EMPIRICAL EVALUATION OF THE TRAVEL TIME RELIABILITY INDICATORS: A CASE STUDY FOR BRISBANE CORRIDOR UNDER RECURRENT AND NON-RECURRENT CONDITIONS

Wathsala Jayanthi Dehideniya Udugamage Ranasinghe
Masters Candidate

Submitted in partial fulfilment of the requirements for the degree of

Master of Engineering (Research)

School of Civil Engineering and Built Environment

Science and Engineering Faculty

Queensland University of Technology

March 2015

Dedicated to my parents, my husband Deepal, and my daughters Jayamini and Nethmini

Keywords

Bluetooth, Buffer time index, Coefficient of variation, incidents, Planning Time Index, Reliability, Travel time index

Abstract

The performance of the transport systems has a significant impact on the economy, environment and social developments. Travel time is an important transport network performance measure as it is easily understood by both transport users and operators.

As in any complex and dynamic system, there are many factors which can adversely affect transport network performance. Different type of incidents, either short term (e.g. road crashes) or long term (e.g. road works) can happen at any time and the effect of these incidents will lead to high travel time variability with potentially important consequences to the community.

Acknowledging the importance of travel time reliability, many researchers have attempted to incorporate it into their studies.

Travel time reliability is defined as a measure of consistency and predictability of travel times over time of day and days of week. In literature, different reliability indicators are defined. However, the empirical studies on the evaluation of the reliability indicators are limited, primarily due to the lack of real data. The availability of the archived transport data at the Smart Transport Research Centre (STRC) motivates this research. This research quantifies the impact of non-recurrent congestion (incidents) through empirically analysing the selected travel time reliability indicators on a major Brisbane arterial corridor (Coronation drive).

Through the review of literature, four reliability indicators: Buffer Time Index (BTI), Planning Time Index (PTI), Travel Time Index (TTI) and Coefficient of variation (Cv) are selected for analysis. The archived Bluetooth MAC Scanners (BMS) and incident records from the STRC server are exploited. BMS data is utilised to estimate the travel time profiles, which is further integrated with incident records to classify the profiles into recurrent and non-recurrent categories.

The results indicate high correlation between different reliability indicators and significant impact of incidents on the travel time reliability. The findings highlight the importance of reducing the incidents and its duration that will not only reduce congestion but also significantly enhance the reliability of the transport networks.

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List of Abbreviations

BBC	Brisbane City Council
BMS	Bluetooth MAC Scanner
BTI	Buffer Time Index
$\mathbf{C_v}$	Coefficient of Variation
FHWA	Federal Highway Administration
F-SHRP	Future Strategic Highway Research Program
HCM	Highway Capacity Manual
LOS	Level of Service
MAC	Media Access Control
NCHRP	National Cooperative Highway Research Program
NZTA	New Zealand Transport Authority
PTI	Planning Time Index
QUT	Queensland University of Technology
SHRP	Strategic Highway Research Program
STRC	Smart Transport Research Centre
TTI	Travel Time Index
$\mathbf{t_f}$	Free Flow Travel Time
$\bar{\mathbf{t}}$	Mean Travel Time
$\mathbf{t_{10}}$	10^{th} Percentile Travel Time
$\mathbf{t_{50}}$	50^{th} Percentile Travel Time
$\mathbf{t_{95}}$	95^{th} Percentile Travel Time
$\boldsymbol{\sigma}$	Standard Deviation

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Signature: ________________________

Date: __28/03/2015______________________

Acknowledgements

First, I would like to express my deepest gratitude to my principal supervisor Dr. Ashish Bhaskar and associate supervisor Professor Edward Chung for their guidance, encouragement and support throughout this thesis. It was their leadership and valuable advice that lead to the successful completion of this thesis. I would also express my gratitude to the examiners for their valuable critiques and feedbacks, which helped me to improve the final presentation of this thesis.

Secondly, I would like to thank to the Brisbane City Council and Smart Transport Research Centre for providing me access to the valuable data used for this research.

Thirdly, I would like to thank my beloved husband Deepal Methiwala and my two daughters Jayamini and Nethmini for their support, encouragement and patience. Without their support, the completion of this thesis would have been a miracle.

Last but not least, I would like to thank Rupika, Rakkitha and Ajantha for their support, and to all my friends of the Queensland University of Technology who were always there with me sharing love and friendship.

Chapter 1: Introduction

Travel time reliability has become a major issue for transport system operators and transport professionals. This study analyses the travel time reliability on a major arterial road corridor in Brisbane, incorporating the impact of incidents into the analysis.

This chapter provides an introduction, describing the research procedure. Section 1.1 describes the research background, followed by Section 1.2 which demonstrates the motivation of this research. Section 1.3 identifies the research questions, for which, answers seek in literature. Section 1.4 describes the objective of the research. Section 1.5 discusses the scope and the limitation of the research, followed by section 1.6, which highlights the significance of the research. Section 1.7 concludes the chapter giving thesis outline. The research program is illustrated in figure 1.2.

1.1 Research Background

This research was planned and commenced with the objective of studying and analysing the traffic congestion and travel time reliability on arterial roads, which has been an important issue studied by researchers in recent decades. Traffic congestion and associated impacts such as user delays and air pollution pose major concerns to the public.

Travel time reliability has been a key performance indicator for transportation planning systems. Accurate prediction of travel times are extremely important for transportation planning purposes as well as for operating of traffic management centres and traveller information systems.

Transport authorities design and maintain road networks and transport systems in order to provide reliable travels to road users. But it has been a challenge to them, and therefore it is vital to identify and assess the less reliable routes in a road network. Development of suitable metrics for travel time reliability and then ranking the different links according to the performance will be important to transport planners in order to prioritise the improvements to road corridors and to implement the mitigation strategies for traffic incidents.

1.2 Research Motivation

The motivation of this research is the availability of the Bluetooth MAC Scanner (BMS) data from the Brisbane arterial network managed by Brisbane City Council (BCC). Brisbane is equipped with over 400 BMS scanners (see Figure 1-1). The availability of the BMS data provides opportunities for direct estimation of travel time along the signalised urban corridors (more details in Chapter 3), which can be further used to estimate the travel time reliability.

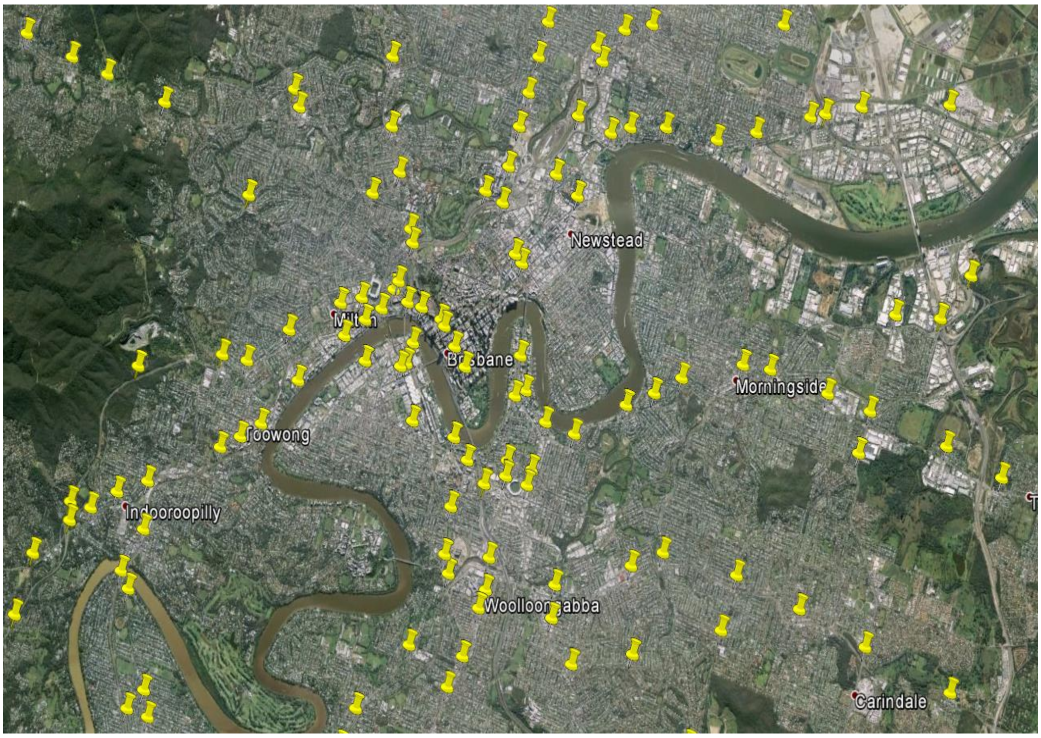

Figure 1-1: Locations (Yellow markers) of the Bluetooth scanners along Brisbane Arterial Corridors.

1.3 Research Questions

Travellers are interested in how long it will take to reach their destination, but are even more concerned with the reliability of their prediction of total travel time. Transport planners want to identify and assess the less reliable routes in their road networks. Recognizing the importance of travel time reliability, this research is planned and carried out to answer the following questions.

1. What is the travel time reliability and what are the indices available to measure the travel time reliability?

2. How to analyse the reliability indicators and how to use the results to find the degree of impact of incidents on travel time reliability?

1.4 Objectives

With the case-study along a Brisbane arterial corridor, this research aims to develop a framework for reliability analysis using the BMS data. Specifically, the objectives include:

1. Review of the existing literature on travel time reliability**:**
   It is intended to achieve knowledge of the studies done by researchers on traffic congestion, travel time variability and reliability indicators including Buffer Index, Travel Time Index, Planning Time Index and other performance indicators.
2. Extraction and analysis of Bluetooth data for selected arterial corridors in Brisbane**:** Travel time data on the main arterial corridors on Brisbane Network will be analysed.
3. Empirical evaluation of reliability indicators using Bluetooth data**:** The data prepared in step 2 above, will be used to evaluate the reliability indicators identified in Step-1.
4. Comparative overview of the different reliability indicators at Brisbane network**:** Relationships between the different reliability indicators will be explored and their significance will be highlighted.

Evaluation of the impact of incidents on travel time reliability**:** The results of the analysis in step-4 will be further supported by the analysis of incidents for recurrent and non-recurrent conditions, and practical significance from transport operator's point of view will be provided.

1.5 Scope and Limitations of the Research

This study uses the travel time data obtained from Bluetooth scanners on arterial roads of Brisbane network and investigates the travel time reliability. It evaluates reliability metrics and analyses the performance of selected arterial links. Also it reviews the impact of incidents on travel time reliability. Finally it analyses and compares the results for recurrent and non-recurrent congestion. With the outcome of this case study on selected arterial corridor on Brisbane network, the framework can be easily extended to other corridors and networks.

This study limits the analysis and assessment of travel time reliability on arterial roads due to following reasons:

Once the travel time data is evaluated using Bluetooth MAC scanner data, there would be a considerable rate of outliers inserted to these travel times due to various reasons, as described in Chapter 3. This will result in lower sample size of estimated travel time and corresponding lower confidence in average travel time estimation.

This research does not focus on improving the accuracy of travel time measurements from BMS. Studies have been performed to enhance the accuracy of travel time estimation by fusing multi-data sources: BMS, and loops (Bhaskar et al. 2014). In this study, periods with low sample size are removed from the data analysis.

1.6 Significance of the Research

This research has a practical and scientific significance.

It provides a comparative overview of the state-of-the-art travel time reliability indicators which will be derived from the case study on Brisbane network.

Travellers want to know information about the reliable travel times compared to their typical trip. With the outcome of this research it is intended to supply with reliable travel time information to traveller information systems.

The practical significance of different indicators are identified which is valuable for the transport authorities to identify vulnerable routes on their networks and develop congestion relief strategies such as improvements to signalised and non-signalised intersections, Identify and improve black spots and bottlenecks, providing slip lanes, right turn bays and other infrastructure development work to enhance the reliability of the network.

For scientific community, it provides an insight on the indicators that can be used for research, integrating reliability with modelling such as dynamic traffic assignment and route choice.

1.7 Thesis Outline

This thesis consists of five chapters as given below.

Chapter 1 (this chapter) presents the background, research questions, research objectives and scope and limitations of the research. Subsequently, the significance of the research is presented. Finally, an outline of the thesis is discussed.

Chapter 2 discusses the literature relevant to the research questions and critically reviews the perspective of different authors.

Chapter 3 describes the Blue tooth MAC Scanner data collection process and travel time estimation process.

Chapter 4 presents the case study of this research. It estimates the selected reliability indicators on Coronation Drive for recurrent and non-recurrent congestion, and summarises the research outcome.

Chapter 5 concludes the research and identifies the directions for further research.

The program of the research is given in Figure 1-2.

