FINAL REPORT

Project Title: R22 Measuring On-road Congestion Costs for Multi-modal Travel - Methodology (2014/15 - 2015/16)

Project No: 010580

Author/s: Dr James Luk, Dr Clarissa Han, Michael Byrne

Client: Queensland Department of Transport and Main Roads

Date: August 2016

SUMMARY

Austroads, ARRB and TMR have researched and implemented the measurement of vehicle-based congestion costs. The purpose of Project R22 is to produce a methodology for estimating congestion costs associated with road users that include cars, heavy vehicles (HVs), buses, cyclists and pedestrians. Two case studies, one for bus delay cost estimation and one for freeway before-and-after congestion cost comparison will also be conducted to test the methodology.

This is the first-year report for Project R22 and it documents the main findings from a literature review and also proposes the methodology framework for congestion cost estimation for multiple road users.

The key findings from the first-year work are as follows:

- Total congestion cost is defined as the sum of excessive travel time delay cost and travel time reliability cost. The excessive travel delay is estimated by comparing prevailing travel times (or speeds) with reference travel times (or reference speeds). Passenger waiting times at a bus stop are also considered in the bus delay cost framework. A few commonly used metrics for the measurement of travel time reliability were reviewed and the buffer time method has been recommended. Buffer time is the additional time commuters allow for their journey to arrive on time and is estimated as the difference between the 95th percentile and 50th percentile travel times.
- Online traffic data is available for the proposed two study routes of Bruce Highway and Gympie Road. Bus arrival times, bus travel times between two bus stops and passenger waiting times are to be estimated from automatic ticketing transaction time data, sourced from the TMR *go* card system for buses. Four-bin vehicle classified counts from inductive loop detectors are available from freeways such as the Bruce Highway.
- There are insufficient sensors for the detection of pedestrians and cyclists on a road network for online congestion analysis. The report proposes offline analysis frameworks for the comparison of delays to pedestrians and cyclists in before-and-after studies. For example, this will estimate pedestrian delay reduction due to less vehicular traffic on an arterial road and reduced signal cycle times subsequent to traffic diverted to a new adjacent freeway bypass.

It is recommended that the second year of the project should focus on the application of the methodology by using data retrieved from the *go* card ticketing system and freeway inductive loop detector stations. Two separate reports will be produced for the two case studies

Although the Report is believed to be correct at the time of publication, ARRB Group Ltd, to the extent lawful, excludes all liability for loss (whether arising under contract, tort, statute or otherwise) arising from the contents of the Report or from its use. Where such liability cannot be excluded, it is reduced to the full extent lawful. Without limiting the foregoing, people should apply their own skill and judgement when using the information contained in the Report.

ACKNOWLEDGEMENTS

This project received funding under the *National Assets Centre of Excellence* (NACOE) program and direct funding from TMR. It was managed by Katherine Johnston, and also by Miranda Blogg at the beginning of the project.

CONTENTS

1 INTRODUCTION 1

2 LITERATURE REVIEW 3

2.1 Definition of Excessive Congestion Delay 3

2.2 Multi-modal Level of Service (MMLOS) 4
  2.2.1 Austroads Research into MMLOS 4
  2.2.2 HCM2010 Congestion Estimation and Measurement Methods 5
  2.2.3 Other Multi-modal Congestion Estimation and Measurement Methods 5

2.3 Travel Time Reliability 6
  2.3.1 Importance of Travel Time Reliability 6
  2.3.2 Defining Travel Time Reliability 6
  2.3.3 Costing Travel Time Reliability 7
  2.3.4 Aggregation of Excessive Congestion Delay and Travel Time Reliability 10
  2.3.5 Possible Components of Bus Delay Cost 12

2.4 Review and Update of Unit Travel Time Costs 12

3 CONGESTION DELAY COST ESTIMATION FRAMEWORK FOR FOUR VEHICLE CLASSES 15

3.1 Link Level Analysis 15

3.2 Route Level Analysis 18

4 CONGESTION DELAY COST ESTIMATION FRAMEWORK FOR BUSES 19

5 OFFLINE CONGESTION DELAY ESTIMATION FRAMEWORK FOR PEDESTRIANS AND CYCLISTS 23

5.1 Pedestrians 23

5.2 Cyclists 24

6 CONCLUSIONS AND RECOMMENDATIONS 25

6.1 Conclusions 25

6.2 Recommendations 25

REFERENCES 27

APPENDIX A EXAMPLES OF PREVIOUS RESEARCH ON RELIABILITY RATIOS 29
APPENDIX B UNIT TRAVEL TIME COST IN TRANSPORT AND INFRASTRUCTURE COUNCIL (2015) 31

TABLES

Table 2.1: Reference speeds expressed as a percentage of speed limits 4
Table 2.2: More examples of reliability ratio 9
Table 2.3: Applicability of buffer times for different trip purposes 9
Table 2.4: Unit cost for travel time (in 2013 Australian $) 13
Table 3.1: Offline input data for delay cost estimation for four vehicle classes 15
Table 3.2: Calculation of link delay costs for four vehicle classes 16
Table 3.3: Calculation of link reliability costs for four vehicle classes 17
Table 4.1: Framework for the online calculation of congestion delay cost for buses 21
Table 5.1: Congestion delay estimation framework for pedestrians 23
Table 5.2: Congestion delay estimation framework for cyclists 24
Table 6.1: Project tasks for 2015/16 26

FIGURES

Figure 2.1: The day-to-day travel time distribution for defining reliability metrics 8
Figure 2.2: Aggregation of excessive delay and travel time reliability cost 11

1 INTRODUCTION

Austroads, ARRB and Department of Transport and Main Roads (TMR) have researched and implemented the measurement of vehicle-based congestion costs (Austroads 2009a and 2009b, Dekker et al. 2015, TMR 2015a). The purpose of Project R22 is to produce a methodology for estimating congestion costs associated with a range of road users and confirm this methodology through pilot case studies.

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

The TMR cost-of-congestion tool has been developed as an initiative under the *Congestion Management Approach for Queensland* to analyse the user delay costs associated with network congestion. The intention is for this tool to be used to benchmark performance and undertake ex-post assessments of projects to determine their congestion cost impacts. During the recent proof-of-concept phase at TMR, a number of refinements to the tool were proposed, one of which is to extend the tool to capture the costs of all road-based modes as opposed to the vehicle-based methodology currently used. The inclusion of all modes would provide a more complete understanding of user costs, as well as possibly providing whole-of-network congestion costs for Brisbane.

Understanding the economic cost of traffic congestion is an important part of developing the appropriate response strategies for congestion management. The inclusion of modes other than vehicle-only travel enables a better balance when considering the merit of a given project, for example, widening a road may decrease cost to one user group but increase cost to other road users. Project R22 would enhance the TMR cost-of-congestion tool, which will be used to inform investment, benchmark performance, and to test and evaluate the effectiveness of congestion reduction options.

Project R22 is a two-year project and the main tasks are:

- The first year (2014-15) of the project aimed to provide a literature review and investigate available multi-modal congestion measurement methods. A methodology framework was also to be proposed for estimating congestion costs associated with multi-modal road users.
- The second year (2015-16) focuses on the refinement of the measurement method and its implementation through two pilot case studies. Data from STREAMS and automatic bus ticketing systems (such as the *go* card system) will be collected and analysed.

The measurement of the congestion costs of HVs, buses, pedestrians and cyclists is a complex issue and seldom carried out in an automatic, online manner. In particular, the lack of sensors for the detection of pedestrians and cyclists makes it difficult to monitor the congestion costs associated with these modes automatically.

It is therefore useful to limit the project scope as follows:

- On-road public transport is limited to buses.
- Congestion cost is initially time delay cost, with environmental and vehicle operating costs similar to those in Austroads (2009a) considered at a later stage.

- Wherever possible, traffic counts are classified into four classes or bins according to length as follows (Austroads 2006):
  - short vehicles (< 6 m)
  - medium vehicles (6 m ≤ length < 13 m)
  - long vehicles (13 m ≤ length < 21 m)
  - combination vehicles (≥ 21 m).
- As mentioned, delay or other costs of pedestrians and cyclists are unlikely to be measured online due to the lack of sensors for their detection, but can be estimated offline in before-after studies.

This report constitutes the first-year report and provides the following information:

- problem statement, motivation, contents and project scope (Section 1)
- literature review on congestion-related concepts and measures including the definition of congestion delay, multi-modal level of service (MMLOS), travel time reliability and unit travel time costs (Section 2)
- congestion delay cost measurement framework for four vehicle classes (Section 3)
- congestion delay cost measurement framework for buses (Section 4)
- congestion delay cost measurement frameworks for pedestrians and cyclists (Section 5)
- conclusions and recommendations (Section 6).

2 LITERATURE REVIEW

This section provides the following reviews:

- definition of excessive congestion delay (Section 2.1)
- description of MMLOS framework research by Austroads and others Section 2.2)
- reliability (i.e. variability) of travel times (Section 2.3)
- review and update of unit travel time costs (Section 2.4).

The information from these reviews is used for the development of the congestion cost measurement frameworks in Section 3 to Section 5.

2.1 Definition of Excessive Congestion Delay

The excessive congestion delay has been reported in BTRE (2007), Austroads (2009a) and Dekker et al. (2015). It is the *extra delay* cost or *excessive delay* cost with reference to an optimal (spatial) speed for a road user group (spatial speed is the inverse of travel time), rather than the free-flow speed or the posted speed limit. The traffic flow at this optimal speed leads to maximum overall road user benefit and is closely linked to the speed before flow breakdowns in a traffic facility.

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

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

Austroads (2009a) also discussed possible options for proposing the optimal reference speeds, such as using volume-capacity ratios for freeways and using empirically determined speed-flow functions for arterials.

It is debatable if the excessive congestion delay captures more non-recurrent congestion, and further research would be required to validate and clarify the sources of excessive congestion delays.

Table 2.1 shows initial reference speeds that can be used for the estimation of excessive congestion delay. The reference speeds are expressed as a percentage of the speed limits but can be converted to absolute values as required by the relevant implementation software (see also Table 3.1).

