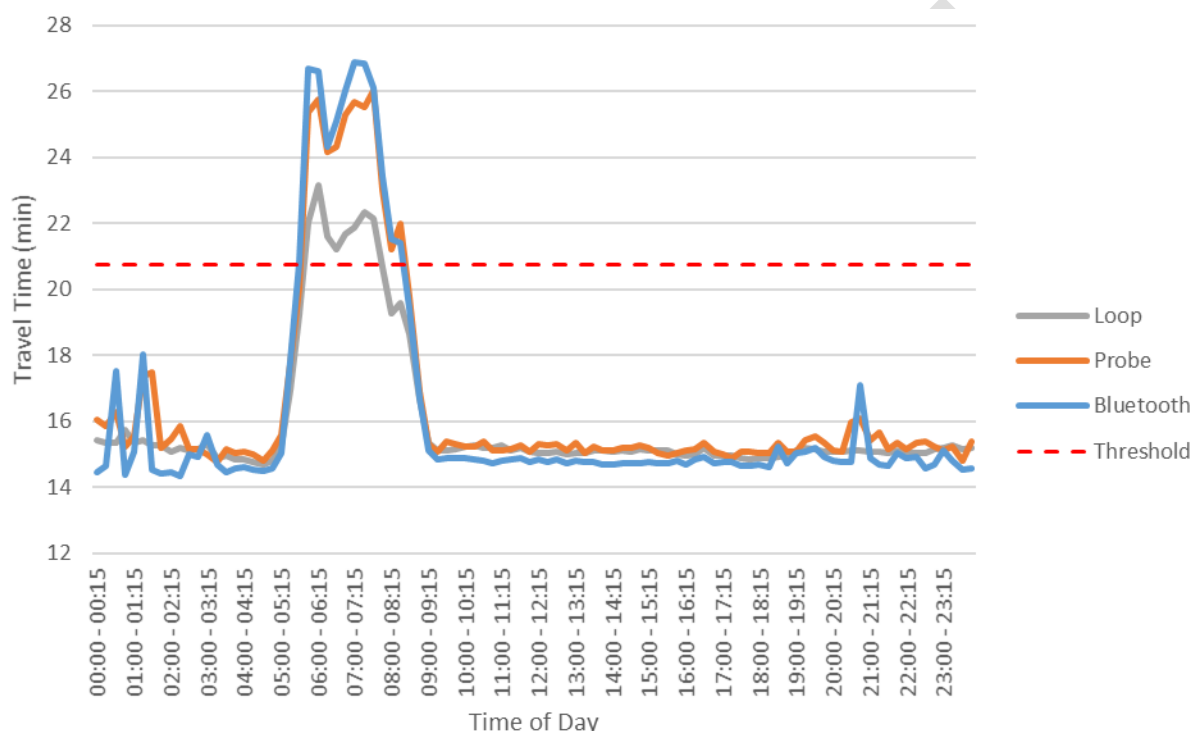
Table B 3: Bluetooth link length

Link number	Link name	Link length (m)
1	1026 to 1019	1,700
2	1019 to 1018	4,000
3	1018 to 1023	1,400
4	1023 to 1017	6,800
5	1017 to 1007	4,600
6	1007 to 1115	2,300
7	1115 to 1015	1,200
8	1015 to 1025	2,000

APPENDIX C AVERAGE THURSDAY TRAVEL TIME

Figure C 1 shows the average travel time of four Thursdays over the study period. It shows that the three data sources followed the same pattern, where the inductive loop data had the lowest values and the probe and Bluetooth data were closer with each other for most of the time. When the data was averaged over the four Thursdays, a second peak at 7:15 am has been picked up by all three data sets.