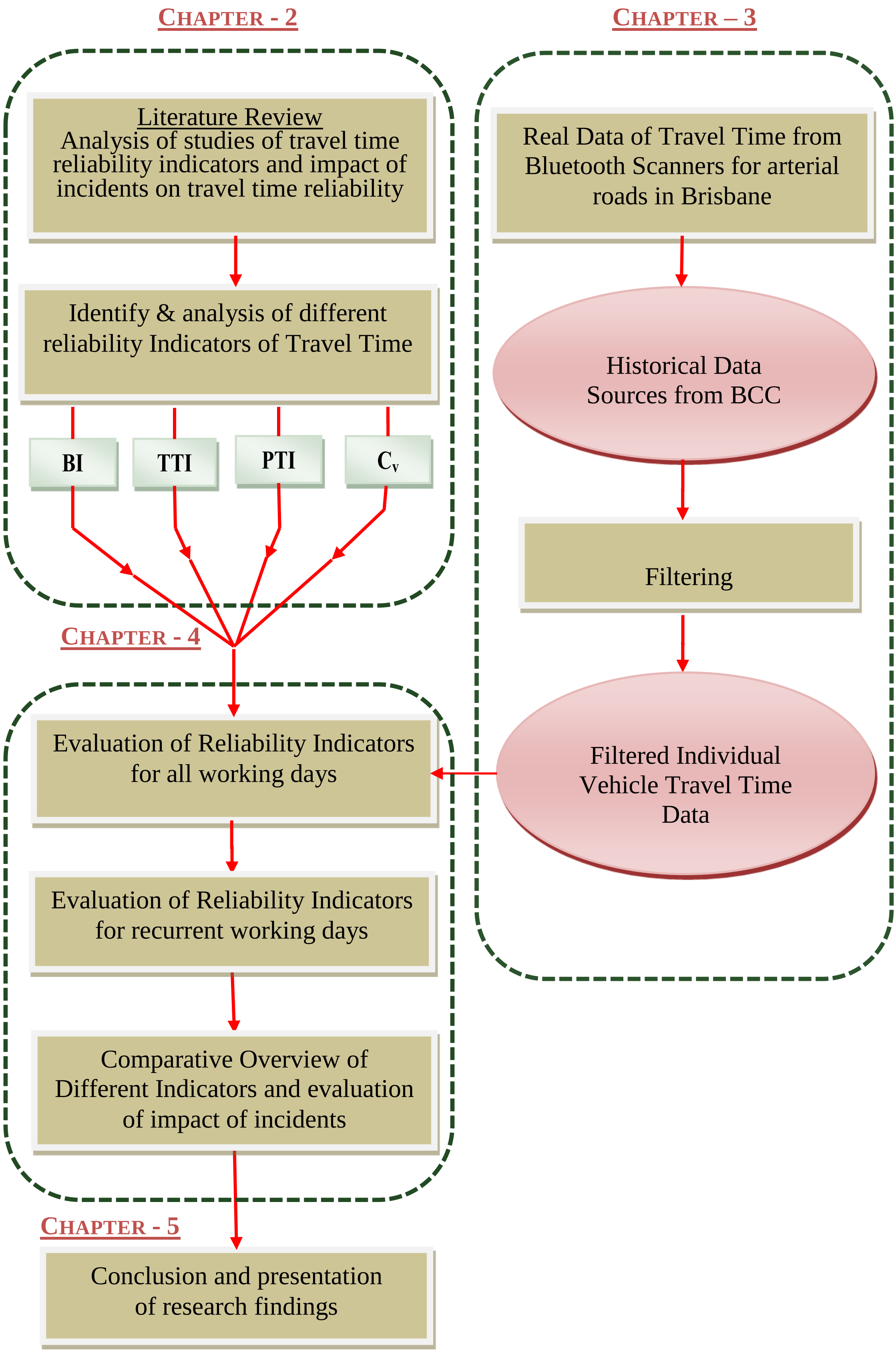

Figure 1-2: Program of the Research

Chapter 2: Literature Review

2.1 Overview

The performance of the transport network is generally measured in terms of travel time (or speed). The reliability of travel time on the network is an important indicator for both transport operators and users.

In general, system reliability relates to the consistency and persistency of a system under certain conditions for a period of time. System reliability can be also defined as the probability of a system operating in a specific state, under a given set of circumstances (Kececioglu 1991). As in any complex and dynamic system, there are numerous factors which can affect transport network performance.

Many empirical studies have identified the importance of travel time reliability and covered a wide range of applications including freeway and arterial transport network reliability.

This chapter reviews the topics of research interest in the field of travel time reliability under five subsections. Section 2.1 gives the overview, followed by Section 2.2 which provides a review of development of the travel time reliability concept and how it is defined. Section 2.3 describes the impact of the sources of congestion on reliability and unreliable travel. Section 2.4 explains the impact of incidents on travel time reliability, followed by Section 2.5, which gives an overview of different reliability indicators. Finally, section 2.6 summarises and concludes the chapter describing the research gap.

2.2 Classification of concepts and of definitions of travel time reliability

The concepts, definitions, theories, models and applications of travel time reliability are diverse, even that from literature, mainly two categories are identified on this concept. These two categories are identified by many studies (Kaparias 2008; Taylor 2013; Pu 2011)and classified as:

a. Appropriate measures to assess the transport network performance reliability, where both the regular (cyclical) variations on travel time (e.g. over the hours of the day) or irregular (perhaps ‘incident based’) variations in travel time are of concern.

b. Suitable measures to assess the travel behaviour, where the factors that influence the choice that individuals make, and the attitudes to risk by travellers may be particularly concerned, especially when the consequences of late arrival are severe.

Pu (2011) further defines these two types of measures as “performance - driven measures” and “response measures”. He describes that performance-driven measures are used largely for practical application purposes, in monitoring the performance of transportation systems, whereas response measures are researched to incorporate uncertainty in travel demand or economic modelling to reflect travellers’ choice behaviour accurately.

2.2.1 Definitions of travel time reliability in literature

Primarily Asakura and Kashiwadani (1991) analysed the concept of travel time reliability and defined it as probability that a trip between a given Origin and Destination pair can be made successfully within a given time interval and a specified level of service. Many researchers acknowledged this definition (Iida 1999; Xiong, Shao and Yao 2007; Eman 2006).

Al-Deek and Emam (2006a) further described this definition and stated that reliability of a highway system is measured by the percentage of travel on a corridor that takes no longer to complete than the expected travel time plus a certain acceptable additional time and the percentage of reliable travel is then given by the probability that the actual travel time will be less than this threshold.

According to the definitions presented by Lomax et al.(2003), International Transport Forum (2010) and HCM (2010), travel time reliability is the ability of the transport system to provide an expected level of service quality, upon which users have to organise their activities. Here, the Level of Service (LOS) is described as a quantitative classification of the performance measure.

Chen et al.(2003) defined the travel time reliability as the variability between the average travel time and the actual travel time in terms of the standard deviation of travel time distribution.

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The empirical based studies were initiated by Federal Highway Administration (2005),and defined travel time reliability as the consistency or dependability of the travel time, as a measure of day to day and or across different times of the day.

Pu (2011)suggested the same definition performing a broad analysis on number of reliability indicators.

Lyman et al.(2007)suggested defining the travel time reliability as a measure of the amount of congestion experienced by users of the transportation system at a given time. New Zealand Transport Authority (NZTA) (2008) proposed the same idea and offered a more detailed definition as below:

> *Trip time reliability is measured by 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 congestion, typically as a result of day-to-day variations in flow. This is distinct from variations in individual journey times, which occur within a particular period.*

As discussed in above definitions in the literature, travel time reliability is defined as the probability of finishing a trip within a specified time period under different traffic conditions, as well as a measure of consistency and predictability of travel times over time of day and days of week. In order to analyse the travel time reliability on arterial roads in Brisbane, this study selects the definitions suggested by FHWA (2005) and Pu (2011).

2.3 Factors affecting travel time reliability

When study the travel time reliability, it is important to evaluate the sources of congestion which cause unreliable travel. Increasing congestion and occurrence of incidents lead to high variability of travel times, and hence, the knowledge of the sources of travel time unreliability will be useful to transport planners to analyze the network performance and to evaluate the mitigation strategies.

In literature of reliability research, seven sources of traffic congestion and travel time variability may be reported (Lomax and Margiotta 2003; FHWA and Texas 2005; Kwon et al. 2011; F-SHARP 2010). These sources include traffic incidents, work zones, weather, traffic control devices, special events, fluctuations in normal traffic flow and physical capacity.

The traffic congestion resulted due to these sources can be categorized into two groups as recurrent congestion and non – recurrent congestion. Recurrent congestion occurs in every day peak period traffic flow when the demand exceeds the capacity. Commuters are used to this kind of congestion and they plan for it. Non-recurrent congestion occurs when the demand significantly increases due to special events (say sports events) and/or the capacity drops due to traffic incidents.

Sources related to recurrent congestion

1) Physical Bottlenecks ("Capacity") – Capacity is the maximum amount of traffic capable of being handled by a given road section. Congestion occurs when the demand increases the capacity.
2) Traffic Control Devices – The congestion occurs due to intermittent disruption of traffic flow by control devices such as railroad grade crossings, poorly timed traffic signals etc.
3) Fluctuations in Normal Traffic flow ("Demand") – Day-to-day variability in demand leads to some days with higher traffic volumes than others. Varying demand volumes superimposed on a system with fixed capacity results in variable travel times.

Sources related to non-recurrent congestion

1) Traffic Incidents – Are events that disrupt the normal flow of traffic. Events such as vehicular crashes, breakdowns, and debris in travel lanes are the most common form of incidents.
2) Work Zones – Are planned construction activities on the roadway that result in physical changes to the road environment. These changes may include a reduction in the number or width of travel lanes, lane "shifts," lane diversions, reduction, or elimination of shoulders, and even temporary roadway closures.
3) Weather – Climatic changes can lead to changes in driver behavior that affect traffic flow.
4) Special Events – Special events such as sports events or special meetings cause demand fluctuations, consequently the traffic flow in the vicinity of the event will be considerably different from "typical" patterns.

How much each of above sources contributes to total congestion is depicted in Figure 2-1.

The graph is from a study conducted in US (2005) and it indicates that the impact of incidents on total congestion is approximately 25%.There's a considerable contribution of incidents on total congestion.

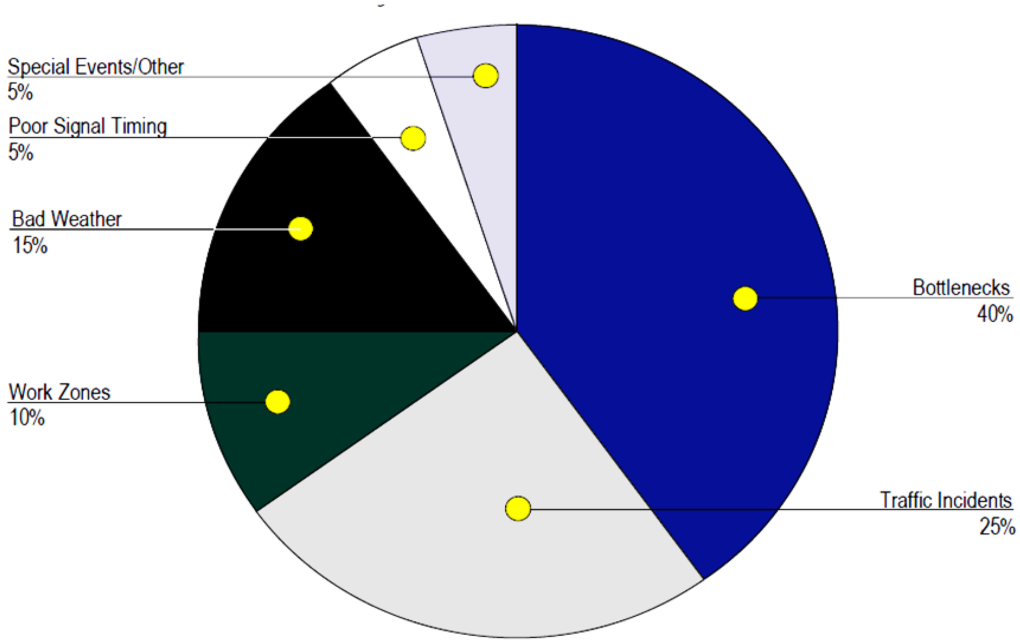

Figure 2-1: The Sources of Congestion (Source:http://www.ops.fhwa.dot.gov/ aboutus/ opstory.htm)

2.4 Impact of incidents on travel time reliability

Traffic incidents such as crashes and vehicle breakdowns can have a major effect on traffic flow.

The Figure 2-2 depicts the results of a case study done on week day travel times on State Route 520 Eastbound, Seattle, Washington (FHWA and Texas 2005). As per the results of this study the average travel time was 17.5 minutes on this route. But when events (traffic incidents and weather) are present, it was nearly 25 minutes, or 43 percent longer than the average. Commuters who took State Route 520 corridor had to plan for this unpredictable variability if they wanted to reliably arrive on time, the average just won't do.