Table 2.1: Reference speeds expressed as a percentage of speed limits

Road user or vehicle classes	Reference speeds as a % of speed limits	
	Freeways	Arterials
Short vehicles	70	55
Medium vehicles/HVs	70	55
Long vehicles/HVs	70	55
Combination HVs	60 (Note 1)	55
Buses	70	See Section 4

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

Section 3 and Section 4 provide further information on the measurement of excessive congestion delay for different road users or vehicle classes that would be used in Project R 22.

2.2 Multi-modal Level of Service (MMLOS)

The concept of level of service (LOS) is therefore quite well-defined and has been used for road traffic design and operation since the 1950s. The measurement of LOS and the measurement of congestion costs are related. Apart from the key measure of travel times (or space speeds), LOS measures can include reliability of travel times, space and comfort for pedestrians, or accessibility and connectivity for cyclists.

The costing of space or comfort is subjective and open to debate. The initial focus for this project is to address delay time and reliability of travel times. The need to review the concept of MMLOS was raised at an R22 project meeting in July 2014 and a brief review is given below to provide a broad context for congestion cost estimation.

2.2.1 Austroads Research into MMLOS

The latest LOS framework for network operation planning is shown in *Level of service metrics for network operation planning* (Austroads 2015). The framework aims to balance the priorities given to different road users in a road network. It consists of the following four elements:

- user groups (private motorist, public transport user, pedestrian, cyclist, freight vehicles)
- five common LOS needs or requirements associated with each user group (mobility, safety, access, information, activity)
- specific service measures associated with each road user need, e.g. congestion, travel time reliability and travel speed are associated with the mobility need of a private motorist
- service (measure) values are *subjective ratings* associated with each service measure at each LOS grade from A to F, e.g. congestion can be E for a situation subjectively judged to be near-saturation.

The Austroads Assets Program also carries out research on LOS for asset management. At a strategic level, both a road asset manager and a traffic manager share the same goal of providing safe and efficient movement of people and freight in a road network. An asset manager generally pays attention to road conditions such as roughness, rutting, texture or bridge strength, and also to road configurations and traffic facilities that are of concern also to a traffic manager.

Two current Assets Program projects relevant to MMLOS are as follows:

- AT1732 - *Level of Service Requirements for Freight on Rural Roads*
- AT1737 - *Level of Service Requirements for Non-freight Customers*.

2.2.2 HCM2010 Congestion Estimation and Measurement Methods

The concept of LOS, as defined in the latest edition of the US *Highway Capacity Manual* or HCM 2010 (TRB 2010) is as follows:

> LOS is a quantitative stratification of a performance measure or measures that represent quality of service. The LOS concept facilitates the presentation of results, through the use of a familiar A (best) to F (worse) scale. LOS is defined by one or more service measures that both reflect the traveller perspective and are *useful to operating agencies.*

In HCM2010, LOS measures and their service values are reported separately for different road facilities, and for different transport modes including walking, cycling and public transport. Some other modes, such as large trucks, recreational vehicles, and motorcycles are considered members of the automobile model for HCM analysis.

HCM2010 incorporated the results of considerable research activity undertaken in the decade since the publication of the previous 2000 edition, funded under the National Cooperative Highway Research Program (NCHRP) (see, e.g. Dowling Associates 2008). The NCHRP research work further recognised that user perceptions are heavily influenced by non-operational factors, such as environmental and aesthetic considerations – especially for pedestrians and cyclists. For example, additional factors contributing to the perceived LOS for pedestrian facilities include:

- comfort (weather protection, climate control, shelter)
- convenience (walking distance, path directions, grades, signing information)
- economy (costs from delays and queuing)
- safety (physical and temporal separation from vehicular traffic)
- security (lighting, open sight lines).

An overall blended LOS score for all modes is not calculated in HCM2010. The HCM2010 LOS for pedestrians and cyclists has moved away from efficiency-based LOS measures (speed, delay, etc.) to those related more to road user perceptions (comfort, safety, and security etc.).

For Project R22, the focus is on the congestion cost as it aims to aggregate congestion costs from multiple modes by using monetary values.

2.2.3 Other Multi-modal Congestion Estimation and Measurement Methods

The multi-modal LOS approach and framework have been used for network operations planning in a few jurisdictions such as:

- SmartRoads LOS framework in *Network fit assessment manual* (VicRoads 2012)
- LOS framework used in the *Christchurch network management plan* (NZTA 2013)
- LOS framework used in the TMR *Pedestrian crossing facility guidelines and prioritisation system user guide – Traffic and road use management* volume 1 Part 6 (TMR 2015b)
- ARRB/TMR *Level-of-service model for bicycle riders* (Munro 2013).

For cyclists' LOS, VicRoads (2012) has moved to non-delay-based measure. Travel delay, however, remains the prominent LOS measure in NZTA (2013) and TMR (2015b) for all modes including pedestrians and cyclists.

2.3 Travel Time Reliability

2.3.1 Importance of Travel Time Reliability

The costing of the reliability or variability of travel times has received considerable attention in recent years in both freight and passenger transport (e.g. Austroads 2011, de Jong & Bliemer 2015).

It has been widely recognised that travellers not only take experienced travel time into account, but also travel time reliability (de Jong and Bliemer 2015). In the presence of travel time unreliability, travellers typically allow more time for their trips in order to reduce the possibility of arriving late to their destination. Reducing the unreliability (in other words, increasing the travel time reliability) means that this extra time allowance could be decreased or avoided completely, presenting a clear user time benefit. It has been argued that unit costs of travel time unreliability are about the same magnitude as travel time costs. Therefore, in project cost benefit analysis (CBA) there may not only be user benefits in terms of travel time savings, but also in terms of travel time reliability improvement.

The NCHRP Report 431 *Valuation of travel time savings and predictability in congested conditions for highway user-cost estimation* (Small et al. 1999) identified that both passenger and freight carriers were strongly adverse to the scheduling mismatches that occur because they cannot predict precisely what their travel time will be. The penalties for late arrival for freight carriers may be greater than the benefit of reduced travel time. These penalties can represent actual loss of income or non-pecuniary effects that can lead to eventual loss of income. For these reasons, they might pay a premium to avoid congestion and to achieve greater reliability in travel times.

Fosgerau and Karlstrom (2009) reported a Danish study that was based on measured travel time data from a congested radial urban road in Greater Copenhagen and used a simple probability model to estimate travel time unreliability. It found that travel time uncertainty could account for about 15% of time costs on a typical urban road.

US Department of Transportation has recently published a practical guide *Incorporating Travel Time Reliability into the Congestion Management Process: A Primer* (Dowling et al. 2015). It reported that travel time reliability is a metric that is important to and innately understood by travellers and shippers. Variable or unpredictable travel times make it more difficult for travellers and shippers to plan their travel, often forcing them to add extra time to protect themselves against the uncertainty of arrival times. This uncertainty may lead to ineffective or even counterproductive travel decisions that waste time and money.

Dowling et al. (2015) provides important guidelines on how to incorporate travel time reliability into the congestion management process such as setting reliability performance measures and objectives (e.g. operation objectives on delay, buffer index, planning time index, travel time etc.), diagnosing causes of reliability problems, generating strategies for addressing reliability and evaluation of strategies.

2.3.2 Defining Travel Time Reliability

Dowling et al. (2015) defined that travel-time reliability is consistent travel times for the same trip as measured day-to-day or across different times of the day. If trip times are inconsistent, the travel time is considered to be unreliable, because it is difficult to generate consistent and accurate estimates for it.

In Australian Transport Council (2006), travel time reliability is defined as the unpredictable variations in journey times, which are experienced for a journey undertaken at broadly the same time every day. The impact is related to the day-to-day variations in traffic congestions, typically as a result of day-to-day variations in flow. However, the variation does not account for the delays that may result from major incidents on the road network.

The Austroads national performance indicator (NPI) program also measures the variability/reliability of route speeds and route travel times by calculating the coefficient of variation, which is the ratio of standard deviation to the mean (Austroads 2009b, 2016). The meaning of reliability here is the percentage of additional time (compared to mean travel time) that users would need to ensure that they could arrive on time.

Section 2.3.3 provides further discussion on using different methods to calculate the value of travel time reliability.

2.3.3 Costing Travel Time Reliability

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

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

De Jong and Bliemer (2015) reported that governments from all over the world are currently considering including travel time reliability benefits in project appraisals. However, only a few countries (such as Australia and New Zealand) have included travel time reliability explicitly in CBA. Australian Transport Council (2006) and New Zealand Transport Agency (2010) adopted the SD of travel times as a measure of travel time unreliability.

The following discussion provides some explanation of two commonly used methods of measuring reliability.