Figure C 1: Average daily Thursday route travel time



The additional statistical test results (Table C 1) show that:

- On average, the route travel times derived from probe and Bluetooth were 9% and 11% higher than for the inductive loops during peak time (5:00 – 10:00 am) for average Thursdays. During other times (10:00 – 5:00 am), probe travel time was 1% higher and Bluetooth travel time was 1% lower than that of inductive loops. All these differences were statistically significant, which indicates that they were systematic differences.
- The differences between the route travel times obtained from Bluetooth and probe were either not statistically significant or statistically significant but with very small differences. This indicates that route travel times derived from both datasets are aligned quite well.
- The results were consistent with the average weekday comparison in Section 2.5.1.

Table C 1: Route travel time statistical test matrix

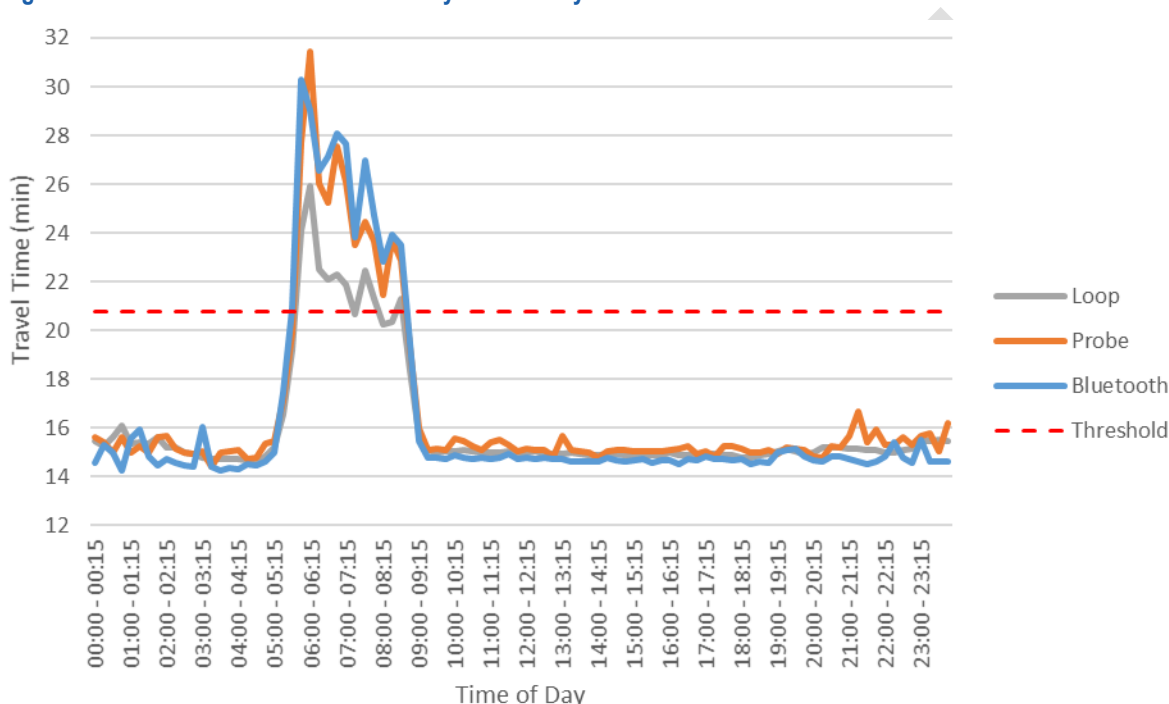
Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Between probe and inductive loop	Peak	9%	2.29	0.986	YES
	Other times	1%	0.45	0.226	YES
	All day	3%	1.12	0.981	YES

Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Between Bluetooth and inductive loop	Peak	11%	2.81	0.98	YES
	Other times	-1%	0.60	0.08	YES
	All day	2%	1.39	0.97	NO
Between Bluetooth and probe	Peak	1%	0.68	0.99	NO
	Other times	-3%	0.67	0	YES
	All day	-2%	0.67	0.98	YES

APPENDIX D A TYPICAL WEEKDAY TRAVEL TIME

Figure D 1 shows the travel time comparison on a typical weekday, Thursday 25 February. It shows that the three data sources followed a similar pattern, where the inductive loop data had lower values while the probe and Bluetooth data were closely aligned for most of the time. The figure indicates that both probe and Bluetooth data had picked up a peak around 7:15 am, however the inductive loop data did not.