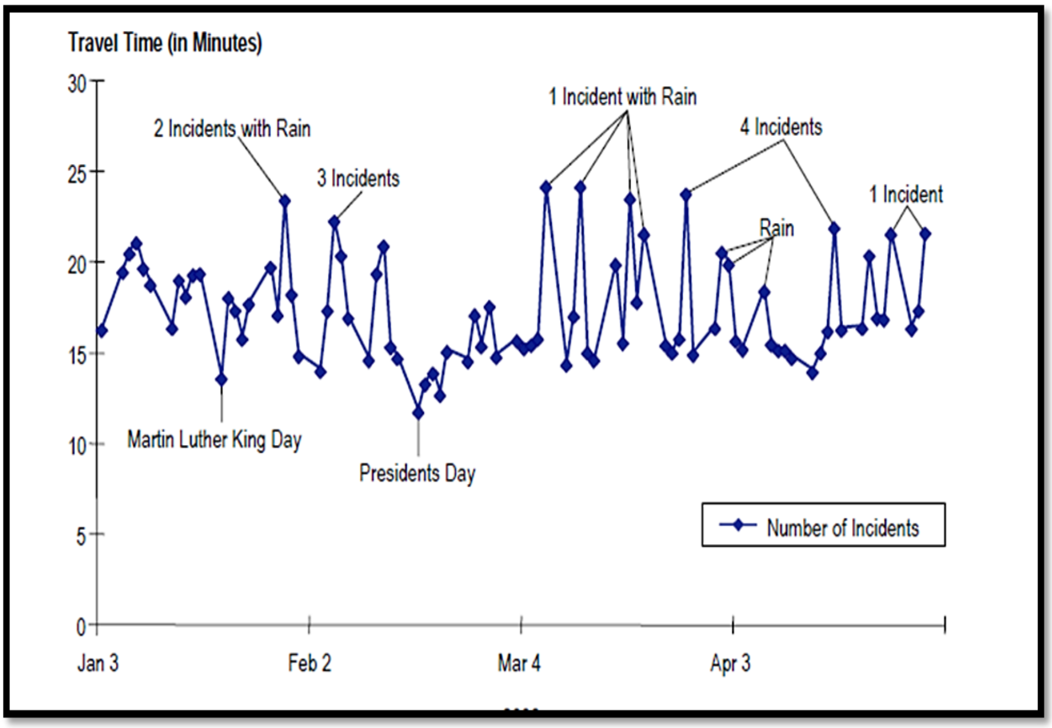

Figure 2-2 : Weekday Travel Times 5.00-6.00pm on State Route 520 Eastbound, Seattle, Washington. (Adopted from Traffic Congestion and Reliability (FHWA 2005))

These results provide a clear picture of the impact of incidents and traffic influencing events on travel time reliability and the need for mitigation strategies.

Over the last two decades, there have been extensive developments in international research on transport system reliability. Initial interest arose after the massive earthquake in the city of Kobe in Japan in 1995, which led to substantial degradation of the transport networks and services in the region, not only for evacuation processes but also for emergency services (Lam 1999).

Smith et al. (2003) studied the capacity reduction due to accidents, analysing over 200 accidents that occurred on urban freeways in the Hampton Roads region of Virginia. They found that accidents significantly reduce the capacity remaining on freeway segments. An accident blocking one of three freeway lanes resulted in a mean capacity reduction of 63%, while an accident blocking two of three freeway lanes resulted in a mean capacity reduction of 77%.

Knoop et al. (2008) collected high quality videos of the traffic flow around two accidents on Dutch freeways recorded from a helicopter in 2007 and measured the two-directional traffic passing the accident locations. They observed, during the accidents, drivers would take the time to watch the accident and it happened for both directions of the freeway on which accident occurred. They concluded that the capacity of the road in the direction of the accident is reduced by more than half as not all lanes are in use, and the capacity at the opposite direction is reduced by half by the "rubbernecking" effect.

Chen et al. (2003) analysed the effect of accidents on travel times by obtaining the accident records from the California Highway Patrol. In these records, each accident has a start and an end time, a type classification, and a location. They concluded that both the standard deviation and the median of travel times are larger when there are accidents. They quantified the effect of accidents, and evaluated the cost of accidents as 5 minutes per accident per vehicle.

Traffic modellers commonly accept that there is strong relationship between vehicle collisions and transport system reliability. A multi-state travel time reliability model was developed by Park et al. (2011) to quantify the impact of traffic incidents on travel time reliability. Park has analysed the simulated data from 1-66 eastbound, Washington D. C. over 17 days.

Since field-measured travel time data sets under incident conditions were very limited, their study used microscopic simulation models to obtain travel times under typical traffic conditions and under incident conditions.

Through simulation, they generated the information that provides the probabilities of encountering congested and uncongested states over a time period of interest as well as the mean and variance of the travel time distributions.

Their finding indicates, as the congestion level increased, 90^{th} percentile travel time was increased between 5.00am and 8.00am. As more incidents were introduced, 90^{th} percentile travel time has increased significantly. Introduction of the traffic incidents decreased the travel time reliability significantly, and the congested state became more dominant. The travel time distribution expanded wider. As per the observations of the study, the incidents do not introduce an additional component when congestion has already onset; instead they increase the mean travel time and variability in travel time for the congested condition. Another finding of this study was that the multi-state travel time reliability model provided better fits than a single-mode distribution model when analysing the reliability of the travel times under traffic incident conditions; it is possible to quantify the impact of incidents more accurately.

Tu at el. (2008a) discuss the effects of accidents on travel time reliability. Their study presents an empirical travel time reliability analysis using a large dataset of registered traffic accident data and empirical traffic flow data. The aim of the study was to gain insight into the relationship between traffic accidents and travel time reliability by linking speed and flow measurement data from loop detectors, to accident records collected on some freeways in the Netherlands. They states that accidents result in both higher travel time variability and higher probability of traffic breakdown on freeways and thereby higher travel time unreliability.

A travel time reliability model was used for this study. This model was regarded as a function of inflow levels, thus, the inflows could be considered as the principal parameter in the travel time reliability model.

As per the results of the study, this paper concludes that traffic accidents increase variability of travel times four times higher than that without traffic accidents and increase travel time unreliability.

Recker (2005) states that the better understanding of travel time reliability and variability might assist transport planner to select proper transport policy in order to relieve the congestion problems as well as lessening the impact of different types of incidents.

2.5 Indicators for travel time reliability

In literature, different indicators for travel time reliability are considered. This section first introduces the indicators, thereafter reviews the literature where they have been used.

2.5.1 Statistical Measures

Travel time reliability can be statistically evaluated considering the distribution of the day to day travel time values observed over a specific section and during specific time periods. For instance, the distribution of the average travels time from 7:00 to 7:30 am observed along a specific section of a road for 30 days. The spread of the distribution represents the variability (or unreliability) of the travel time. In addition to the standard measures of **Standard deviation** and **Coefficient of**

variation, Lint and Zuylen (2005) have also proposed other measures such as: **skewness of the travel time** (λ^{skew}) and the **width of travel time** (λ^{var}).

$$\lambda^{skew} = \frac{t_{90} - t_{50}}{t_{50} - t_{10}} \quad (1)$$

$$\lambda^{var} = \frac{t_{90} - t_{10}}{t_{50}} \quad (2)$$

Where t_{90}, t_{50} and t_{10} are the 90th percentile, 50th percentile and 10th percentile of travel times, respectively.

Considering the above statistics, Lint at el.(2008b) has proposed **Unreliability Index (UI)** as a measure of unreliability in the travel time. Higher the UI more is the unreliability and vice versa.

$$UI = \frac{\lambda^{var}.\ln(\lambda^{skew})}{L} \quad if \quad \lambda^{skew} > 1 \quad (3)$$

$$UI = \frac{\lambda^{var}.}{L} \quad otherwise \quad (4)$$

where L is the section length.

Buffer time

The concept of 'buffer time' relates to the travellers decisions on travel time. Travellers may think "how much extra time do I need to allow?" and decide the departure time on that. This additional time is the 'buffer' that most of the travellers allow in their trips for uncertainty in their travel conditions. These conditions include both recurrent and non-recurrent traffic conditions. Buffer time is the additional travel time above the average travel time required for on-time arrival. For instance, for 95% confidence to arrive on-time, the buffer time is the difference between the 95th percentile travel timet_{95} and the mean travel time ($\bar{t}$) (Lomax and Margiotta (2003)).

$$Buffer\ time = t_{95} - \bar{t} \quad (5)$$

Buffer Time Index (BTI)

Buffer time index is expressed as the percentage of the extra travel time needed to accomplish a trip 19 times out of 20 chances in relation to the average travel time for that trip(Lomax and Margiotta (2003)).

$$BTI = \left(\frac{t_{95} - \bar{t}}{\bar{t}}\right) \quad (6)$$

The concept of 'buffer time' and Buffer Time Index (BTI) is explained by the example given in Figure 2-3, where the graph represents the frequency distribution of the travel time. In the example the buffer time is 7 min and the BTI is 0.47 (=7/15).

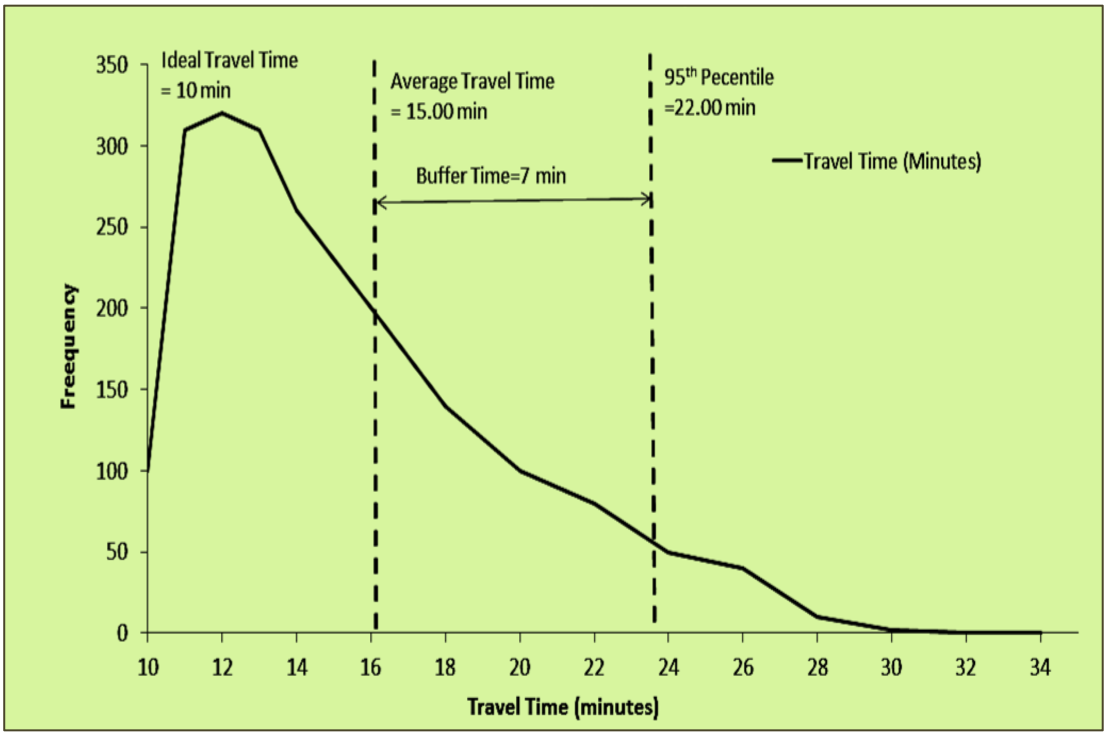

Figure 2-3 : Systematic representation of the Buffer Time Index (Adopted from Traffic Congestion and Reliability (FHWA 2005))

The above definition of the BTI is based on the mean travel time. Mean is sensitive to the outliers, and therefore median is considered as a better statics. Therefore, median based Buffer time index (BTI_{median}) is also defined in literature (Pu 2011).

$$BTI_{median} = \left(\frac{t_{95}-t_{50}}{t_{50}}\right) \tag{7}$$

Where t_{50} is the median (50th percentile) travel time.

<u>Planning Time</u>

Planning time is expressed as the travel time that traveller should plan for so as to be confident to arrive on time for 95% of the travels; i.e., it is the 95th percentile of travel time.

<u>Planning Time Index (PTI)</u>

Planning Time Index (PTI) is defined as how much larger the planning time is than the "ideal" or "free flow" travel time (i.e., the ratio of the 95th percentile to the "free flow" travel time). Planning time index provides the total time needed to plan for an on-time arrival 95% of the time.

$$PTI = \frac{t_{95}}{t_f} \tag{8}$$

According to Lomax et al.(2003), PTI is relatively easy to communicate and could be used as a trip planning measure for trips that require on-time arrival.