Reliability ratio (RR) method

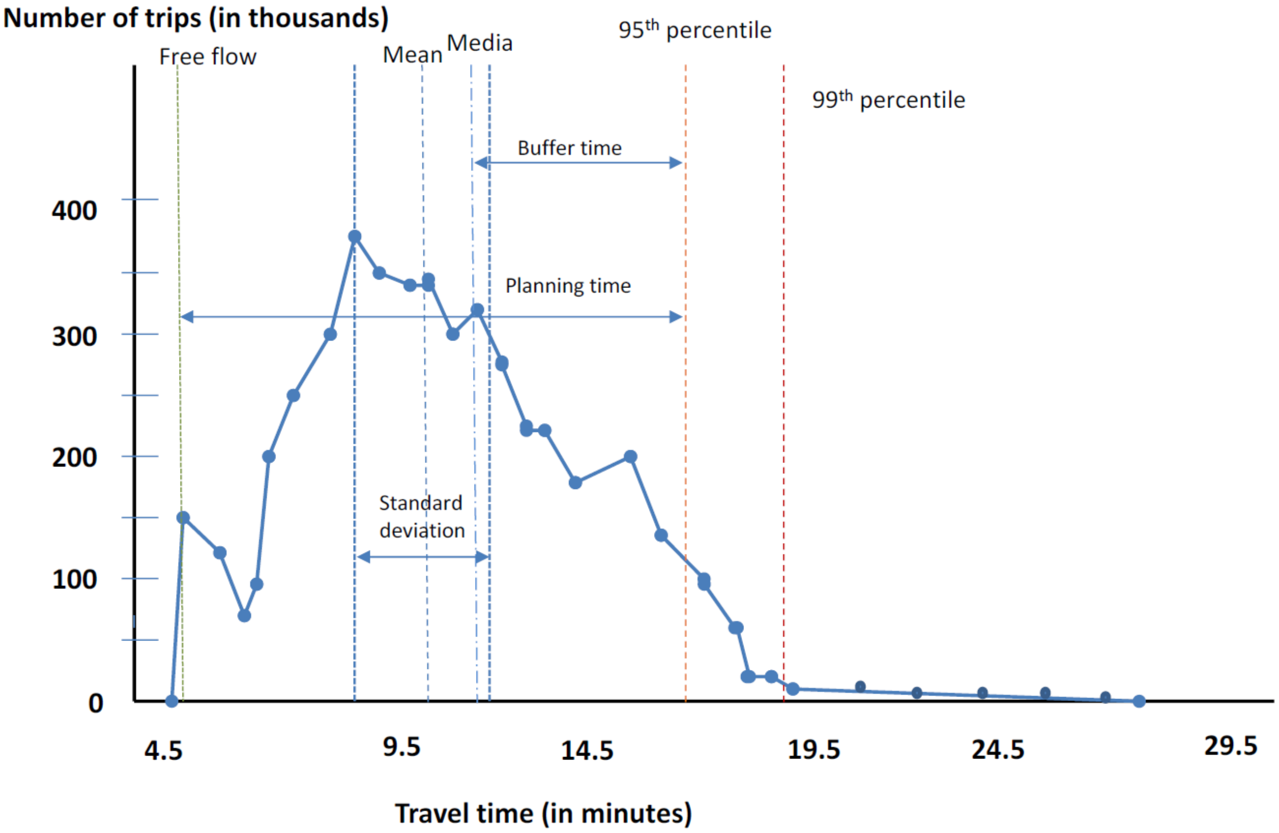
RR is defined as the ratio of the cost of reliability/variability (COR) to the cost of travel time delay (COT). The RR can then be used as a multiplier for travel time measurements.

Cambridge Systematics (2012) did a review (in draft) on the reliability ratios from a much broader perspective and reported that they could range from 0.50 to 2.69 for personal car use. The COR could be estimated by using SD, $90_{th} – 50_{th}$ percentile, SD per unit distance etc. Table A.1 in

Appendix A shows some examples that were identified. de Jong and Bliemer (2015) reviewed empirical findings on the RRs by using SD method to estimate COR and found that the RR could range from 0.4 to 1.3 for different users including commuters, business, shoppers etc. The RRs also vary significantly in research from different countries and short and long trips as shown in Table A.2 of Appendix A.

Figure 2.1 shows an example of travel time distribution derived from freeway detector data, and how it can be used to define reliability metrics such as SD, 95th percentile, mean, median and buffer time etc. (Cambridge Systematics 2012). The shape of the distribution in Figure 2.1 is typical of what is found on freeways, and it is skewed toward higher travel times. The skew is reflective of the impacts of disruptions such as incidents, weather events, work zones, and fluctuating/high demand traffic flow.

Figure 2.1: The day-to-day travel time distribution for defining reliability metrics



Source: Adapted from Cambridge Systematics (2012)

Some more examples of the RRs of multi-model users based on trip types are shown in Table 2.2.

Table 2.2: More examples of reliability ratio

Country	Reliability ratio (RR)	Trip type
Netherlands	0.8 1.4 1.24	Personal car Bus and train Freight transport
New Zealand	0.8	Personal car
Australia: - Li, Henscher & Rose (2010) - Wang (2014)	 0.7 1	 Personal car Personal car
Sweden	0.9	All trip types
Canada	1.0	All trip types

Sources: Adapted from Cambridge Systematics (2012).

With RR, the total congestion delay cost for a study site could be obtained by multiplying COT by a factor equal to (1 + RR).

Australian Transport Council (2006) reported that based on literature research, the RR value (using the SD method) around 1.3 appeared plausible for car travel, somewhat higher values may be appropriate for scheduled public transport, but values above 2 were unlikely. In practice, this means that if the value of travel time per vehicle assumed for a benefit-cost-analysis (BCA) is $10 per hour, then reliability improvements could be valued at $13 per vehicle per hour reduction in the SD of travel time.

Buffer time method

Another practical approach for the costing of the reliability of travel times is the use of a *buffer time*. Wang (2014) contains a description of the road travel time reliability model for New South Wales. It explains the buffer time (defined as the 95th percentile minus the median of the travel time distribution) as a function of day-to-day traffic variation and road incidents (including the likelihood of being impacted by an incident and incident delay).

Buffer time = 95th percentile arrival time – 50th percentile travel time

This equation can be applied to data from a traffic flow model in combination with crash statistics. In project appraisal, the resulting predicted buffer time is given the same weight per minute as travel time.

There is a general consensus in existing literature that the 95th percentile should be used to estimate buffer time, although others such as the 99th or the 90th percentile can also be adopted.

The buffer time applicability ratio considers whether travellers are likely to budget a buffer time for on-time arrival. Not all trip purposes need to apply buffer times and some trips need higher buffer times than other trip types. However, some limited research is available. Wang (2014) provided some subjective applicability factors for different trip purposes as shown in Table 2.3.

Table 2.3: Applicability of buffer times for different trip purposes

Trip purpose	Applicability factor	Estimated purpose share based on Sydney survey data
Work-related business trips (HVs, business cars and other business trips)	1.0	10.3%
Served passengers, e.g. bus and rail passengers	1.0	29.3%
Commuting trips	0.6	23.7%

Trip purpose	Applicability factor	Estimated purpose share based on Sydney survey data
Education, childcare	0.6	14.3%
Other purposes	0.0	22.4%
	Purpose-weighted average = 0.624	Sum = 100%

Notes:

The applicability factors in the table are estimated based on the household travel survey dataset for Sydney from 3 years pooled data (2009 – 11) including vehicle trips only.

The applicability factors are applicable for both link and route level.

Source: Adapted from Wang (2014).

By using the buffer time method, COR is calculated using Equation 1.

$$\text{COR} = \text{Buffer time x Applicability factor x Value of travel time} \qquad 1$$

Total congestion delay cost per link or per route is then the sum of COT and COR as per Equation 2.

$$\text{COT} + \text{COR} = \text{Value of time x (Delay time + Buffer time x Applicability factor).} \qquad 2$$

Comparing the RR method and the buffer time method, the latter appears to be more suitable for Project R22 as:

1. The generic RR method is very difficult to apply, as RR values vary significantly from different research (even when using the same reliability metric) and limited evidence is available for validation.
2. The SD method in Australian Transport Council (2006) does not account for the delays that may result from major incidents on the road network. However, the buffer time (defined as the 95th percentile minus the median of the travel time distribution in Wang 2014) is a function of day-to-day traffic variation and includes the likelihood of being impacted by an incident and corresponding incident delay.
3. The RR method could be used when ongoing measurement of travel time reliability/variability is not available.
4. In the buffer time method, the applicability ratio considers whether travellers are likely to budget a buffer time for on-time arrival, and it makes the estimation of the cost of extra/wasted time for the travellers more realistic.
5. The buffer time method is relatively simple and practical when the empirical travel time can be collected directly. The applicability factor recommended for NSW in Wang (2014) could be adopted for the R22 case studies.

2.3.4 Aggregation of Excessive Congestion Delay and Travel Time Reliability

Figure 2.2 illustrates the concept of aggregating the cost of excessive congestion delay with the cost of travel time reliability. If using freeway link/route travel time as an example, for each time slice t_x (e.g. every 15 min) during the monitoring period, there are a few travel time metrics as follows:

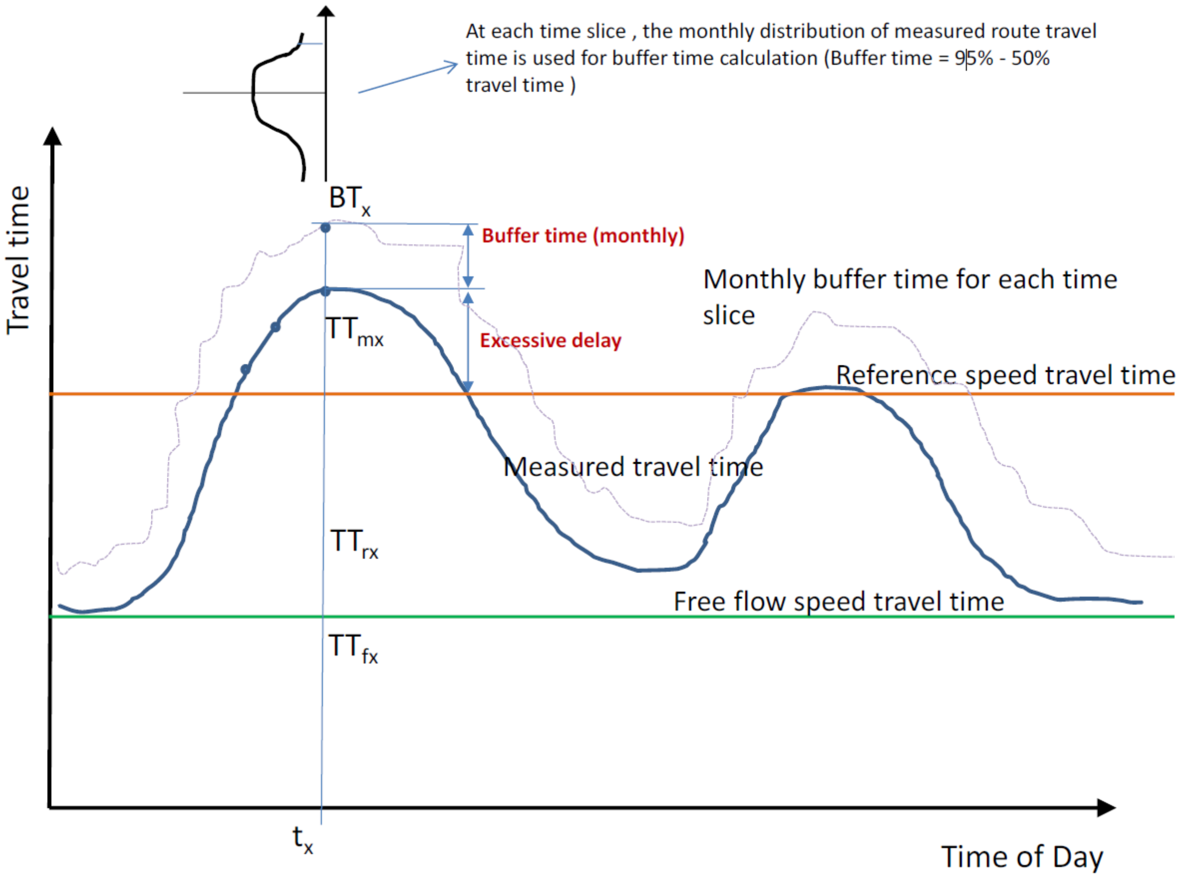
- free-flow-speed travel time (TT_{fx}), assuming free-flow-speed is equivalent to posted speed limit
- reference-speed travel time (TT_{rx}), e.g. the travel time calculated at 70% of free-flow-speed
- measured travel time (TT_{mx}), the mean of all measured travel times in that time slice

- buffer time (BT_x), is the indicator of travel time reliability and is calculated as the difference between the 95th percentile travel time and the median travel time based on a monthly distribution of route travel times (Wang 2014). In theory, travel time reliability only applies to the route level and should reflect the day-by-day variations.