Figure D 1: Route travel time for Thursday 25 February



The additional statistical test results (Table D 1) show that:

- On average, the route travel times derived from probe and Bluetooth were 10% and 13% higher than for the inductive loops during peak time (5:00 – 10:00 am). During other times (10:00 – 5:00 am), probe travel time was 1% higher and Bluetooth travel time was 2% lower than for inductive loops. All these differences were statistically significant, which indicates that they were systematic differences.
- The differences between the route travel times obtained from Bluetooth and probe were either not statistically significant or statistically significant but with very small differences. This indicates that route travel times derived from both datasets were aligned quite well.
- The results are consistent with the average weekday comparison in Section 2.5.1.

Table D 1: Route travel time statistical test matrix

Category	Time of comparison	% Difference	RMSD	R ²	Significance test at 95% CL (Y/N)
Between probe and inductive loops	Peak	10%	2.70	0.97	YES
	Other times	1%	0.35	0.23	YES
	All day	3%	1.27	0.98	YES
Between Bluetooth and inductive loops	Peak	13%	3.38	0.96	YES
	Other times	-2%	0.47	0.03	YES
	All day	2%	1.60	0.97	NO
Between Bluetooth and probe	Peak	2%	1.24	0.96	NO
	Other times	-2%	0.64	0.004	YES
	All day	-2%	0.81	0.97	YES

APPENDIX E INCIDENT DAY BLUETOOTH DATA ANALYSIS

Section 2.5.4 identified that Bluetooth data appeared to underestimate the route travel time significantly during peak time on the day of the incident on Friday 4 March 2016. To further investigate this issue, a comparison of Bluetooth link travel time between a normal Friday and the day of the incident was conducted. Travel times for the eight Bluetooth links on the day of the incident are plotted in Figure E.1. Travel times for the eight Bluetooth links on a normal Friday (26 February 2016) are plotted in Figure E.2. Note that Bluetooth links 6 and 7 and a small part of link 8 (loop links 14 and 15) were the locations where the incident occurred.

A comparison between Figure E 1 and Figure E 2 shows that:

- On a normal Friday, the travel time for Bluetooth links 1 to 4 appeared to be consistent between peak and off-peak times, which means there were no obvious bottlenecks along these links during the morning peak. The morning peak congestion started at about 5:30 am for links 5 and 6, and at about 6:30 am for links 7 and 8. In general, the congestion level on a normal Friday was not so significant. This is also consistent with findings from Table 2.7, which shows that route travel time (measured from the three data sources) for an average Friday was the shortest of all weekdays.
- On the day of the incident, the travel time for Bluetooth links 1 to 3 showed the same pattern as the normal day. The delay was picked up by links 4 and 5 between 6:15 to 10:30 am. However, link 5 data were very volatile between 6:15 – 7:15 am, and appeared to underestimate the excessive delay. For links 6 and 7 (loop link 14), some delays were identified between 5:30 and 10:15 am; although travel times during this period were higher than for a normal Friday, they were still significantly lower than the travel times measured by probes or loops as shown in Figure 2.11. Link 8 was able to pick up some delay between 6:30 and 9:00 am.
- Further investigation of Bluetooth data quality on the incident day (Table E.1) showed that during the morning peak, 15%, 40% and 35% of data cells was empty for the three links 5, 6 and 7. Note that for normal weekdays, only about 0.06% of Bluetooth data cells were empty during the morning peak. As the empty data cells were filled by free-flow speed travel time, it was likely that these data were the key reason that Bluetooth was unable to pick up the full range of delays during the morning peak.