Travel Time Index (TTI)

The travel time index is the ratio of actual average travel time to free-flow travel time (t_f). This is defined as the mean time ($\bar{t}$) it takes to travel during peak hours compared with free-flow conditions.

$$TTI = \frac{\bar{t}}{t_f} \tag{9}$$

Tardy Trip Indicators

Tardy trip indicators represent the unreliability impacts using the amount of late trips(Lomax and Margiotta (2003)). This includes: Misery index, On-time arrival and Florida Reliability Statistics, which can represent the unreliability impacts using the amount of late trips. This category includes Misery index, On-time arrival and Florida Reliability Statistics and recommends the Misery index.

On-time arrival: On-time arrival estimates the percentage of time that a traveller arrives on time on the basis of an acceptable lateness threshold. If the threshold is suggested as 10% higher than the average travel time (or travel rate),

$$On - time\ Arrival = 100\% - \begin{pmatrix} Percentage\ of\ travel\ rates\ greater \\ than\ 110\%\ of\ the\ average\ travel\ rate \end{pmatrix} \tag{10}$$

Misery index: Misery index would give a measure of "how bad are the worst days?".

The negative aspect of the trip reliability can be examined by this index. This might be calculated by taking the average of the data for worst 20 % of the days and comparing that to the average travel rate for all trips.

$$Misery\ Index\ (\boldsymbol{MI}) = \left[\frac{\begin{pmatrix} (Average\ travel \\ rate\ of \\ longest\ 20\%\ of\ trips \end{pmatrix} - \begin{pmatrix} Average\ travel\ rate \\ of\ all\ trips \end{pmatrix}}{Average\ travel\ rate\ of\ all\ trips} \right] \tag{11}$$

Several studies in literature have reported the aforementioned reliability indicators. Table 2-1 provides an overview of the indicators reviewed. Following are the main references in chronological order.

The final report prepared by Texas Transportation Institution, Federal Highway Administration (FHWA 2005), recommends Buffer Time Index, Planning Time, and the Planning Time Index as the standard measures of reliability.

Lyman and Bertini (2007) investigated BTI, TTI and PTI for travel time data along the northbound Interstate 5 corridor, a major freeway through Portland, Oregon. Data analysis of the study indicated that the three travel time reliability indices gave the same pattern along the roadway. Among the three different travel time reliability measures, they observed that the PTI gave higher index than the BTI and TTI, thus it seems to underestimate the travel time reliability for that corridor.

Lint (2008a) carried out a study on travel time reliability on a freeway around the metropolitan area of Netherlands. His article on this study contributed to the debate on travel time reliability and focused on two questions:

1. When should travel time be considered unreliable?

2. How can travel time unreliability be measured and monitored in a traffic network?

As per the observations of the study, he suggests that a number of findings are likely to apply in general:

- The travel time distribution is often wide and (left) skewed, particularly in periods where mostly congestion occurs, sets in or dissolves. Particularly this skew is relevant in a reliability context. Given the fact that extreme delays may have extreme consequences (e.g. missing appointments or even flights), he argued skew must be considered an indicator of unreliability; particularly a policy viewpoint. The study has acknowledged that the commonly used measures for travel time reliability, do not explicitly take skew into consideration.

- Given an often skewed travel time distribution, usage of classical measures based on mean and/or variance of travel times may not be advisable – these measures may lead to a biased estimate of reliability. Moreover, measures based on mean and variances are sensitive to outliers. He has proposed more robust percentile based reliability indicators for both *width* and *skew*.

- During a typical weekday, one can identify structural differences (phases) in the shape of the day-to-day distribution of travel times. From free flow to congestion and back to free flow conditions the distribution evolves from (a) small and symmetrical to (b) wide and left-skewed to (c) wide and slightly right skewed to (d) Wide and left-skewed to (a) small and symmetrical and so on.

Pu (2011) analytically examined a number of reliability measures and explored their mathematical relationships and interdependencies. With the assumption of lognormal distributed travel times, following conclusions were made:

- The coefficient of variation, a well-defined traditional statistic, is a good proxy for a number of other reliability measures, including PTI, BTI-median, and skew statistics. Another well-defined traditional statistic, standard deviation, is not recommended as a proxy because its magnitude relative to other measures is not stable. However, given that the coefficient of variation is the ratio of the standard deviation to the mean, there might be a way to replace standard deviation with coefficient of variation in the assessment of the value of reliability and other occasions. If that can be achieved, the coefficient of variation would build the linkage between performance-driven reliability measures and travellers response measures; a gap found in the two literature groups of travel time reliability.
- Defining the BTI and failure rate on the basis of the median, rather than the average, is recommended to avoid underestimating unreliability, especially for heavily right-skewed travel time distributions. Here the failure rate is defined as 100% - percent of on-time arrival.
- The proposed mathematical relationships between the reliability measures could easily be used to predict one measure on the basis of another, or estimate their relative magnitudes.
- Travel time reliability generally deteriorates as traffic congestion increases.

Table 2-1: Travel Time Reliability Measures, Recommended and used by Different Sources and Studies

Travel Time Reliability Measure	Lomax (2003)	FHWA Guide (2006)	NCHRP (NCHRP 2010) Report 618 (2010)	SHRP 2 (2008)	Lyman & Bertiny (2007)	Wenging Pu (2011)	Hotagi &Ferreira (Hojati, Ferreira and Phi. 2009) (2009)	Robinson (Robinson 2005) (2005)	Bharthi A (2013)	Herman R (Herman R 1974) (1974)
95th or other percentile travel time	N/A	√	N/A	N/A	N/A	√	N/A	N/A	N/A	N/A
Standard deviation	N/A	X	x	N/A	N/A	X	N/A	N/A	N/A	N/A
Coefficient of variation	N/A	X	x	N/A	N/A	√	N/A	√	N/A	√
Percent variation	√	N/A	√	N/A	N/A	√	N/A	N/A	√	N/A
Skew statistic	N/A	N/A	N/A	√	N/A	√	N/A	N/A	N/A	N/A
Buffer Time index	√	√	√	√	√	√	√	N/A	√	N/A
Planning time index	N/A	√	√	√	x	√	N/A	N/A	N/A	N/A
Frequency of congestion	N/A	√	N/A	N/A	N/A	√	N/A	N/A	N/A	N/A
Failure rate (percent on-time arrival)	N/A	N/A	√	√	N/A	√	N/A	N/A	N/A	N/A
Misery index	√	N/A	√	√	N/A	X	√	N/A	N/A	N/A
Travel time index	N/A	N/A	N/A	N/A	√	√	N/A	N/A	√	N/A

NOTE: √ = use encouraged; x = use discouraged; N/A = not applicable

2.6 Summery and conclusion

Reliability of the travel time is of increasing importance to travellers and transportation professionals alike, as congestion worsens in major urban areas; hence, many empirical studies have developed to address this issue.

There are several definitions of travel time reliability, and according to these definitions, travel time reliability measures are categorised into two main groups.

a. Appropriate measures for transportation agencies to monitor the reliability on road networks.(system performance assessment)
b. Suitable measures for travellers to plan their trip travel times. (assessment of travel behaviour)

Many studies have developed to analyse and quantify the travel time reliability, and various types of measures are suggested by researchers, analysing the reliability in different perspectives. Even that, still there's no clear detailed definition of travel time reliability, or general agreement on using suitable reliability indicators.

Travel time unreliability occurs due to traffic congestion. There are seven sources of congestion discussed in the literature. According to the impact of different sources, traffic congestion is divided into two groups as recurrent congestion and non-recurrent congestion. Travel time unreliability increases during non-recurrent congestion.

The impact of incidents on total congestion is approximately 25%. This indicates that there's a considerable contribution of traffic incidents on total congestion.

Acknowledging the impact of incidents on travel time reliability, traffic modellers have developed various models to study the relationship between traffic incidents and transport system reliability. Promising results have been achieved by the transport network simulations (Smith 2003; Park, Rakha and Guo 2011; Tu, Van Lint and Van Zuylen 2008a) which suggest that traffic incidents are likely to increase travel times in the affected road networks and to decrease travel time reliability. However, the empirical studies quantifying the impact of incidents on travel time reliability are limited and this research fills this gap.

This study uses the real travel time data obtained from the Brisbane road network to estimate the travel time and to evaluate the reliability indicators. Brisbane is equipped with over 400 BMS scanners. The availability of the BMS data provides opportunities for direct estimation of travel time along the signalised urban corridors, which can be further used to estimate the travel time reliability.

Reliability analysis is done for recurrent and non-recurrent congestion, using incident records.

Chapter 3: Travel Time Estimation Using Bluetooth Media Access Control Scanner (BMS)

3.1 Overview

Overview This chapter describes the Bluetooth Media Access Control (MAC) Scanner data acquisition process and analyses the practical situations and outcome of the technology. Section 3.1 gives the overview, followed by Section 3.2 which provides a description of Bluetooth technology and BMS data available in Brisbane. Section 3.3 describes the travel time estimation process using Bluetooth BMS data. Finally, section 3.4 summarizes and concludes the chapter.

3.2 Data Collection Techniques and Bluetooth MAC Scanner Data

With the rapid development of technology, data collection techniques related to transportation have seen innovative findings and currently, the transport authorities are capable to deal with 'big data'.

For the maintenance, control, planning and development of road network, transportation agencies collect data using various methods and systems.

Such systems are broadly classified as:

(a) Fixed sensors (such as inductive loops, Automatic Number Plate Recognition System (ANPR)) that provide traffic information at the location where the sensors are installed and,

(b) Mobile sensors such as GPS equipped vehicles, Automatic Vehicle Location (AVL) that provide data for the entire journey of the vehicle equipped with such sensors.

Bluetooth technology (BT) was invented and explored in early 2000 for the automotive industry and, Nusser at el. (2000)presented the Bluetooth network system and revealed its interconnection with in-car communication and information systems.

Researchers (Sawant 2004; Murphy 2002; Pasolini 2002)have tested the proof-of-concept for the use of BT for Intelligent Transport System services, and have verified that the BT equipped devices in moving vehicles could be discovered.

Currently, Bluetooth technology is increasingly used in the Intelligent Transport Systems and road management sector. In some studies, the data collected by Bluetooth scanners is fused with other data sources such as loop detectors for the estimation of Bluetooth vehicle trajectories (Bhaskar, Ming Qu and Chung 2014; Nantes et al. 2014), and traffic states. Recently, Wi-Fi MAC Scanner (WMS) is also explored as complementary data and has been applied for applications related to space tracking crowd movements (Abedi, Bhaskar and Chung 2014). A study done in Brisbane (Abbott-Jard, Shah and Bhaskar 2013) has compared WMS and BMS data samples for both public transport and road networks. WMS data samples from public transport network are observed to be much higher than that from road network. However, on the road network, BMS samples are better. Further study is needed to compare BMS and WMS samples over the road network. However, for this research, we have access to BMS data from Brisbane and we use it for travel time estimation. The comparison of BMS and WMS is outside the scope of this project.

3.2.1 Bluetooth scanning concept/ Data acquisition process

Travel time data collection on road networks using BMS has been significantly interested as an easy, cost-effective method among stakeholders.

Bluetooth is a short-range communication protocol. The communication range (termed as zone) of the Bluetooth devices depends on the characteristics of the scanner antenna and includes a radius of around 100-150m.This zone is scanned to read the Media Access Control addresses (MAC-ID) of the discoverable BT devices transiting within the zone (Bhaskar and Chung 2013).

MAC-ID is the unique identification for an electronic device equipped with Bluetooth. It is a 48-bit, 12 alpha-numeric character, which is specific for the device manufacture and unique for each device. This number can be captured and registered by compatible Bluetooth scanners.

3.2.2 The travel time estimation mechanism

When two stations *O* and *D* are covered by Bluetooth scanners, the travel time taken by a Bluetooth discoverable motorist to go from *O* to *D* is given by the time difference between the matching identifiers. If the vehicle first detected by the scanner at station *O* at time t_o and later at the station *D* at time $t_{d,}$ the travel time TT^{od} between these two stations will be given by equation (1)

$$TT^{od} = t_d - t_o \qquad (12)$$

3.2.3 Bluetooth data from Brisbane

Smart Transport research Centre (STRC) of QUT has access to a large Bluetooth data set from Brisbane. Brisbane is densely equipped with BMS locations. There are about 200 BMS locations on Brisbane arterials maintained by the Brisbane City Council and around 400 BMS locations are being targeted by the Department of Main Roads for motorways.

Some of the BMS locations around the Brisbane city are shown by the aerial map given in Figure 1-1, where the yellow markers represent the locations of the BMS stations.

Sample BMS data from Brisbane, Australia.

BMS from Brisbane data includes the following fields.

- *Number:* The record number
- *Device ID:* MAC-ID of the BT device
- *Station ID:* ID of the location where BMS is located
- *Time stamp:* The time when the device is first discovered
- *Duration:* Time difference between the last and first discoveries of a BT device at the respective BMS location expressed in seconds.