In Figure 2.2, the excessive congestion delay time (i.e. delay time) is represented by the difference between the measured travel time (TT_{mx}) and the reference-speed travel time (TT_{rx}) at each time slice. Buffer time is calculated based on monthly distribution of travel times and applies to each individual time slice. Note that buffer time is a constant value cross the month while excessive delay could be different every day for each time slice.

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

Figure 2.2: Aggregation of excessive delay and travel time reliability cost



In TMR, STREAMS can calculate the travel times between two inductive loop detector stations from spot speeds measured at these stations. For each route, it is possible to determine the travel time distribution and therefore the buffer times from the 95th and 50th percentile travel times. Different applicability factors such as those in Table 2.3 can also be used for different vehicle classes: cars and three HV classes (see Section 3). The buffer time approach can be implemented quite easily and is a practical way for implementation in STREAMS. However, whether it is the best way to cost the reliability of travel times is still a subject for further research.

Both route and link reliability cost estimations are discussed in Section 3. The travel time reliability makes more sense at a trip/route level, therefore a proposed method to disaggregate route reliability costs to individual link reliability costs is also provided for computing and reporting purposes.

In Project R22, the study period for the buffer time calculation is suggested to be one month. Within one month, a sufficient sample size could be obtained to estimate the travel time distribution and the travel time variability could be consistently measured without significant shifting due to seasonal factors. The buffer time estimation should also separate weekdays from weekends, and public and school holidays where applicable.

2.3.5 Possible Components of Bus Delay Cost

The reliability cost of bus travel times should also be considered using the buffer time concept. Given there is limited research in the area, it is suggested that bus travellers are assumed to have the same applicability factor as other vehicle travellers as suggested by Wang (2014). However, the reference speed/travel time for buses is the scheduled travel time and it will not be a constant as was the case with the freeway scenarios shown Figure 2.2.

The Australian Transport Council (2006) *National Guidelines for Transport System Management* introduced the concept of generalised perceived cost of public transport travel. It suggests that the perceived costs of public transport travel may cover the following six items:

- ticket fare
- access time between an origin and bus facility
- expected waiting time at a bus stop for initial boarding
- unexpected waiting time or travel time associated with service unreliability
- in-vehicle time
- transfer time, including access/walk time on transfer and waiting time on transfer multiplied by number of transfers).

For the purpose of congestion delay estimation, all of the above cost items except the ticket fare would be relevant (if required data is available) for bus delay cost estimation where data is available.

In Project R22, bus delay cost estimation would cover in-vehicle delay, passenger waiting time and travel time reliability or buffer time based on the data availability. Further details are given in Section 4.

2.4 Review and Update of Unit Travel Time Costs

Values of travel time costs for economic evaluation often lead to many debates. Project R22 reviewed Australian Transport Council (2006), Austroads (2012) and Transport and Infrastructure Council (2015) values.

The Transport and Infrastructure Council (2015) *National Guidelines for Transport System Management - Road parameter values* (PV2) have provided the latest guidelines on updated parameter values for travel time of vehicle occupants (passenger and freight) and freight per vehicle type. The estimated values of travel time for vehicle occupants and freight are shown in Appendix B. Table 2.4 shows the relevant unit costs that are recommended for this project.

Table 2.4: Unit cost for travel time (in 2013 Australian $)

Road users (urban)	Travel time cost ($/person-h)	Average vehicle occupancy (person/vehicle)	Travel time cost ($/vehicle per hour)	Freight travel time cost ($/vehicle per hour)
Car private	$14.99	1.6	$23.98	n. a.
Car business	$48.63	1.4	$68.02	n. a.
Bus driver	$25.72	1	$25.72	n. a.
Bus passenger	$14.99	20	$14.99 (per person) $299.8 (average per bus)	n. a.
Medium HV	$25.72	1.3	$33.44	$4.15
Articulated HV	$26.81	1.0	$26.81	$39.01
B-double HV	$27.2	1.0	$27.2	$64.91
Pedestrian	$13.17	1.0	$13.17	n. a.
Cyclist	$13.17	1.0	$13.17	n. a.

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

Note that the values of travel time for occupants of vehicles was updated on 30 June 2013 in Transport and Infrastructure Council (2015) using the change in average weekly earnings (AWE) with appropriate consideration of payroll tax and indexation. Freight travel time values per vehicle have been obtained by multiplying vehicle payloads by estimates of unit freight travel time values estimated at a per-pallet level (Austroads 2012), after having converted the latter into a per-payload-tonne format . The value of travel time for freight was updated using the producer price index (PPI) for road freight. The travel time costs for pedestrian and cyclist are the same as private passengers. Transport and Infrastructure Council (2015) also mentioned that for future updates, travel time values of freight could be based on a more recent and extensive study of the value of travel time for freight taking into account load and vehicle types.

Other than the travel time delay cost due to excessive congestion, there are other components that contributed to the congestion cost such as:

- Extra air pollutants and extra vehicle operating cost (e.g. fuel consumption) when the measured speeds are less than the reference speeds. However, air pollutants and vehicle operating cost as a function of measurable network traffic parameters only occupy a small percentage of total congestion cost. For example, Austroads (2009a) reported that the delay cost constituted the majority (93.8%) of the total congestion cost. A policy implication could be that the focus of congestion management is on delay and stop reduction in network operations, which should also lead to lower air pollutant emissions and fuel consumption.
- Noise, pollution, public health and road crashes were the other externalities commonly considered in project evaluation. However, they were not considered in this project mainly because their relationship with congestion is not clear. In other words, it is difficult to argue that increased congestion definitely leads to increased noise or road crashes. In the case of noise, the impact tends to plateau as traffic increases. It could also be argued that increased congestion could reduce road crashes (and certainly fatal road crashes) because most vehicles tend to move slowly in congested peak periods.

The focus of the Project R22 is therefore the monetised extra delay cost due to excessive congestion. The environmental and vehicle operating costs similar to those in Austroads (2009a) could be considered at a later stage.

It is debatable if the unit travel time cost for delay and reliability are different. Small et al. (1999) discussed that the congested travel time is valued more than uncongested travel time as there is a greater disutility or discomfort associated with congested travel conditions. Travel time under congested conditions is less predictable than other travel time, thus the measured valuation of congested travel time will include both the discomfort of congestion and the unpredictability or unreliability. Incorporating the cost associated with travel time unreliability is complicated and Small et al. (1999) suggested that the assumed value of time in a given assessment could be multiplied by a mark-up factor of 2.5 when applied to time savings that occur during highly congested peak periods.

However, there is limited research available currently and no evidence was identified to support the Small et al. (1999) factor. Therefore the unit travel time cost for both COT and COR is assumed to be the same in this project.

3 CONGESTION DELAY COST ESTIMATION FRAMEWORK FOR FOUR VEHICLE CLASSES

The aim of Project R22 is to use online data wherever possible to calculate service values, which are then compared with pre-determined reference values to calculate congestion costs. In discussions with TMR, it is likely that the four-bin counts and travel times between inductive loop detector stations on a freeway would be available for a before-after case study. Traffic data on short, medium, long and combination vehicles will therefore be available for analysis.

This section proposes a delay cost estimation framework for these four vehicle classes at the link level (Section 3.1) and at the route level (Section 3.2).

3.1 Link Level Analysis

The input data for a time slice (t) of, say, 15 minutes on a *freeway link* i, defined as the distance between two detector stations, include the following:

- locations of detector station i
- reference (space) speeds v_{rij} for link i (i=1 to N)and vehicle class j (j = 1 to 4)
- 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 (space) speed v_{tij} at time t on link i for vehicle class j.

Reference speed values are critical in the estimation of delay cost and Table 3.1 shows an example of offline input data required for the analysis framework.

Table 3.1: Offline input data for delay cost estimation for four vehicle classes

Vehicle class *j*	**Freeway reference speeds at two speed limits**		**Unit travel time cost $/veh**	**Applicability factor *A_j* for COR calculation**
	100 km/h	**80 km/h**		
1 - Short (< 6 m)	70 (70%)	56 (70%)	23.98 68.02	0.6 (private) 1.0 (business)
2 - Medium (6 - 13 m)	70 (70%)	56 (70%)	37.59	1.0
3 - Long (13 - 21 m)	70 (70%)	56 (70%)	65.82	1.0
4 – Combination (> 21 m)	60 (60%)	48 (60%)	92.11	1.0

Table 3.2 shows a framework for the calculation of 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.

For a route of N links, the number of detector stations is N+1. The initial station is designated as station zero. The vehicle travel time on a link can make use of the data from both upstream and downstream detector stations.