Figure E 1: Incident day (4 March 2016) link-by-link travel time for Bluetooth

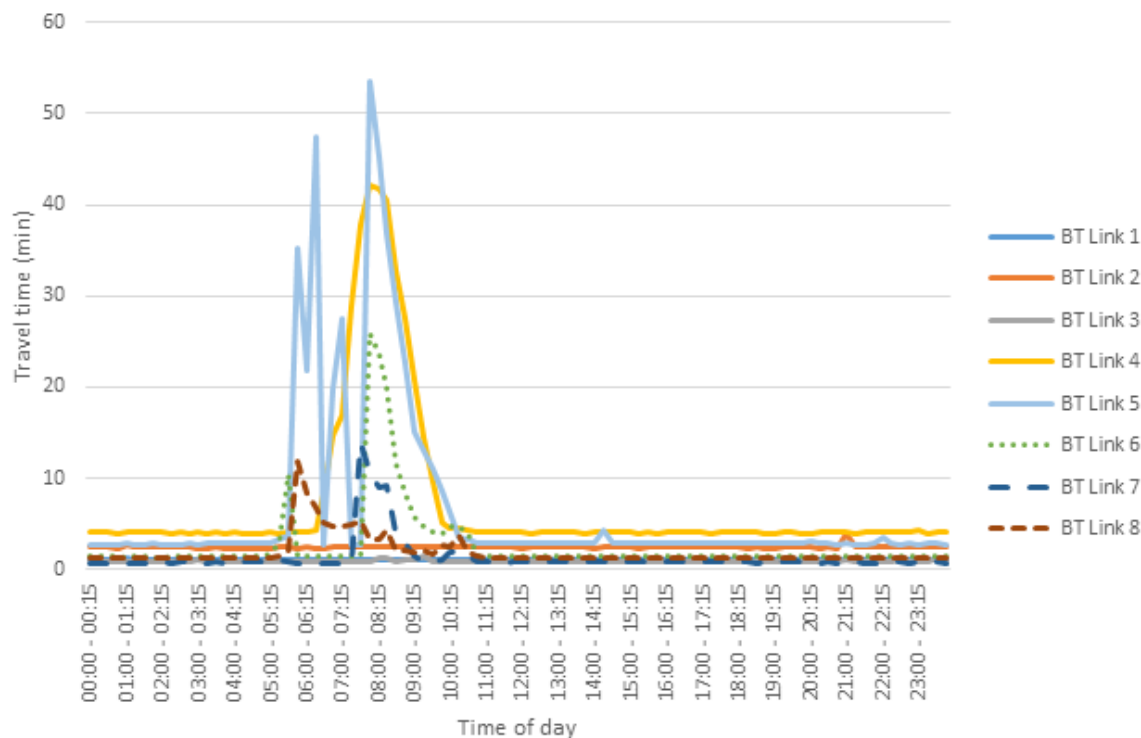


Figure E 2: A normal Friday (26 February 2016) link-by-link travel time for Bluetooth