A sample of BMS data is presented in Table. On the arterial network, due to logistics reasons the BMS scanner is placed inside the signal controller box.

Figure 3 -1 illustrates a photograph of a BMS equipped signal controlled in Brisbane. The shark fin shaped antenna at the top of the box is the BMS antenna. The BMS is directly plugged with power supply and connected with a fibre optic line that provides seamless download of the data to the server.

Table 3-1: Sample BMS data

Number	Device ID	Station ID	Time-stamp	Duration (s)
1	10	10087	2011/08/04 09:23:26	84
2	25	10087	2011/08/04 09:42:15	14
3	33	10087	2011/08/04 11:32:07	30

Figure 3-1: A photograph of a BMS equipped signal controlled in Brisbane with a shark fin shaped BMS antenna on the top

3.3 Travel time estimation process

Bluetooth traffic detectors are being increasingly used for travel time estimation, due to their relative low cost and ease of installation. Travel time estimation on urban arterial has long been a topic of research. It is challenging to estimate travel time on urban network than that on freeways or motorways, due to numerous reasons such as stop-and-go-running conditions due to signals; non conservation of traffic flow due to side streets (mid-link sink and sources) etc. Researchers have developed various models to estimate and predict travel time using traditional data sources on arterials (Bhaskar 2012, 2011, 2010, 2009; Kwong 2009).

BMS data has been increasingly used to estimate travel time on urban network. Researchers have compared the travel time estimated from BMS data with that from the records of video cameras for motorways and arterials, and the results reported are successful and favourable (Wang 2011; Mei 2012).

3.3.1 Matching MAC Scanner Data

Assuming BMS is at the signal controller near to the intersection, and depending on the delay observed at the signalised intersection, a vehicle can spend a significant time in the BMS zone. This time spend by a device in the detection zone is known as the duration. Figure 3-2 illustrates two BMS zones. The area and the shape of the detection zone of the Bluetooth scanners depend on the type of the antenna used. Depending on the usage, different antennae can be combined together to define the required shape and size of the communication zone. The communication zone should be large enough so that the travel time of vehicles within the zone is at least 5 seconds. As an example, the communication zone of BMSs in Brisbane network is 100m for arterials and 150m for motorways (Bhaskar and Chung 2013). Travel time matched from the Bluetooth scanners, especially on the urban arterials, should clearly specify the type of matching used. For calculating travel time for each pair of detection zones, Enter-to-Enter approach or Exit-to-Exit approach can be used. For instance: (refer to Figure 3-2)

- **Section *En2En***: Travel time calculated corresponds to the section of the entrance of the u/s BMS zone to the entrance of the d/s BMS zone.
- **Section *Ex2Ex*:** If exit time is used then the travel time is for the section that corresponds to the exit of the u/s BMS zone to the exit of d/s BMS zone.

When the traffic flow is in free flow condition, the travel time calculated in both approaches can expected to be the same. When there are delays at intersections, *En2En* travel time experiences the partial delays from both u/s and d/s intersections, whereas, *Ex2Ex* travel time only experiences delay at d/s intersection and no delay from u/s intersection.

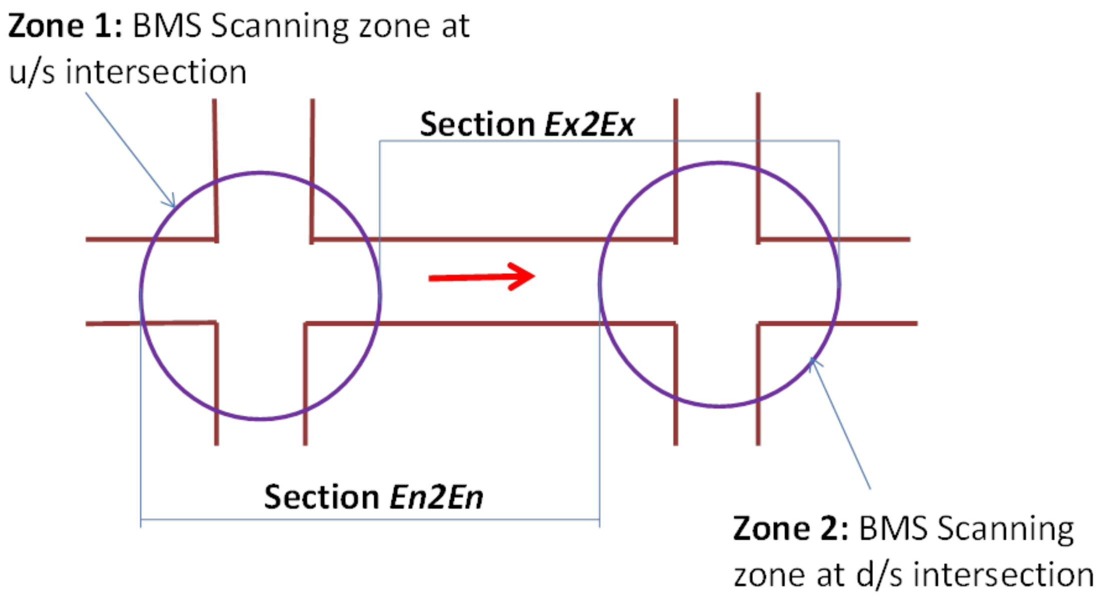

Figure 3-2: Matching MAC Scanner Data

As the distance between the BMS scanners increases, the percentage error in the travel time estimation decreases. In the same way, for a given section, percentage error in the travel time estimation decreases with the decrease in average travel speed (increase in travel time) along the section, as illustrated in the Figure 3-3(Bhaskar and Chung 2013).

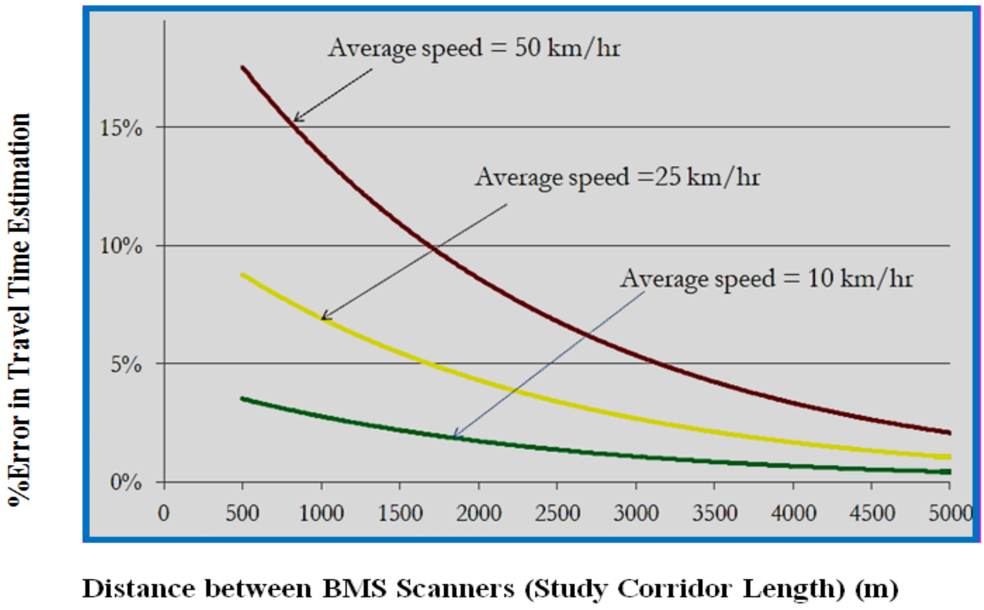

Figure 3-3: Illustration of the percentage error in individual travel time estimation from BMS data as function of the distance between BMS scanners and average travel speed

3.3.2 Filtering

Once the travel time data is evaluated as explained above, there would be a considerable rate of outliers inserted to these travel times. These outliers are experienced on urban arterial corridors due to pedestrians, public transport users and multiple detections recorded by Bluetooth scanners. This is the noise in travel time data observations which is unavoidable in urban traffic analysis by using Bluetooth technique.

In order to remove the explained outliers from calculated travel time values, different types of filtering methods are used by researchers.

In literature, filtering techniques, such as Moving Median Filter (Wang 2011), Median Absolute Deviation (MAD) (Kieu 2012), Box-and-Whisker filter (Tsobota 2011) and other techniques utilising Greenhead's model and least median of Squares(Van Boxtel 2011) and multiple matched filter (Kieu 2012) have been utilised to reduce noise from the directly matched travel time values.

In this research, Median Absolute Deviation (MAD) filtering process is used to filter the outliers. MAD has been successfully used by the practitioners (Kieu 2012)in the filtering process. Also it is currently used by Brisbane City Council and Queensland Transport and Main Roads.

MAD is the median of the absolute deviations from the data's median(Smith and Demetsky 1994). For this method, a moving window of 6 minutes is defined (Δt =6 min).

For each time window, an upper bound value (UBV_t) and a lower bound value (LBV_t) are defined in order to remove the outliers from data set. The points out side these bounds are considered as noise and removed.

For time t, and for moving window Δt, the Median M_t and *MAD* are defined as below.

$$M_t = median(tt_m) \tag{13}$$

$$MAD = median(|tt_m - M_t|) \tag{14}$$

Here tt_m is the corresponding stop line to stop line travel time, where *median* is an operator that provides the median of the data values.

The UBV_t and LBV_t at time t are defined as below.

$$\mathrm{UBV}_t = M_t + f\sigma_t \quad (15)$$

$$\mathrm{LBV}_t = M_t - f\sigma_t \quad (16)$$

f represents the scale factor for the confidence bound. Lower *f* results in higher confidence with lower sample size and *vice versa.* The value of *f* given in literature is in-between 2 to 5.

f =2 would be recommended for higher confidence in the travel time estimation.
σ_t is the standard deviation from the *MAD* and for a normally distributed data set; it is expressed as in equation (17).

$$\boldsymbol{\sigma_t = 1.4326 * MAD} \quad (17)$$

3.3.3 Average Travel Time Estimation

When the filtering process is completed, next step will be the estimation of average travel time between selected BMS stations along a road corridor. In this study, filtered Bluetooth data were used to calculate the average travel time. For this analysis, only working days were selected excluding school holydays. For each day, average travel time for 15 minutes was evaluated. These average travel time values were used to evaluate further statistics intended to analyse from this study which will describe in chapter 4.

3.4 Discussions

Traffic state analysis and estimation is a challenging task for transport authorities and practitioners due to complex network performance of urban road corridors. The introduction of Bluetooth technology into the transport system presented a key to this problem and large scale data sets are becoming available for traffic monitoring purposes. However it is important to identify the errors in this data, and the reliability of the travel time estimates obtained using this technology should be carefully analysed.

The magnitude of error in travel time from BMS data depends on number of factors. As the distance between the BMS scanner increases, or speed along the corridor decreases, the percentage error in the travel time estimation decreases.

The type of matching is important to minimise errors. *En2En* travel time includes a portion of delay observed at the upstream intersection, whereas, *Ex2Ex* travel time only experiences delay at d/s intersection and no delay from u/s intersection. Hence, it is recommended that for utilising the travel time estimates from Bluetooth for ITS applications, Exit-to-exit (or Stop-to-Stop) should be used.

Chapter 4: Analysis of Reliability Indicators

4.1 Overview

This chapter presents the development of a comprehensive research methodology to evaluate the travel time reliability indicators on selected arterial road corridors in Brisbane, and then analyses the impact of incidents on travel time reliability, in order to address the knowledge gaps identified in Chapter 2. Section 4.1 gives the overview, followed by Section 4.2 which provides a description of study site. Section 4.3 identifies the suitable reliability indicators and performs the analysis.The impacts of the incidents are analysed quantitatively and graphically using reliability indicators. Finally, section 4.4 concludes the chapter.

4.2 Study Site Description

This section provides the characteristics of the study site. Travel time data collected by Bluetooth scanners on Coronation Drive in Brisbane were used for this research. This is a prominent road corridor used by commuters to reach Brisbane Central Business District (CBD).

The available time period for the analysis is from August 2013 to March2014.

Study Site - Coronation Drive

Coronation Drive is a signalized arterial road, connects the south western suburbs to Brisbane CBD. This route experiences heavy traffic congestion during morning and afternoon peak periods. For calculating travel time along this route, two sections are defined by selecting three BMS stations. As shown in Figure 4-1, the first section (A-B) starts from Toowong suburb and continues to Milton suburb with length of 2 km. The second section (B-C) with about 800 metres length is located between Milton and the “Go Between Bridge” entrance near Brisbane CBD.

This route has three vehicle lanes for each direction (inbound and outbound) and contains four traffic lights in the whole corridor length (three midblock intersections on section A-B and one mid-block intersection on section B-C).