Table 3.2: Calculation of link delay costs for four vehicle classes

Time slice t	Link. i	Length L_i km	Veh 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 classes $\$\ COT_{ti}$
t = 1	1		1				$U_1 q_{111}[\frac{L_1}{v_{111}} - \frac{L_1}{v^r_{11}}]$	$\sum_{j=1}^{4} COT_{11j}$
			2				$U_2 q_{112}[\frac{L_1}{v_{112}} - \frac{L_1}{v^r_{12}}]$	
			3				$U_3 q_{113}[\frac{L_1}{v_{113}} - \frac{L_1}{v^r_{13}}]$	
			4				$U_4 q_{114}[\frac{L_1}{v_{114}} - \frac{L_1}{v^r_{14}}]$	
	2		1				$U_1 q_{121}[\frac{L_1}{v_{122}} - \frac{L_1}{v^r_{22}}]$	$\sum_{j=1}^{4} COT_{12j}$
			2				$U_2 q_{122}[\frac{L_1}{v_{122}} - \frac{L_1}{v^r_{22}}]$	
			3				$U_3 q_{123}[\frac{L_1}{v_{123}} - \frac{L_1}{v^r_{23}}]$	
			4				$U_4 q_{124}[\frac{L_1}{v_{124}} - \frac{L_1}{v^r_{24}}]$	
	:						:	:
	N		1				As above	$\sum_{j=1}^{4} COT_{1Nj}$
			2					
			3					
			4					
t = 2	1		1 2 3 4				As above	$\sum_{j=1}^{4} COT_{21j}$
	2		1 2 3 4				As above	$\sum_{j=1}^{4} COT_{22j}$
	:		:				:	:
	N		1				As above	
			2					
			3					
			4					
: :	: :	: :	: :	: :	: :	: :	: :	: :
t = T	As above							As above

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

A similar framework for the calculation of the *link* reliability cost (COR) is shown in Table 3.3, where BT_{tij} is the buffer time at time slice t, link i and vehicle class j.

Table 3.3: Calculation of link reliability costs for four vehicle classes

Time slice *t*	Link *i*	Length L_i km	Veh class *j*	Measured buffer time $MBT_{t,i,j}$ (Note 2)	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 4	A_1 (Note 1)		$U_1MBT_{111}A_1$	$\sum_{j=1}^{4} COR_{11j}$
			2		1.0		$U_2MBT_{112}A_2$	
			3		1.0		$U_3MBT_{113}A_3$	
			4		1.0		$U_4MBT_{114}A_4$	
	2		1	As above for link 2	A_1 (Note 1)		$U_1MBT_{121}A_1$	$\sum_{j=1}^{4} COR_{12j}$
			2		1.0		$U_2MBT_{122}A_2$	
			3		1.0		$U_3MBT_{123}A_3$	
			4		1.0		$U_4MBT_{124}A_4$	
	:			:			:	:
	N		1		A_1 (Note 1)		As above	$\sum_{j=1}^{4} COR_{1Nj}$
			2		1.0			
			3		1.0			
			4		1.0			
t = 2	1		1 2 3 4				As above	$\sum_{j=1}^{4} COR_{21j}$
	2		1 2 3 4				As above	$\sum_{j=1}^{4} COR_{22j}$
	:		:				:	:
	N		1				As above	
			2					
			3					
			4					
: :	: :	: :	: :	: :	: :	: :	: :	: :
t = T	As above							As above

Note 1: A_1 is a purpose-weighted value; for 20% business travel and 80% private travel, $A_1 = 0.2 \times 1 + 0.8 \times 0.6 = 0.68$. The model should be able to vary the business-private travel split by time of day or day f week etc. when data is available.

Note 2: 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 then a total congestion cost at link level could be calculated and reported. The details are explained in Section 3.2.

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 3)

$$TD_{tij} = COT_{tij} + COR_{tij} \qquad 3$$

The *route* delay cost including reliability cost for vehicle class j at time t (Equation 4)

$$TD_{tj} = \sum_{i=1}^{N} TD_{tji} \quad (4)$$

- The delay cost including reliability cost in *time period T* for vehicle class j (Equation 5)

$$TD_j = \sum_{t=1}^{T} TD_{tj} \quad (5)$$

- The *total* delay cost including reliability cost in time period T for all vehicle classes (Equation 6)

$$TD = \sum_{j=1}^{4} \sum_{t=1}^{T} TD_{tj} = \sum_{j=1}^{4} TD_j \quad (6)$$

The proposed framework is applicable for either freeway or arterial routes with the distance between two signals defined as a link. A time slice (t) of 15 minutes is also recommended due to possibly low HV counts on some freeway links.

3.2 Route Level Analysis

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, one can argue that 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.

It is proposed that the framework at the link level (Table 3.3) be adapted for route level analysis by introducing the link *estimated buffer time* (EBT_{tij}), shown in Equation 7.

$$EBT_{tij} = MBT_t \times \frac{MBT_{tij}}{\sum_{i=1}^{N} MBT_{tij}} \quad (7)$$

This approach therefore 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 3.3, the results from the table should be consistent with a route buffer time obtained from route travel times.

Note that the route reliability cost at time t for vehicle class j (COR_{tj}) can also be directly calculated, shown in Equation 8.

$$COR_{tj} = MBT_{tj} \times A_j \times U_j = \sum_{i=1}^{N} EBT_{tij} \times A_j \times U_j \quad (8)$$

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}.

The concept of estimating link buffer time from measured route and link buffer times is also used in the following section for the calculation of the reliability cost of bus travel.

4 CONGESTION DELAY COST ESTIMATION FRAMEWORK FOR BUSES

TMR is able to provide automatic ticketing data, from which the bus travel times and occupancy data can be determined with good accuracy. The data comes from the electronic ticket (*go* card) that travellers use to touch on and off during each trip. In discussions with TMR, Gympie Road would be a good test site and all bus routes along Gympie Road would provide good data for a bus delay cost analysis. An analysis framework is proposed in this section.

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

The premise of the bus congestion cost framework is that the bus timetable or schedule provides the scheduled bus travel times and arrival times as reference data. Bus travel delay is the time difference between the prevailing travel time of a bus on a link between two stops and the scheduled travel time (or zero if the bus arrives early). Assuming the bus timetable already takes into account recurrent congestion, the bus travel delay here mainly reflects non-recurrent congestion delay, which is consistent with the definition of excessive congestion delay as explained in Section 2.1. Note that TMR has been reviewing and updating the bus timetable periodically (e.g. every 6 to 12 months) to incorporate changes to recurring congestion into bus operation.

The variability or unreliability of bus travel times is again considered in terms of a bus buffer time as in Section 2.3. Passenger waiting times at a stop due to late arrival of buses are also considered, which is called excessive passenger waiting time.

On link i at time t, there will be zero, one or more buses (from all bus routes) travelling on the link, designated bus number b = 0, 1, …, B(ti). The measurement time period is again t = 1, 2, …, T.

Based on the availability of electronic ticket data, bus congestion delay considers the following three components:

- *Bus in-vehicle travel time delay*: defined as the prevailing travel time of the bus at time t on link i, minus the scheduled bus travel time at time t on the same link. The prevailing travel time could be estimated as the time difference between the last *go* card transaction at an upstream bus stop and the last *go* card transaction at the next downstream bus stop. This metric includes the ‘dwell’ time – the time a bus stays stopped at a bus stop while passengers board or alight.

  For simplicity, if the bus arrives earlier than scheduled, the bus delay can be treated as zero. The bus arrival time is the first touch-on time or the first touch-off time at a bus stop, whichever is the earlier. The case of a bus not stopping at a bus stop must be identified with travel times adjusted for those links affected.
- *Measured buffer time (MBT) for a bus route*: this is determined from the 95th and 50th percentile bus route travel times for each time slice t. The reliability applicability factor is 1.0 according to Table 2.3.
- *Estimated buffer time for a bus link* (see Section 3.2)*:* from the measured route (MBT_t) and link buffer times (MBT_{ti}), the estimated buffer time (EBT_{ti}) for link i at time t is shown in Equation 9.

$$EBT_{ti} = MBT_t \times \frac{MBT_{ti}}{\sum_{i=1}^{N} MBT_{ti}} \qquad 9$$

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

- *Excessive passenger waiting time*: defined as the time difference between a passenger's *go* card touch-on time and the bus scheduled arrival time at a stop (or zero if the bus arrives early). The total passenger waiting time at this stop for an arriving bus is the sum of all these time differences for all passengers boarding at this stop.

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

In summary, the data required in a bus delay cost framework are:

- locations of bus stops for references and checking
- scheduled link bus travel times (T_{ti}^{s}) between bus stops for different bus routes on the selected road at time t from bus timetables
- unit travel time costs of the driver (U_d) and each passenger (U_p), which are different
- number of buses at time t on link i (determined from bus departures times at a bus stop)
- bus travel times of each bus b (T_{tib}) on a link identified with a stop (i)
- passenger waiting time (W_{tib}) on each bus b on a link i at time t, given by summing the waiting times of all boarding passengers at the stop identified with link i in that time slice (Equation 10)

$$W_{tib} = \sum_{\substack{All\ boarding\\ passengers\ on\ bus\ b\\ at\ time\ t\ and\ stop\ i}} [Passenger\ touch - on\ times - Scheduled\ bus\ arrival\ times] \qquad 10$$

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

Table 4.1 shows the framework for bus delay calculations (valid only when T_{tib} is equal or higher than T_{ti}).

Table 4.1: Framework for the online calculation of congestion delay cost for buses

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

Therefore the bus congestion delay cost at time t and link i (C_{ti}) includes in-vehicle travel delay cost, buffer time cost and passenger waiting time cost. This is calculated using Equation 11.

$$C_{ti} = \sum_{b=1}^{B(ti)} [U_d + U_p\Omega_{tib}][T_{tib} - T^s_{ti}] + \sum_{b=1}^{B(ti)} U_p[\Omega_{tib}EBT_{ti} + W_{tib}] \tag{11}$$

The bus congestion delay cost for the whole bus route of N links at time t (C_t) is calculated through Equation 12.

$$C_t = \sum_{i=1}^{N} C_{ti} \tag{12}$$

The total bus congestion delay cost for the whole bus road in a measurement time period T is calculated through Equation 13.

$$\sum_{t=1}^{T} C_t \tag{13}$$

The use of the estimated buffer time term at the link level ensures consistency with a measured route buffer time while maintaining compatibility with occupancy and passenger waiting time data, which naturally exists at the link level. Note again that a bus link is defined as the distance between two bus stops, with the first bus stop designated as the initial stop or stop 0. The following bus stop is designated as stop no. 1. In other words, for N bus links, there will be (N + 1) bus stops.