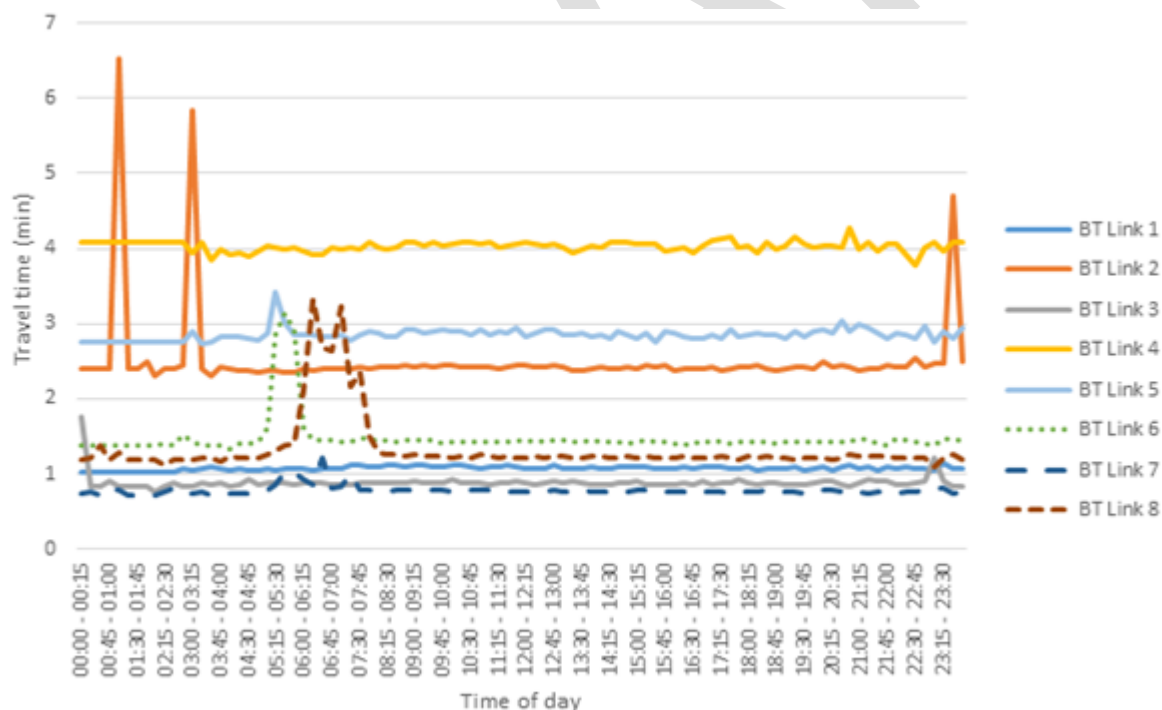


Table E 1: Percentage of missing Bluetooth data on the incident day

		Peak time (5 – 10 am)							
		Link 1	Link 2	Link 3	Link 4	Link 5	Link 6	Link 7	Link 8
Empty data cells		0	0	0	0	3	8	7	0
All available data cells		20	20	20	20	20	20	20	20
Percentage		0%	0%	0%	0%	15%	40%	35%	0%
		Other time (10 – 5 am)							
		Link 1	Link 2	Link 3	Link 4	Link 5	Link 6	Link 7	Link 8
Empty data cells		15	10	8	15	12	10	7	8
All available data cells		76	76	76	76	76	76	76	76
Percentage		20%	13%	11%	20%	16%	13%	9%	11%
All day	Empty data cells	103							
	All available data cells	768							
	Percentage	13%							

APPENDIX F DAILY EXCESSIVE CONGESTION COSTS

Table F 1: Daily congestion cost from inductive loop data

Date (in 2016)	Excessive delay cost (\$)	Reliability cost (\$)
Monday, 15 February	44,246	39,231
Tuesday, 16 February	15,736	41,072
Wednesday, 17 February	25,909	40,484
Thursday, 18 February	34,183	40,529
Friday, 19 February	21,929	40,399
Saturday, 20 February	7,762	8,460
Sunday, 21 February	335	5,375
Monday, 22 February	41,862	38,034
Tuesday, 23 February	26,505	39,921
Wednesday, 24 February	22,267	39,216
Thursday, 25 February	31,397	40,063
Friday, 26 February (note1)	4,061	40,050
Saturday, 27 February	0	9,595
Sunday, 28 February	1,232	5,571
Monday, 29 February	36,267	37,967
Tuesday, 1 March	26,349	39,009
Wednesday, 2 March	24,495	40,031
Thursday, 3 March	16,476	39,508
Friday, 4 March		
Saturday, 5 March	0	9,959
Sunday, 6 March	763	4,923
Monday, 7 March	50,924	34,552
Tuesday, 8 March	45,064	36,363
Wednesday, 9 March	47,050	35,965
Thursday, 10 March	27,602	38,789
Friday, 11 March		
Saturday, 12 March	0	9,733
Sunday, 13 March	40	5,171

Note 1:

- The excessive delay costs on Friday 26 February appeared much lower than other weekdays from all three sources. The raw speed data for the three sources were checked and they were consistently high (rarely dropping below 70 km/h) for that particular Friday.
- However, the reliability cost on Friday 26 February was still quite high and was consistent with other weekdays from all three sources. The reason is that buffer time is calculated by using the whole month route travel time distribution, and it should remain constant every day for the same time intervals. The reliability cost only varies depending on traffic volume changes day-by-day for each of the 15-minute intervals.