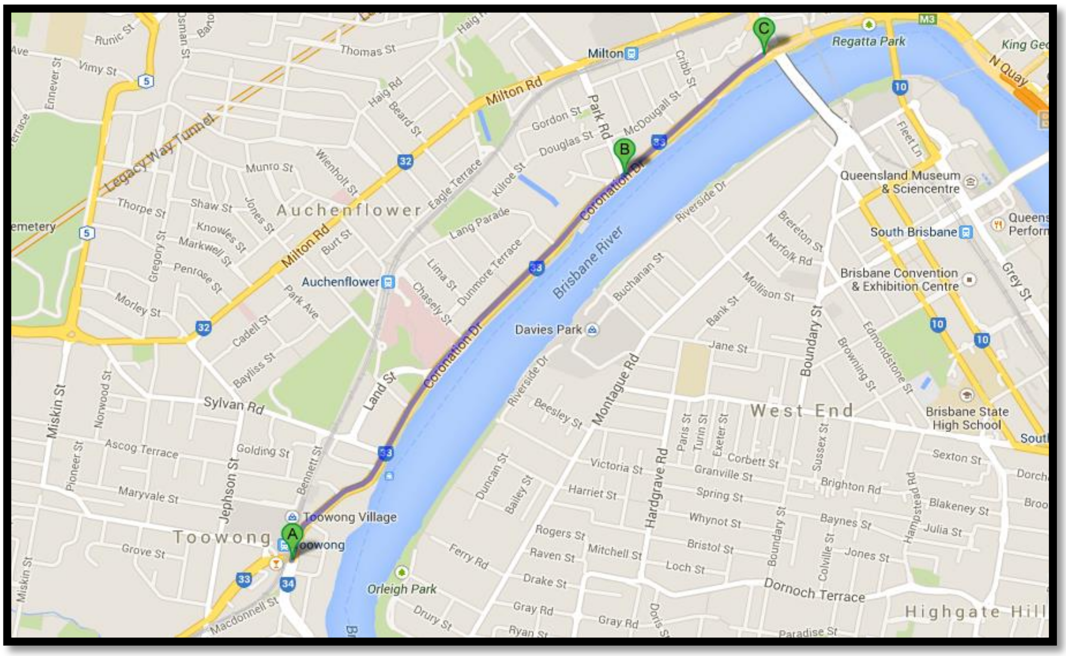

Figure 4-1: Study Site - Coronation Drive

4.3 Travel Time Reliability Analysis

This study investigates the use of Buffer Time Index (BTI), Planning Time Index (PTI) as well as the Travel Time Index (TTI) to analyse the traffic performance in the Brisbane road networks using the aforementioned eight months consecutive travel time data. Furthermore, this study also evaluates Coefficient of Variation (C_v) as a reliability indicator on Brisbane arterial roads. Selected indicators are the most widely used measures in the literature for analysis of travel time reliability (as given in Table 2-1). These indicators well represent the variation pattern of travel time on above corridor. Also, a good correlation between them could be observed.

4.3.1 Analysis of results on Coronation Drive

The travel time data estimated for inbound traffic on Coronation Drive for all working days in eight months were analysed. The ***All working days*** and ***Recurrent Working Days*** are defined as below.

- ***All Working Days***: This is defined, by excluding the data with days corresponding to the weekends, school holidays, and public holidays from the database.
- ***Recurrent Working Days:*** This is defined by further excluding the records corresponding to the incident days from the ***All Working Days*** database.

The relevant codes were written for Matlab, in order to obtain the travel time distribution as well as to evaluate the reliability indicators. As per the variation pattern illustrated in Figure 4-2, both the morning and the evening peak periods are congested. When analyse the morning peak time, it is observed this corridor experiences a regular congestion in the morning and it is more reliable compared to evening peak period.

As per the observations, evening peak period is highly congested and significant travel time variations were recorded resulting unreliability in travel time. Therefore the reliability analysis was performed mainly focusing on evening peak period of this road corridor and the results were recorded.

Then the analysis was performed for recurrent working days omitting incident dates from the data set and the results were recorded.

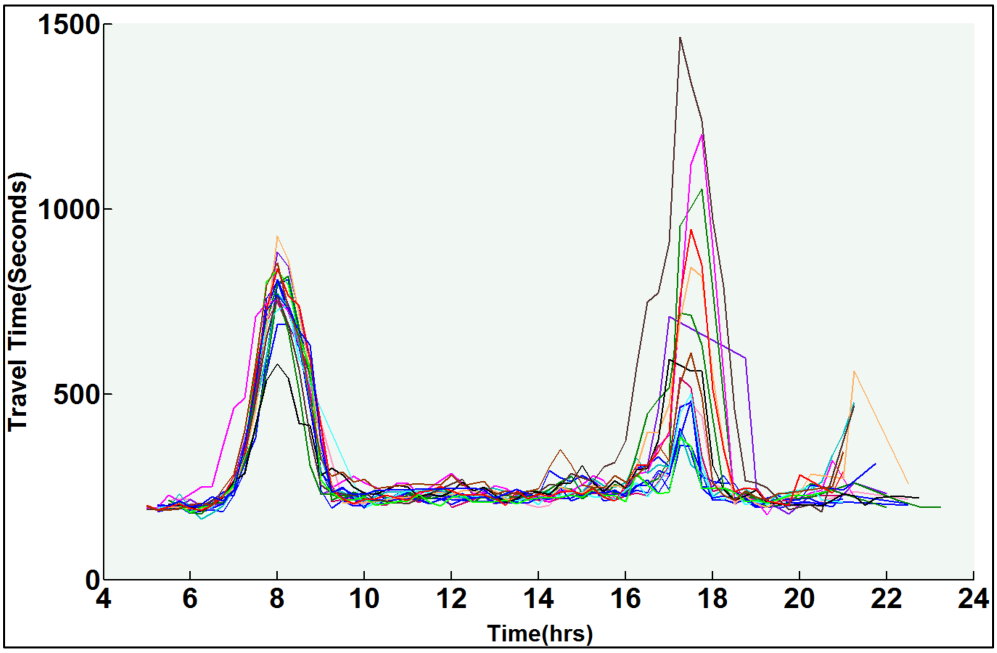

Figure 4-2: Travel Time Variation (Inbound) February 2014-Coronation Drive All Working Days

4.3.2 Variation of Buffer Time Index(BTI) – All working Days

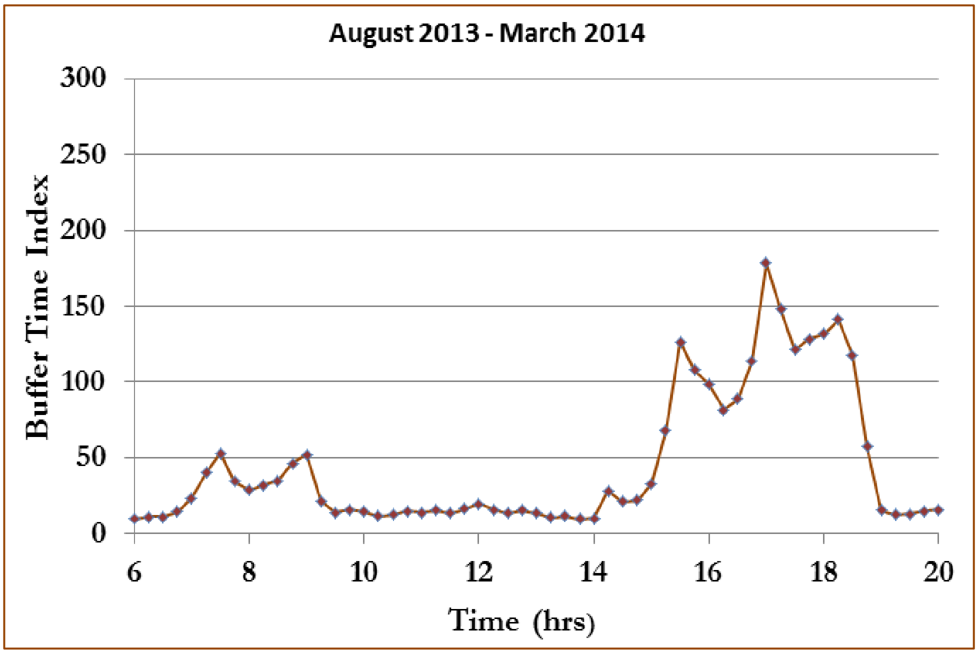

Figure 4-3: Variation of Buffer Time Index – All working Days

Analysing the results for ***All Working Days***, it is observed that compared to the evening peak the morning peak does not experience high congestion. The Buffer Time Index (BTI) varies between 9.50% – 53.00% in morning peak period (Figure 4-3). As per the analysis done for evening peak time, results show that this corridor is highly congested for inbound traffic in the evening peak period, and the BTI varies between 15% -178% within this time period.

4.3.3 Variation of Buffer Time Index - Recurrent Working Days

Refer to Figure 4-4: for ***Recurrent Working Days***, the range for BTI was 9.00% -52.00% in the morning peak time . This shows, there's no that much of impact of incidents on the travel time reliability of inbound traffic in the morning peak period of Corronation Drive. However, for the evening peak time the corridor is highly congested for inbound traffic. For ***All Working Days***, BTI varies between 15% -178%, while for ***Recurrent Working Days*** this range becomes 15.00% - 111.00%.

Refer to Figure 4-5 and Figure 4-6: The buffer time (orange region in the figures) experiences high values when analysing for ***All Working Days*** (Figure 4-5). These values drop down when the analysis perform for ***Recurrent Working Days*** (Figure 4-6).

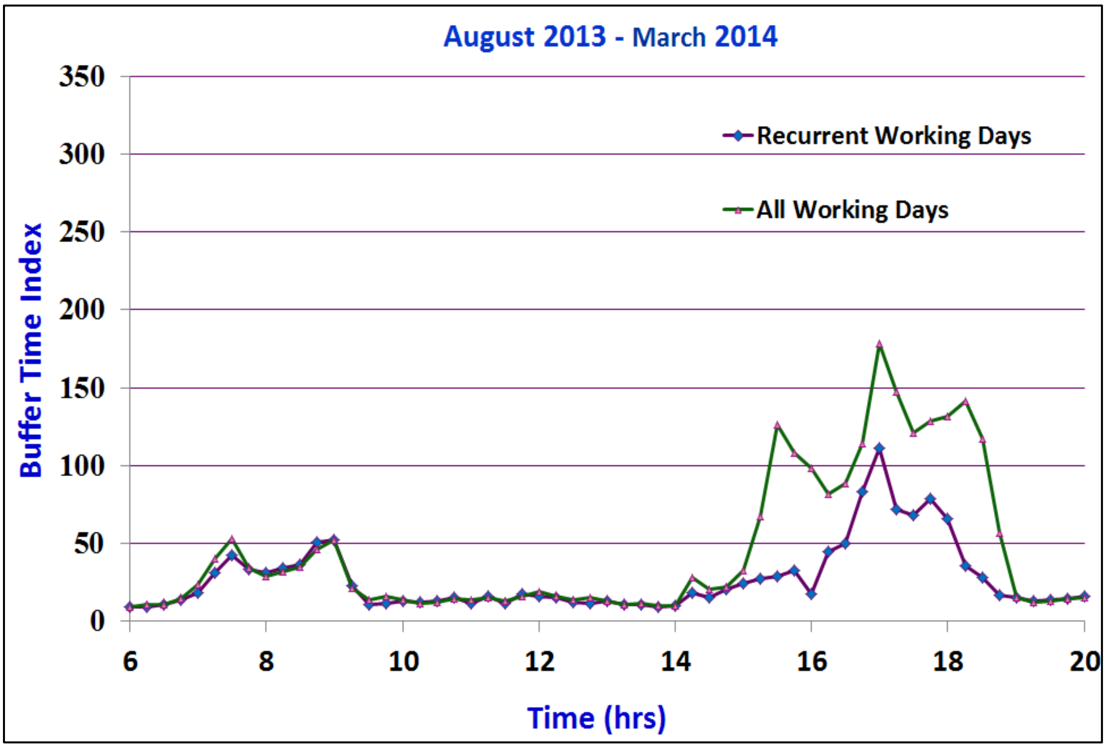

Figure 4-4: Variation of Buffer Index –All working days and recurrent working days