The bus congestion delay framework and its formulae may appear complex but can be readily implemented in a spreadsheet. The challenge is the need for TMR to provide assistance in compiling and formatting the bus data.

5 OFFLINE CONGESTION DELAY ESTIMATION FRAMEWORK FOR PEDESTRIANS AND CYCLISTS

The technologies for the detection of pedestrians and cyclists are available, but a network of sensors for their monitoring along a corridor or at specific sites is expensive. These sensors are unlikely to be available in the short term to provide online traffic data similar to those described in previous sections for vehicles and buses.

However, it is still meaningful to address the impact of an infrastructure investment or traffic management scheme on pedestrians and cyclists in the context of a before-and-after or ex-post study. This is discussed below.

5.1 Pedestrians

The pedestrian LOS review in Section 2.2 and Austroads (2015) suggested that the concerns for pedestrians are not just walking delay due to, say, footpath congestion. Other issues such as safety, walking path connectivity, crossing opportunity, footpath conditions, security, etc. are also important. Some of these other issues cannot be regarded as part of the congestion cost.

In the context of this project, the focus would be whether pedestrians may experience changes in delay in a before-and-after case study. In other words, what would be the change in pedestrian delay due to the implementation of an infrastructure project or the introduction of a traffic management scheme along an arterial road study site?

Due to the lack of pedestrian detector infrastructure on arterial roads, the analysis framework for pedestrians would have to use data collected specifically for a before-after evaluation study. Table 5.1 is a proposed framework for estimating congestion delay to pedestrians on an arterial road.

Table 5.1: Congestion delay estimation framework for pedestrians

Level-of-service scenarios	Performance measure	Before-and-after analysis method	Change in delay and cost per person
Reduction in pedestrian delay due to less vehicular traffic, e.g. as a result of traffic diverted to a new adjacent freeway bypass	Cycle time decreases at intersection i and pedestrian movement j	* analysis using basic traffic signal calculation method or, say, SIDRA	
Reduction in pedestrian delay due to the provision of a walk path to a crossing (e.g. in a new shopping mall)	Travel time or delay changes	* site-specific calculations based on walk speeds and distances	
Reduction in pedestrian delay due to the provision of a walk path and/or crossing to a bus station	Travel time or delay changes	* site-specific calculations based on walk speeds and distances	
: :	: :	: :	: :

Note that if signalised pedestrian crossings have a log of activation, this might be used as a proxy, even though it would only record the number of crossing events, not the number of people crossing. A measure in the reduction of pedestrian non-compliance with crossing signals could also suggest an improvement in the before-and-after analysis.

The congestion delay is expressed on a per person basis. If pedestrian volumes are available, then the total pedestrian delay can be costed.

5.2 Cyclists

The concerns of cyclists are mobility (delay), accessibility (provision of cycle paths), safety (separation from vehicular traffic) and cycle path conditions (potholes) (Austroads 2015).

Due to the lack of detector infrastructure for cyclists, it will be difficult again to estimate the cyclist demand or flow at an arterial road study site. The proposed approach is similar to that for pedestrians. Cyclist delay is estimated in a before-after situation, i.e. has the infrastructure project or traffic management scheme change the delay experienced by a cyclist?

Table 5.2 is a proposed framework for estimating delay to cyclists under various scenarios.

Table 5.2: Congestion delay estimation framework for cyclists

Level of service scenarios	Performance measure	'Before-after' analysis method	Change in delay and cost per person
Reduction in cyclist travel time due to the provision of a separate cyclist path along the study route	Travel time or delay changes	* site specific calculations based on cycle speeds and distances	
Reduction in cyclist travel time due to the provision of new facilitates for cyclists along or close to the study site (e.g. a path to a railway station or cycle parking bays at the station)	Travel time or delay changes	* site specific calculations based on cycle speeds and distances	
Reduction in cyclist delay due to less vehicular traffic, e.g. as a result of traffic diverted to a new adjacent freeway bypass	Cycle time decreases at intersection i and cyclist or vehicle movement j	* analysis using basic traffic signal calculation method or, say, SIDRA	
: :	: :	: :	: :

In consultation with TMR stakeholders, it was also commented that there is a need for cyclists and pedestrians to be included in all traffic surveys undertaken by TMR, as they are road users and do influence the operation of the road, although the technology for detecting pedestrians and cyclists could be expensive. There are some on-going initiatives such as bicycle GPS tracking data collection that could help detecting cyclist speed and delay etc.

6 CONCLUSIONS AND RECOMMENDATIONS

Online delay analysis frameworks were successfully developed for cars, three HV classes and buses in this first year of Project R22. These frameworks consider excessive travel delay by comparing prevailing travel times (or speeds) with reference travel times (or reference speeds) and also the buffer times to take into consideration the reliability cost of travel. Passenger waiting times at a bus stop are also considered in the bus delay cost framework.

6.1 Conclusions

The key findings from the first-year work were as follows:

- The definition for congestion delay for this study is the *extra delay* cost or *excessive delay* cost with reference to an optimal (spatial) speed for a road user group (spatial speed is the inverse of travel time). The traffic flow at this optimal speed leads to maximum overall road user benefit and is closely linked to the speed before flow breakdowns in a traffic facility.
- The costing of the variability or reliability of travel times is an active area of research. Some commonly used metrics were reviewed and the buffer time is recommended for the travel time reliability measure for this project. Buffer time is estimated as the difference between the 95th percentile and 50th percentile travel times which should reflect the day-by-day variations of route level travel times.
- Online traffic data are available on the proposed study routes (Gympie Road and Bruce Highway). Four-bin vehicle classified counts from inductive loops are available from a freeway such as the Bruce Highway. Bus arrival times, bus travel times between two bus stops and passenger waiting times are to be estimated from *go* card touch-on and touch-off times generated by the TMR's automatic ticketing system.
- There are insufficient sensors for the detection of pedestrians and cyclists in a road network for online congestion analysis. This report proposes offline analysis frameworks for the comparison of delays to pedestrians and cyclists in before-and-after studies. For example, what is the reduction in pedestrian delay due to less vehicular traffic on an arterial road and reduced signal cycle times subsequent to traffic diverted to a new adjacent freeway bypass.

6.2 Recommendations

A project workshop was conducted in July 2015 in Brisbane to finalise the second-year activities including the collection of bus and freeway data. It was recommended that:

- The buffer time approach is to be employed for costing the reliability of travel times, making use of measured 95th and 50th percentile vehicle travel times.
- TMR and ARRB are to finalise the arterial route for bus analysis and the freeway route for car and HV analysis, and data requirements, e.g. number and locations of bus stops and four-bin classified count stations, period of analysis, etc.
- The data retrieved from freeway inductive loop detector stations and the *go* card ticketing system is to be compiled (with TMR assistance) for analysis by ARRB on spreadsheets before implementation as part of ongoing congestion analysis software.

Recommended project tasks for 2015/16 including the two case studies are as shown in Table 6.1.

Table 6.1: Project tasks for 2015/16

Tasks	Task description	Month due
1	▪ Second-year inception workshop ▪ Finalise second-year scope and test routes for data collection	July 2015
2	Case study 1 - Gympie Rd bus congestion cost ▪ Data collection, analysis and reporting for case study 1 ▪ Prepare project report for case study 1 – Gympie Rd bus congestion cost	December 2015
3	Case study 2: Bruce Hwy before-and-after analysis ▪ Extract and format 4-bin freeway counts of Bruce Hwy by TMR ▪ Build model and analyse Bruce Hwy data	April 2016
4	▪ Prepare project report for case study 2 – Bruce Hwy before-and-after analysis ▪ Identify future work (pedestrians, cyclists, etc.)	June 2016

REFERENCES

Australian Transport Council 2006, *National guidelines for transport system management in Australia: vol. 4: urban transport*, ATC, Canberra, ACT.

Transport and Infrastructure Council 2015, *National guidelines for transport system management in Australia: road parameter values (PV2)*, TIC, Canberra, ACT.

Austroads 2006, *Automatic vehicle classification by vehicle length*, AP-T60-06, Austroads, Sydney, NSW.

Austroads 2009a, *Estimating road network congestion and associated costs*, AP-R345-09, Austroads, Sydney, NSW.

Austroads 2009b, *Implementation of national network performance indicators: first round results*, AP-T122-09, Austroads, Sydney, NSW.

Austroads 2011, *Valuation of travel time reliability: a review of current practice*, AP-R391-11, Austroads, Sydney, NSW.

Austroads 2012, *Guide to project evaluation: part 4: project evaluation data*, 3rd edn, AGPE04-12, Austroads, Sydney, NSW.

Austroads 2015, *Level of service metrics for network operation planning*, AP-R475-15, Austroads, Sydney, NSW.

Austroads 2016, *National performance indicators*, website, viewed 12 April 2016, <http://algin.net/austroads/site/index.asp>.

Bureau of Transport and Regional Economics 2007, *Estimating urban traffic and congestion cost trends for Australian cities*, working paper 71, BTRE, Canberra, ACT.

Cambridge Systematics 2012, *Value of travel time reliability, synthesis report and workshop working paper (draft)*, viewed 15 February 2016, <http://onlinepubs.trb.org/onlinepubs/shrp2/L35RFP/DraftSynthesis-ValuingReliability.pdf>.

de Jong, GC & Bliemer, MC 2015, 'On including travel time reliability of road traffic in appraisal', *Transportation Research Part A: Policy & Practice* , vol. 73, pp. 80 -95.

Dekker, F, Dhanjee, A, Johnston, D, Blogg, M & Johnston, K 2015, 'Analysing the cost of excessive congestion on state-controlled roads in Brisbane', *AITPM National traffic and transport conference, 34th, 2015, Brisbane*, Australian Institute of Traffic Planning and Management, Sydney, NSW.

Department of Transport and Main Roads 2015a, 'Cost of congestion: using STREAMS NPI data to estimate daily congestion cost for metropolitan region version 1.1', TMR, Brisbane, Qld.