Table F 2: Daily congestion cost from probe data

Date (in 2016)	Excessive delay cost (\$)	Reliability cost (\$)
Monday, 15 February	67,134	54,234
Tuesday, 16 February	25,898	56,677

Date (in 2016)	Excessive delay cost (\$)	Reliability cost (\$)
Wednesday, 17 February	49,789	55,975
Thursday, 18 February	57,139	55,908
Friday, 19 February	32,060	56,041
Saturday, 20 February	14,892	12,702
Sunday, 21 February	1,379	7,110
Monday, 22 February	67,552	51,705
Tuesday, 23 February	41,001	54,795
Wednesday, 24 February	36,736	53,775
Thursday, 25 February	49,349	54,736
Friday, 26 February (note 1)	6,659	55,017
Saturday, 27 February	6	14,154
Sunday, 28 February	1,178	6,762
Monday, 29 February	55,584	51,726
Tuesday, 1 March	40,043	53,699
Wednesday, 2 March	39,194	55,417
Thursday, 3 March	28,124	54,507
Friday, 4 March		
Saturday, 5 March	10	14,452
Sunday, 6 March	2,373	6,609
Monday, 7 March	70,892	47,000
Tuesday, 8 March	63,010	49,685
Wednesday, 9 March	66,422	48,847
Thursday, 10 March	44,192	52,895
Friday, 11 March		
Saturday, 12 March	7	13,447
Sunday, 13 March	502	6,499

Note 1:

- The excessive delay costs on Friday 26 February appeared much lower than other weekdays from all three sources. The raw speed data for the three sources were checked and they were consistently high (rarely dropping below 70 km/h) for that particular Friday.
- However, the reliability cost on Friday 26 February was still quite high and was consistent with other weekdays from all three sources. The reason is that buffer time is calculated by using the whole month route travel time distribution, and it should remain constant every day for the same time intervals. The reliability cost only varies depending on traffic volume changes day-by-day for each of the 15-minute intervals.

Table F 3: Daily congestion cost from Bluetooth data

Date (in 2016)	Excessive delay cost (\$)	Reliability cost (\$)
Monday, 15 February	64,513	52,198
Tuesday, 16 February	25,783	54,967
Wednesday, 17 February	46,345	54,044
Thursday, 18 February	53,862	53,667
Friday, 19 February	31,141	53,947
Saturday, 20 February	12,723	14,763
Sunday, 21 February	1,417	6,212

Date (in 2016)	Excessive delay cost (\$)	Reliability cost (\$)
Monday, 22 February	68,790	53,935
Tuesday, 23 February	40,154	55,728
Wednesday, 24 February	35,307	57,118
Thursday, 25 February	49,126	55,962
Friday, 26 February (note 1)	5,987	57,811
Saturday, 27 February	0	17,055
Sunday, 28 February	504	6,061
Monday, 29 February	49,621	53,991
Tuesday, 1 March	42,157	55,143
Wednesday, 2 March	36,921	56,990
Thursday, 3 March	25,566	57,919
Friday, 4 March		
Saturday, 5 March	91	18,247
Sunday, 6 March	1,165	5,952
Monday, 7 March	85,133	50,558
Tuesday, 8 March	67,921	52,641
Wednesday, 9 March	70,914	51,881
Thursday, 10 March	40,797	55,064
Friday, 11 March		
Saturday, 12 March	168	17,241
Sunday, 13 March	486	5,854

Note 1:

- The excessive delay costs on Friday 26 February appeared much lower than other weekdays from all three sources. The raw speed data for the three sources were checked and they were consistently high (rarely dropping below 70 km/h) for that particular Friday.
- However, the reliability cost on Friday 26 February was still quite high and was consistent with other weekdays from all three sources. The reason is that buffer time is calculated by using the whole month route travel time distribution, and it should remain constant every day for the same time intervals. The reliability cost only varies depending on traffic volume changes day-by-day for each of the 15-minute intervals.