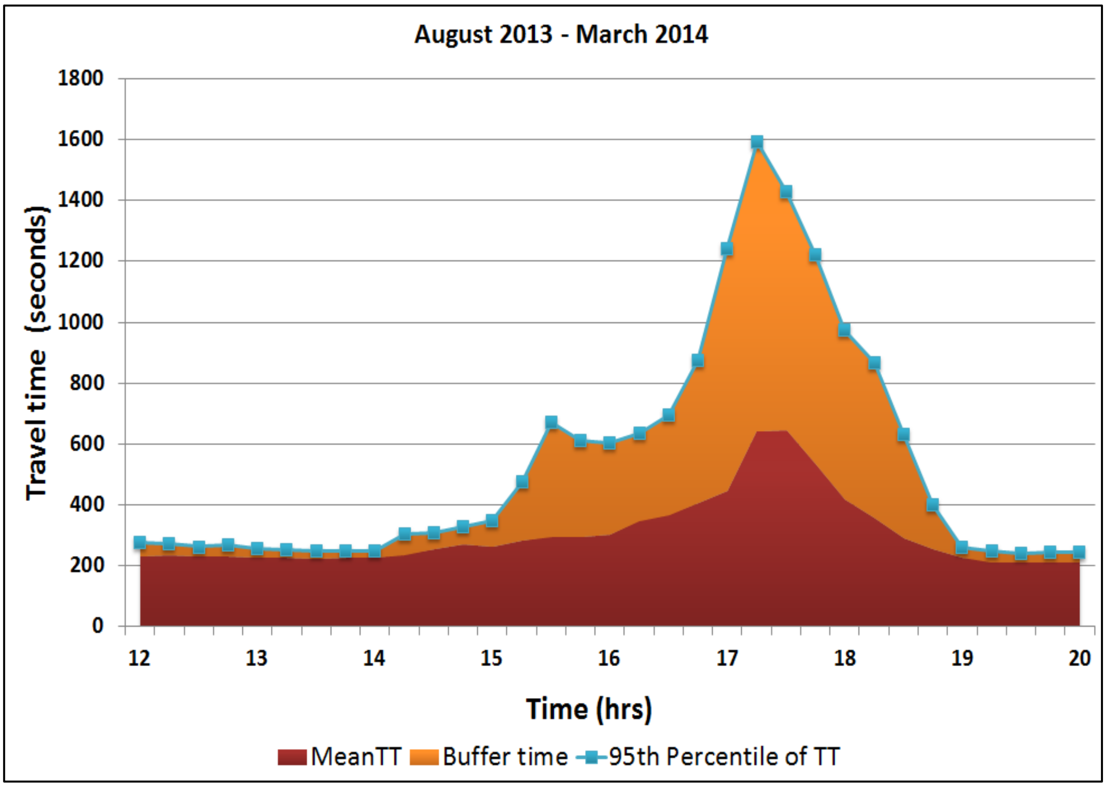

Figure 4-5: Buffer Time – All Working Days

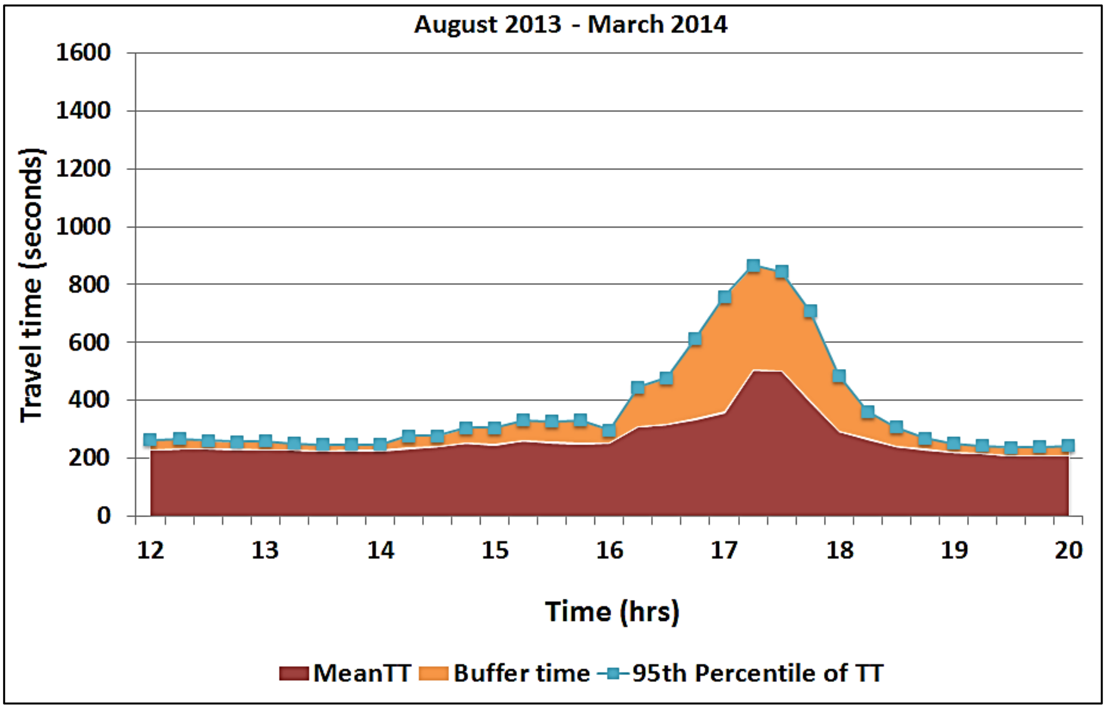

Figure 4-6: Buffer Time – Recurrent Working Days

The results are summarized in Table 4-1, which provides the maximum values of Buffer Time and BTI experienced in the evening peak time for ***All Working Days*** and ***Recurrent Working Days.*** It can be summarised that:

- Percentage increase of Buffer Time Index due to incidents in the evening = 60.00%

Table 4-1**:** Buffer Time and Buffer Time Index values

	All Working Days	**Recurrent Working Days**
Buffer Time Index (6.00am –9.30am)	53.00%	52.00%
Buffer Time Index (3.00pm –7.00pm)	178.00%	111.00%
Buffer Time(seconds) (6.00am –9.30am)	238.00	219.00
Buffer Time(seconds) (3.00pm –7.00pm)	950.00	400.00

4.3.4 Variation of Travel Time Index (TTI)

Travel Time Index (TTI) measures the congestion intensity and compares the average travel time to free flow travel time. Similar to the previous case, the analysis of TTI was performed for evening peak time for ***All Working Days*** and ***Recurrent Working Days*** separately. The results obtained from the analysis are depicted in Figure 4-7.

Variation of TTI – All Working Days:

As per the observations, TTI varies around 1.32 up to 4.00pm when there’s free flow condition. When congestion onset around 4.00pm, TTI starts to increase and rises up to maximum value of 2.80 at 5.30pm. Then it starts to drop down and reaches to free flow condition around 7.00pm.

Variation of TTI – Recurrent Working Days

As per the observations and as illustrated in Figure 4-7, the variation pattern of TTI is approximately similar to that of ***All Working Days***, but at the peak period, the value of TTI reaches to 2.18, which is 0.62 less than that of ***All Working Days***. The difference of TTI clearly demonstrates between 5.15pm and 6.15pm. This difference of TTI shows that there's an impact of incidents on average travel time.

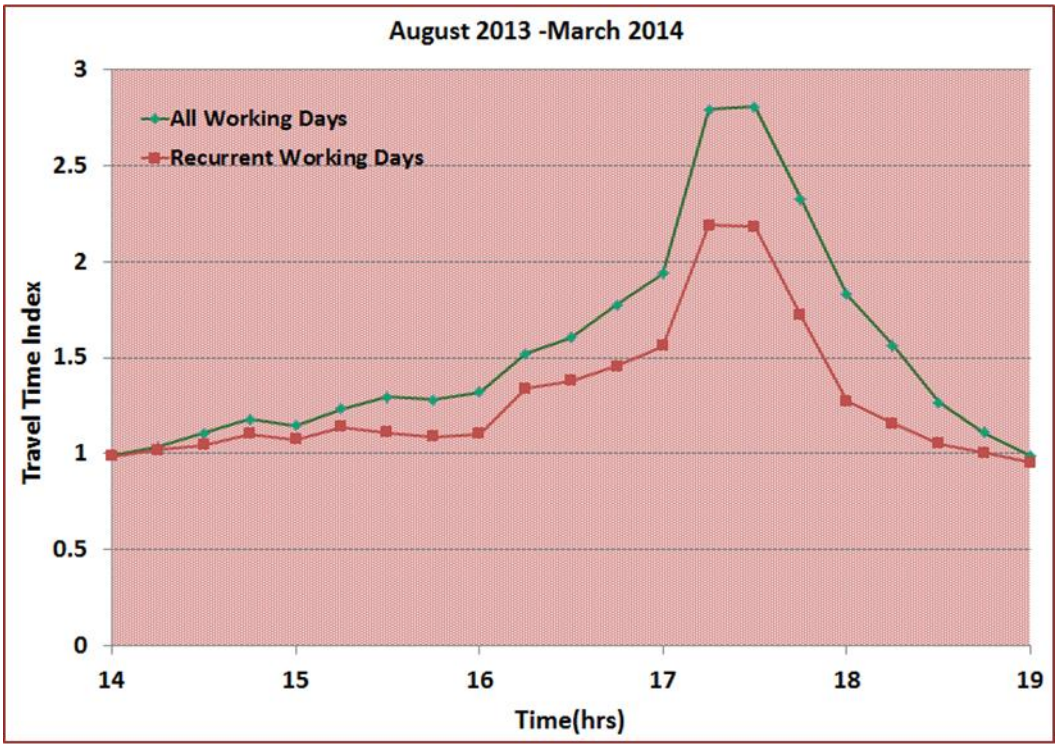

Figure 4-7: Variation of Travel Time Index– Evening Peak Time

Table 4-2: Variation of Travel Time Index – Evening Peak Time

Time	All Working Days	Recurrent Working Days
4.00pm	1.32	1.10
5.30pm	2.80	2.18
6.30pm	1.26	1.05

Table 4-2 provides the maximum values of TTI experienced in the evening peak time from 4.00pm to 6.30pm for ***All working Days*** and ***Recurrent Working days*** respectively.

4.3.5 Variation of Planning Time Index (PTI)

Variation of PTI – All Working Days:

As per the observations (Figure 4-8), variation of PTI could be clearly defined with the travel time variation pattern within the period 3.00pm – 7.00pm, which is evening peak time. When congestion onset, PTI starts to increase from 3.00pm and rises up to maximum value of 6.92 at 5.15pm. Then it starts to drop down and reaches to an average value of 1.14 with free flow condition around 7.00pm. These results indicate that the Coronation Drive is highly congested and unreliable in evening peak time for inbound traffic.

Variation of PTI – Recurrent Working Days

Table 4-3 provides the maximum values of PTI experienced in the evening peak time from 3.00pm to 6.45pm for ***All Working Days*** and ***Recurrent Working Days*** respectively. For ***Recurrent Working Days,*** the variation pattern of PTI is approximately similar to that of ***All Working Days*** up to 3.00pm, but the peak time starts at 4.00pm and PTI reaches to 3.77 at 5.15pm. This value is 3.15 less than that of ***All Working Days***. This difference of PTI indicates that there's a considerable impact of incidents on average travel time.

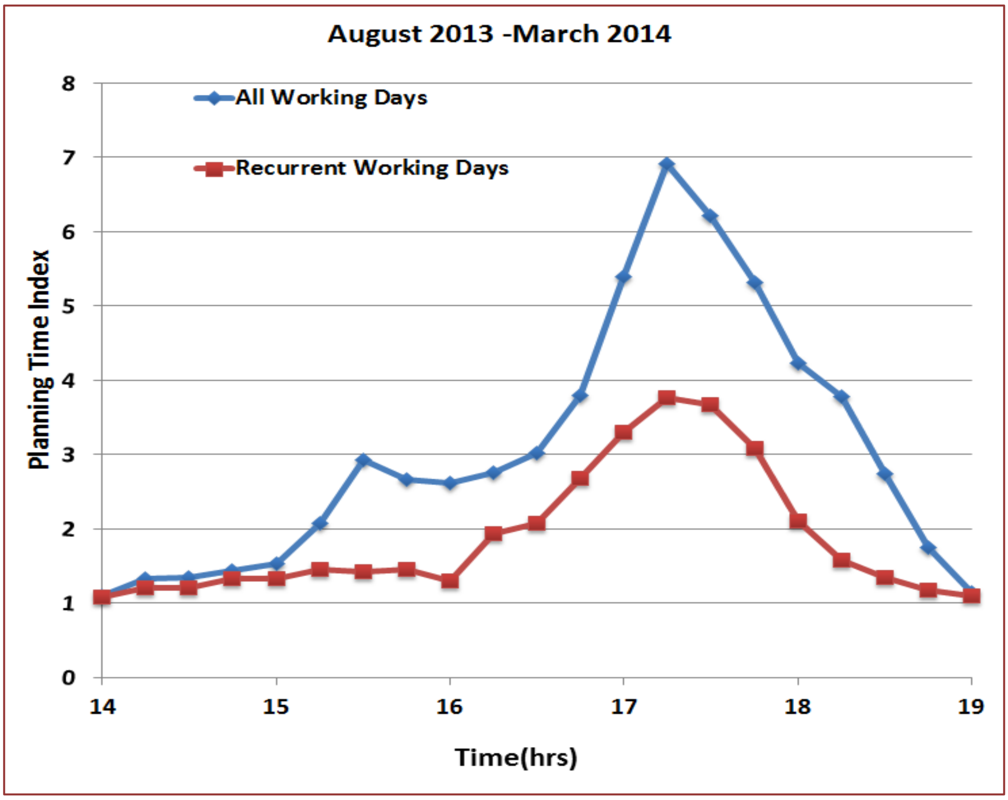

Figure 4-8: Variation of Planning Time Index – Evening Peak Time

Table 4-3: Variation of Planning Time Index – Evening Peak Time

Time	All Working Days	Recurrent Working Days
3.00pm	1.52	1.33
5.15pm	6.92	3.77
6.45pm	1.74	1.18

Table 4-3 provides the maximum values of PTI experienced in the evening peak time from 3.00pm to 6.45pm for ***All Working Days*** and ***Recurrent Working Days*** respectively.