Department of Transport and Main Roads 2015b, 'Pedestrian crossing facility guidelines and prioritisation system user guide' in *Traffic and road use management: volume 1: guide to traffic management: part 6: intersections, interchanges and crossings*, TMR, Brisbane, Qld.

Dowling Associates 2008, *Multimodal level of service analysis for urban streets*, NCHRP report 616, Transportation Research Board, Washington, DC, USA.

Dowling, RG, Parks, KL, Nevers, B, Josselyn, J & Gayle, S 2015, *Incorporating travel time reliability into the congestion management process: a primer*, Federal Highway Administration, Washington, DC, USA.

Fosgerau, M & Karlstrom, A 2009, 'The value of reliability', *Transport Research Part B: Methodological,* vol. 44, pp. 38-49.

Li, Z, Hensher, DA & Rose, J 2010, *Willingness to pay for travel; time reliability in passenger transport: a review and some new empirical evidence*, working paper ITLS-WP-10-05, Institute of Transport and Logistics Studies, University of Sydney, Newtown, NSW.

Munro, C 2013, *Level of service model for bicycle riders*, CDM research, viewed 12 April 2016, <http://bicyclecouncil.com.au/files/research/LevelOfServiceModelForBicycleRiders.pdf>.

NZ Transport Agency 2013, 'Christchurch network management plan (interim)', NZTA, Wellington, New Zealand.

Small, KA, Noland, R, Chu, X & Lewis, D 1999, *'Valuation of travel time savings and predictability in congested conditions for highway user-cost estimation'*, NCHRP report 431, Transportation Research Board, Washington, DC, USA.

Transportation Research Board 2010, *HCM2010: Highway capacity manual*, 5th edn, Transportation Research Board, Washington, DC, USA.

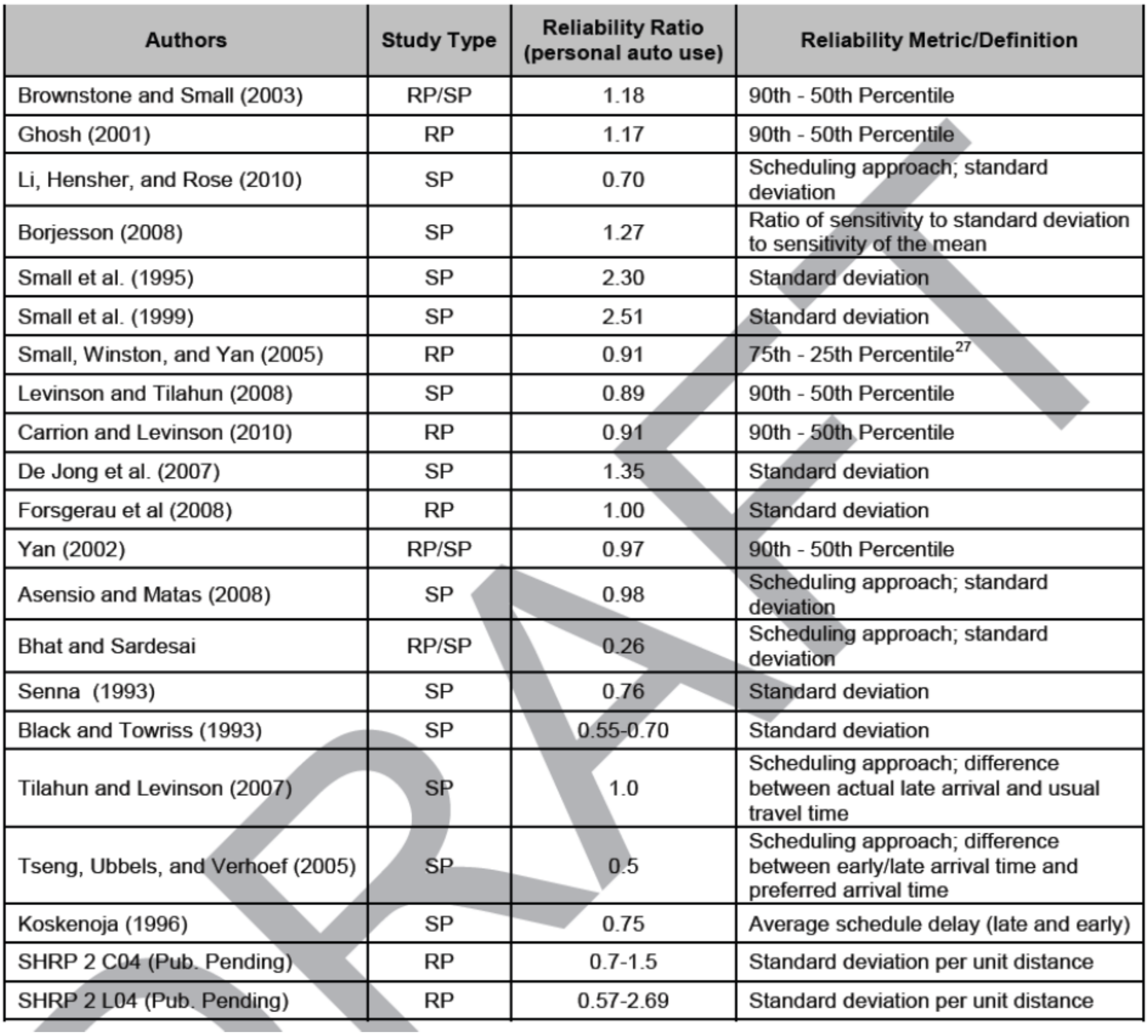
VicRoads 2012, 'Network fit assessment manual', VicRoads internal report, VicRoads, Kew, Vic.

Walsh, D, Su, M & Luk JYK 2008, 'New performance indicators for network operations using real-time traffic data', *Road & Transport Research*, vol. 17, no. 3, pp. 48-54.

Wang, B 2014, 'Economic evaluation of travel time reliability in road project planning: a practitioner's perspective', *ARRB conference, 26th, 2014, Sydney, New South Wales, Australia*, ARRB Group, Vermont South, Vic.

APPENDIX A EXAMPLES OF PREVIOUS RESEARCH ON RELIABILITY RATIOS

Table A 1: Review of previous research on reliability ratios in Cambridge Systematics (2012)



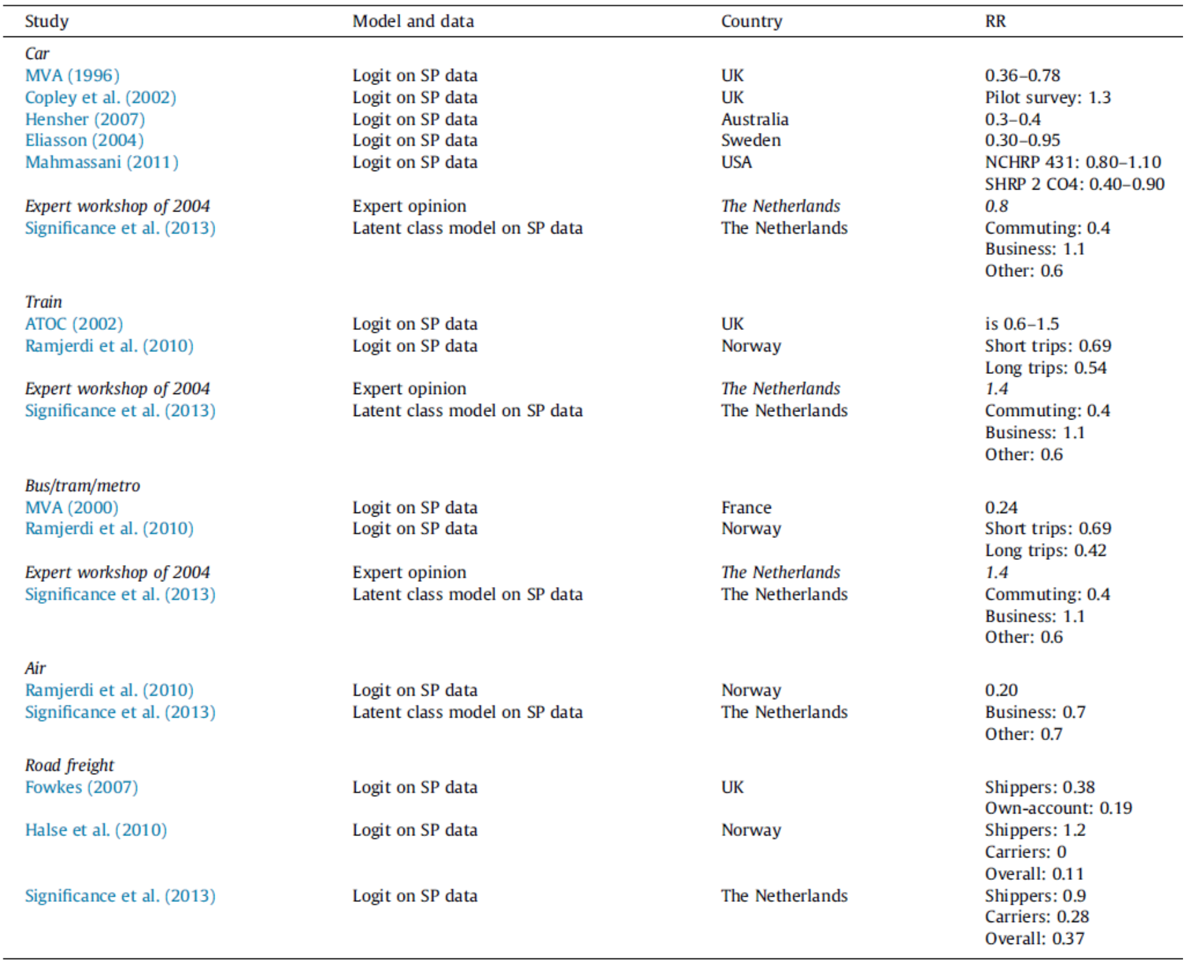
Authors	Study Type	Reliability Ratio (personal auto use)	Reliability Metric/Definition
Brownstone and Small (2003)	RP/SP	1.18	90th - 50th Percentile
Ghosh (2001)	RP	1.17	90th - 50th Percentile
Li, Hensher, and Rose (2010)	SP	0.70	Scheduling approach; standard deviation
Borjesson (2008)	SP	1.27	Ratio of sensitivity to standard deviation to sensitivity of the mean
Small et al. (1995)	SP	2.30	Standard deviation
Small et al. (1999)	SP	2.51	Standard deviation
Small, Winston, and Yan (2005)	RP	0.91	75th - 25th Percentile[27]
Levinson and Tilahun (2008)	SP	0.89	90th - 50th Percentile
Carrion and Levinson (2010)	RP	0.91	90th - 50th Percentile
De Jong et al. (2007)	SP	1.35	Standard deviation
Forsgerau et al (2008)	RP	1.00	Standard deviation
Yan (2002)	RP/SP	0.97	90th - 50th Percentile
Asensio and Matas (2008)	SP	0.98	Scheduling approach; standard deviation
Bhat and Sardesai	RP/SP	0.26	Scheduling approach; standard deviation
Senna (1993)	SP	0.76	Standard deviation
Black and Towriss (1993)	SP	0.55-0.70	Standard deviation
Tilahun and Levinson (2007)	SP	1.0	Scheduling approach; difference between actual late arrival and usual travel time
Tseng, Ubbels, and Verhoef (2005)	SP	0.5	Scheduling approach; difference between early/late arrival time and preferred arrival time
Koskenoja (1996)	SP	0.75	Average schedule delay (late and early)
SHRP 2 C04 (Pub. Pending)	RP	0.7-1.5	Standard deviation per unit distance
SHRP 2 L04 (Pub. Pending)	RP	0.57-2.69	Standard deviation per unit distance