APPENDIX G DAILY VKT FOR THE THREE DATA SOURCES

Table G 1: Estimated daily VKT based on inductive loop links

Date (in 2016)	VKT
Monday, 15 February	1,278,034
Tuesday, 16 February	1,284,640
Wednesday, 17 February	1,305,556
Thursday, 18 February	1,341,220
Friday, 19 February	1,430,408
Saturday, 20 February	1,279,021
Sunday, 21 February	1,314,083
Monday, 22 February	1,279,389
Tuesday, 23 February	1,282,859
Wednesday, 24 February	1,302,243
Thursday, 25 February	1,343,224
Friday, 26 February	1,410,136
Saturday, 27 February	1,221,684
Sunday, 28 February	1,247,299
Monday, 29 February	1,270,155
Tuesday, 1 March	1,255,298
Wednesday, 2 March	1,276,050
Thursday, 3 March	1,308,086
Friday, 4 March	
Saturday, 5 March	1,176,484
Sunday, 6 March	1,222,228
Monday, 7 March	1,256,217
Tuesday, 8 March	1,247,193
Wednesday, 9 March	1,247,832
Thursday, 10 March	1,326,111
Friday, 11 March	
Saturday, 12 March	1,227,843

Table G 2: Estimated Daily VKT based on probe links

Date (in 2016)	VKT
Monday, 15 February	1,286,238
Tuesday, 16 February	1,293,087
Wednesday, 17 February	1,313,987
Thursday, 18 February	1,349,894

Date (in 2016)	VKT
Friday, 19 February	1,439,566
Saturday, 20 February	1,286,213
Sunday, 21 February	1,320,753
Monday, 22 February	1,287,124
Tuesday, 23 February	1,290,698
Wednesday, 24 February	1,310,333
Thursday, 25 February	1,351,304
Friday, 26 February	1,418,686
Saturday, 27 February	1,228,820
Sunday, 28 February	1,253,908
Monday, 29 February	1,277,941
Tuesday, 1 March	1,263,307
Wednesday, 2 March	1,283,998
Thursday, 3 March	1,316,089
Friday, 4 March	
Saturday, 5 March	1,183,621
Sunday, 6 March	1,228,798
Monday, 7 March	1,263,977
Tuesday, 8 March	1,254,965
Wednesday, 9 March	1,255,688
Thursday, 10 March	1,334,333
Friday, 11 March	
Saturday, 12 March	1,334,333

Table G 3: Estimated daily VKT based on Bluetooth links

Date (in 2016)	VKT
Monday, 15 February	1,192,279
Tuesday, 16 February	1,192,168
Wednesday, 17 February	1,211,940
Thursday, 18 February	1,248,133
Friday, 19 February	1,345,163
Saturday, 20 February	1,210,434
Sunday, 21 February	1,270,074
Monday, 22 February	1,215,597
Tuesday, 23 February	1,212,863
Wednesday, 24 February	1,243,499
Thursday, 25 February	1,271,774
Friday, 26 February	1,358,112
Saturday, 27 February	1,184,460

Date (in 2016)	VKT
Sunday, 28 February	1,232,317
Monday, 29 February	1,218,910
Tuesday, 1 March	1,201,841
Wednesday, 2 March	1,224,044
Thursday, 3 March	1,259,114
Friday, 4 March	
Saturday, 5 March	1,131,829
Sunday, 6 March	1,192,686
Monday, 7 March	1,208,939
Tuesday, 8 March	1,194,316
Wednesday, 9 March	1,193,690
Thursday, 10 March	1,264,412
Friday, 11 March	
Saturday, 12 March	1,179,929

Figure G 1: Daily VKT comparison