DRAFT

Note: Econometric analysis favours use of observation data usually related to observed choices, called revealed preference (RP), rather than the hypothetical choice data, generally called stated-preference (SP).

Source: Cambridge Systematics (2012).

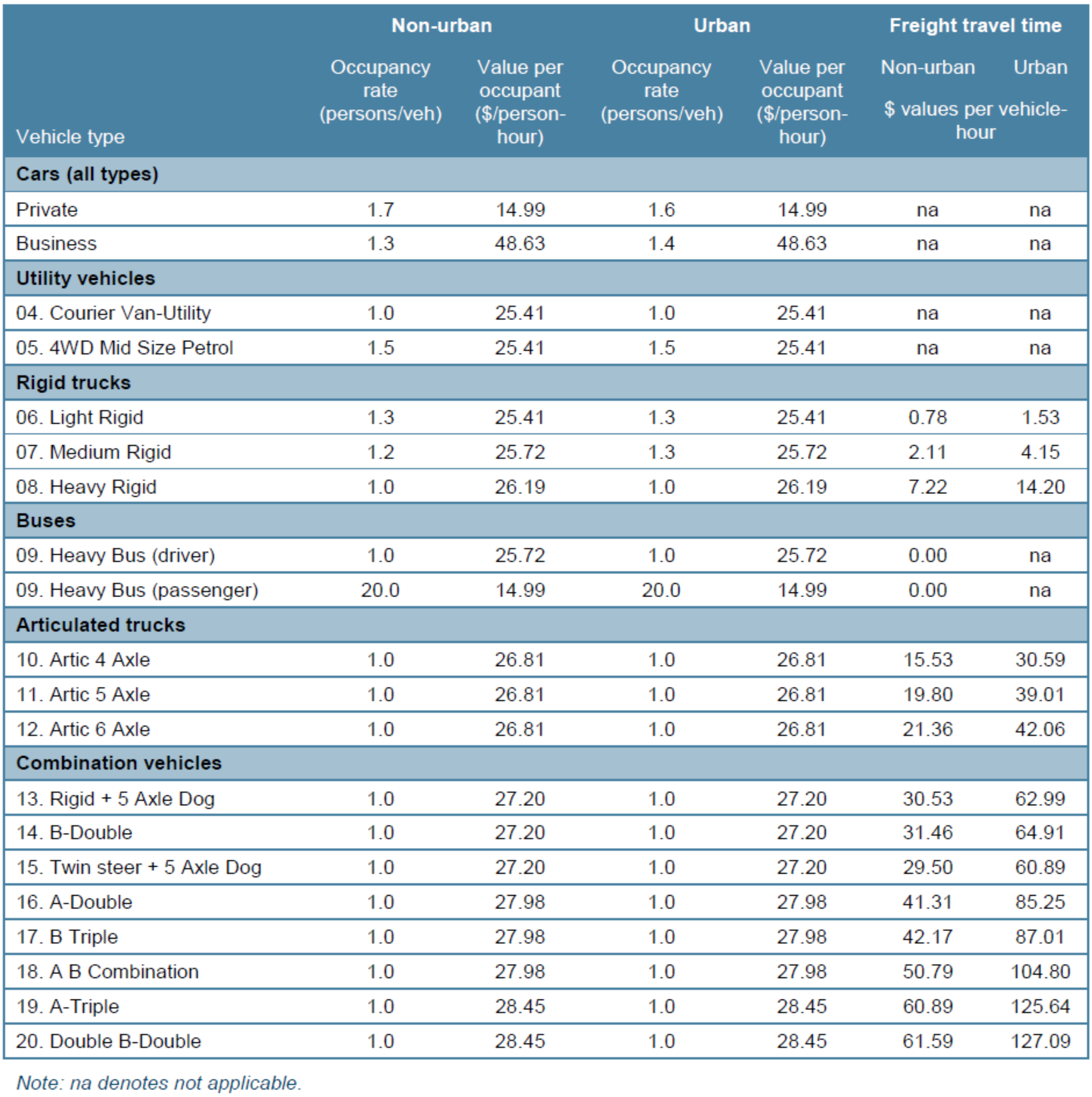
Table A 2: Examples of empirical findings on the RR based on SD method in de Jong and Bliemer (2015)



Study	Model and data	Country	RR
Car			
MVA (1996)	Logit on SP data	UK	0.36–0.78
Copley et al. (2002)	Logit on SP data	UK	Pilot survey: 1.3
Hensher (2007)	Logit on SP data	Australia	0.3–0.4
Eliasson (2004)	Logit on SP data	Sweden	0.30–0.95
Mahmassani (2011)	Logit on SP data	USA	NCHRP 431: 0.80–1.10 SHRP 2 CO4: 0.40–0.90
Expert workshop of 2004	Expert opinion	*The Netherlands*	*0.8*
Significance et al. (2013)	Latent class model on SP data	The Netherlands	Commuting: 0.4 Business: 1.1 Other: 0.6
Train			
ATOC (2002)	Logit on SP data	UK	is 0.6–1.5
Ramjerdi et al. (2010)	Logit on SP data	Norway	Short trips: 0.69 Long trips: 0.54
Expert workshop of 2004	Expert opinion	*The Netherlands*	*1.4*
Significance et al. (2013)	Latent class model on SP data	The Netherlands	Commuting: 0.4 Business: 1.1 Other: 0.6
Bus/tram/metro			
MVA (2000)	Logit on SP data	France	0.24
Ramjerdi et al. (2010)	Logit on SP data	Norway	Short trips: 0.69 Long trips: 0.42
Expert workshop of 2004	Expert opinion	*The Netherlands*	*1.4*
Significance et al. (2013)	Latent class model on SP data	The Netherlands	Commuting: 0.4 Business: 1.1 Other: 0.6
Air			
Ramjerdi et al. (2010)	Logit on SP data	Norway	0.20
Significance et al. (2013)	Latent class model on SP data	The Netherlands	Business: 0.7 Other: 0.7
Road freight			
Fowkes (2007)	Logit on SP data	UK	Shippers: 0.38 Own-account: 0.19
Halse et al. (2010)	Logit on SP data	Norway	Shippers: 1.2 Carriers: 0 Overall: 0.11
Significance et al. (2013)	Logit on SP data	The Netherlands	Shippers: 0.9 Carriers: 0.28 Overall: 0.37

Source: de Jong and Bliemer (2015).

APPENDIX B UNIT TRAVEL TIME COST IN TRANSPORT AND INFRASTRUCTURE COUNCIL (2015)



	Non-urban		Urban		Freight travel time	
Vehicle type	Occupancy rate (persons/veh)	Value per occupant ($/person-hour)	Occupancy rate (persons/veh)	Value per occupant ($/person-hour)	Non-urban $ values per vehicle-hour	Urban
Cars (all types)						
Private	1.7	14.99	1.6	14.99	na	na
Business	1.3	48.63	1.4	48.63	na	na
Utility vehicles						
04. Courier Van-Utility	1.0	25.41	1.0	25.41	na	na
05. 4WD Mid Size Petrol	1.5	25.41	1.5	25.41	na	na
Rigid trucks						
06. Light Rigid	1.3	25.41	1.3	25.41	0.78	1.53
07. Medium Rigid	1.2	25.72	1.3	25.72	2.11	4.15
08. Heavy Rigid	1.0	26.19	1.0	26.19	7.22	14.20
Buses						
09. Heavy Bus (driver)	1.0	25.72	1.0	25.72	0.00	na
09. Heavy Bus (passenger)	20.0	14.99	20.0	14.99	0.00	na
Articulated trucks						
10. Artic 4 Axle	1.0	26.81	1.0	26.81	15.53	30.59
11. Artic 5 Axle	1.0	26.81	1.0	26.81	19.80	39.01
12. Artic 6 Axle	1.0	26.81	1.0	26.81	21.36	42.06
Combination vehicles						
13. Rigid + 5 Axle Dog	1.0	27.20	1.0	27.20	30.53	62.99
14. B-Double	1.0	27.20	1.0	27.20	31.46	64.91
15. Twin steer + 5 Axle Dog	1.0	27.20	1.0	27.20	29.50	60.89
16. A-Double	1.0	27.98	1.0	27.98	41.31	85.25
17. B Triple	1.0	27.98	1.0	27.98	42.17	87.01
18. A B Combination	1.0	27.98	1.0	27.98	50.79	104.80
19. A-Triple	1.0	28.45	1.0	28.45	60.89	125.64
20. Double B-Double	1.0	28.45	1.0	28.45	61.59	127.09

Note: na denotes not applicable.

Source: Transport and Infrastructure Council (2015), produced by ARRB Group Ltd.