4.3.6 Variation of C_v – All Working Days:

As per the observations, and as illustrated in Figure 4 - 9, C_v rises up to 0.3 in the morning peak time at 8.45am. Then it starts to decrease and reach to a value of 0.1 at 10.00am. When there's free flow condition, C_v varies between 0.10 – 0.07 up to 2.00pm. When congestion onset around 2.00pm, C_v starts to increase and rises up to maximum value of 0.77 at 6.00pm. Then it starts to drop down and reaches to an average value of 0.11 around 8.00pm.

Variation of C_v **– Recurrent Working Days**

As illustrated in Figure 4 - 9, the variation pattern of C_v is similar to that of ***All Working Days*** in the morning. But at the evening peak time, the value of C_v reaches to 0.43 at 5.00pm., which is 0.34 less than that of ***All Working Days.*** This difference of C_v indicates that there's a considerable impact of incidents on the variation of average travel time.

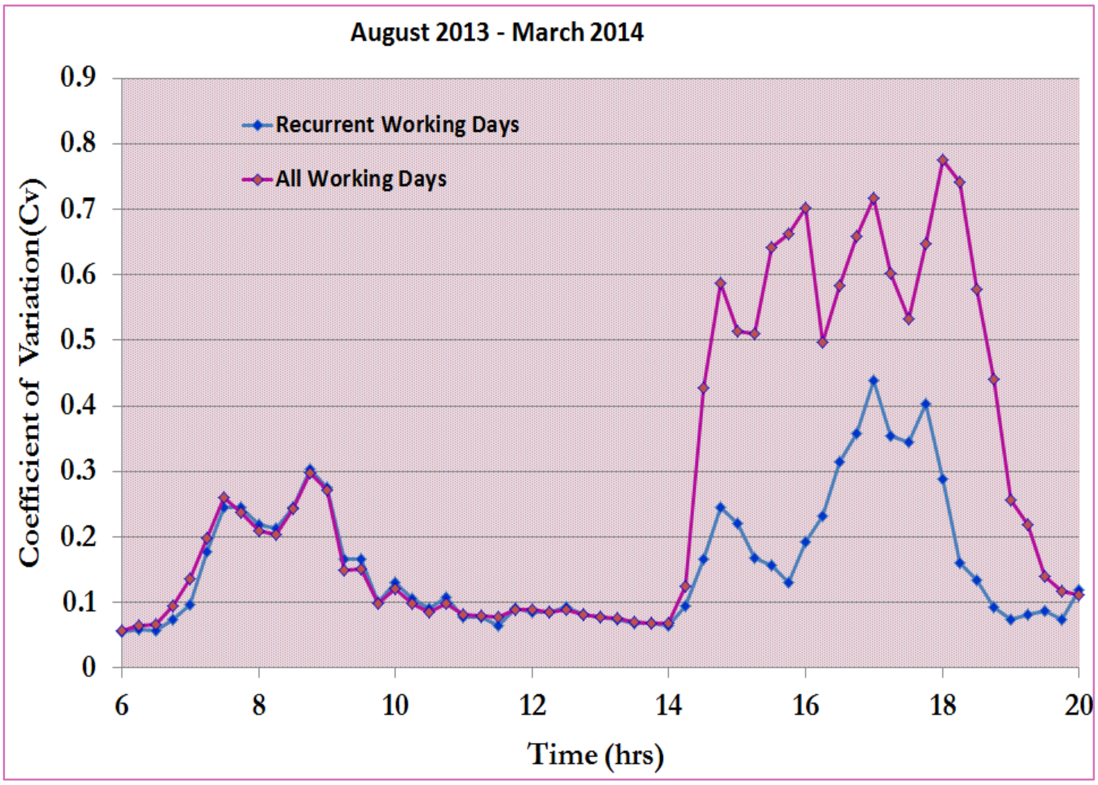

Figure 4-9: Variation of Coefficient of Variation (Cv)

Table 4-4: Variation of Coefficient of Variation (C_v) – Evening Peak Time

Time	All Working Days	Recurrent Working Days
2.00pm	0.07	0.07
5.00pm	0.71	0.43
6.00pm	0.77	0.40
8.00pm	0.11	0.11

Table 4-4 provides the maximum values of $\mathbf{C_v}$ experienced in the evening peak time from 2.00pm to 8.00pm for ***All Working Days*** and ***Recurrent Working Days*** respectively.

4.3.7 Comparison of Reliability measures for Coronation Drive

This study evaluated the Planning Time Index (PTI), Buffer Time Index (BTI), Travel Time Index (TTI) and Coefficient of Variation (Cv). The variation patterns of different indicators for ***All Working Days*** are depicted in Figure (4-10). The results indicate that the different reliability indicators exhibit the similar trend with the increasing traffic congestion, and the traffic congestion and degree of impact of incidents directly related to the travel time reliability.

As per the results, the highest values observed for PTI, BTI, TTI and Cv were 6.92, 1.78, 2.80 and 0.77 respectively, which recorded around 5.30pm. A good correlation between four reliability measures could be observed all the day. The correlation coefficients between different indicators are provided in table 4-5.

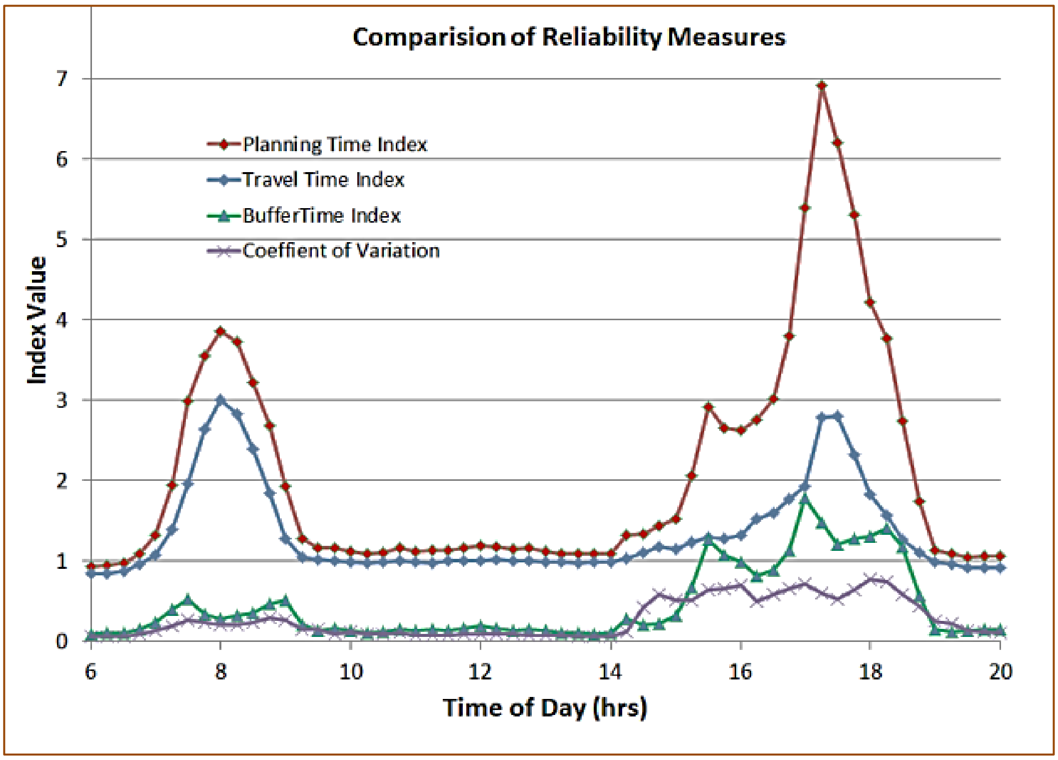

Figure 4-10: Comparison of Reliability measures for Coronation Drive (All Working Days)

Table 4-5**:** Correlation Coefficients

Reliability Indicators	**Correlation Coefficients**
PTI - Cv	0.72
BTI - Cv	0.90
PTI - TTI	0.88
PTI - BTI	0.84

4.4 DISCUSSIONS

In this study, four reliability indicators were evaluated to analyse the travel time reliabilityindicators on selected road corridor, and incident records were used to examine the inpact of incidents on travel time reliability.

According to the results obtained for Coronation Drive, following observations were made.

- Coronation Drive is congested for inbound traffic, both in the morning and the evening peak periods. Analysing the morning peak time, it is observed this corridor experiences a regular congestion in the morning and it is more reliable compared to the high congestion in the evening peak period.
- As per the observations, evening peak period is highly congested and significant travel time variations were recorded resulting unreliability in travel time.
- The travel time reliability and the impact of incidents on travel time reliability with the variation pattern of buffer time, BTI, and PTI could be clearly observed and defined using the BMS data obtained.
- The increase of BTI due to incidents is nearly 60%. This indicates that there's a significant impact of incidents on travel time reliability, and the reduction in incidents and its durations will not only reduce congestion, but also has the potential to enhance its reliability.
- PTI at free flow condition varies between 1.10 – 1.55. This rises upto 6.92 at high cogestion. This indicates, at high congestion, commuters have to plan nearly 5 times on there trips than travel time at free flow condition.

- C_v varies exactly in the same pattern up to the start of evening peak time, in both catogories indicating high travel time reliability. (***All Working Days*** and ***Recurrent Working Days***) Then it starts to increase rapidly after 2.00pm, and the variation pattern becomes different. In the analysis of ***All Working Days***, it rises upto 0.77, and for ***Recurrent Working Days***, the maximum value is 0.40. This difference of C_v indicates the considerable impact of incidents on travel time reliability.

- The selected reliability indicators (BTI, TTI, PTI & Cv) represent the travel time reliability of Coronation Drive well, demonstrating a good correlation between them. This indicates that only few indicators are necessary for studying the travel time reliability. Table 4-6 compares the indicators for ***All Working Days*** and ***Recurrent Working Days.*** It is observed that Cv has the highest difference in the values. This indicates that Cv should be a better indicator to quantify the non-reliability due to incidents.

Table 4-6: Percentage increase of reliability measures due to incidents

Reliability Indicator	*All Working Days*	*Recurrent Working Days*	Percentage Increased
BTI	1.78	1.11	60.36%
PTI	6.92	3.77	83.55%
Cv	0.77	0.40	92.50%
TTI	2.80	2.18	28.44%

Chapter 5: Conclusions

Since high traffic congestion leads to high variability and unreliability of travel times in urban arterial roads, travel time reliability measures are becoming increasingly important input to the congestion management studies; hence, this research investigates the traffic congestion and travel time reliability on a main arterial road in Brisbane analysing the impact of incidents on traffic flow, one of the main sources of congestion and its unreliability.

From the literature, a series of reliability indicators were reviewed. One conclusion is, travel time reliability definitions are diverse and there's no clear detailed definition of travel time reliability, or general agreement in using suitable reliability indicators. The most widely used indicators namely Buffer Time Index, Planning Time Index, Travel Time Index and Coefficient of Variation were selected to analyse the travel time reliability on Coronation Drive, Brisbane.

Seven sources of traffic congestion were reviewed from the literature. According to the impact of different sources, traffic congestion is divided into two groups as recurrent congestion and non-recurrent congestion. Travel time unreliability increases during non- recurrent congestion. In literature, it has been observed that the incidents can contribute to over 25% of the congestion on the urban network. Acknowledging this fact, this study was conducted to empirically evaluate the aforementioned reliability indicators, incorporating the impact of incidents on travel time reliability. The analysis was performed for both recurrent and non-recurrent congestion.

In this research, a review of Bluetooth technology was performed so as to have better understanding on the use of Bluetooth MAC Scanner (BMS) for travel time estimation. In recent years, BMS has gained significant interest of both practitioners and researchers as a cost-effective transport data source. This research analysed BMS and incident records from Brisbane City Council. Travel time profiles from the eight months of BMS data were obtained through appropriate matching and filtering of the BMS records between selected BMS stations on Coronation Drive. The travel time profiles were classified into working days and incident days for analysing the impact of the incidents on the travel time reliability. It is important to identify confidence in the travel time estimates from the BMS data. In this research, the time periods with lower Bluetooth sample size were not considered for the analysis.

From these results, it was concluded that incorporating the impact of incidents on travel time reliability has a considerable effect on analysis, particularly on the evaluation of reliability measures. The traffic incidents decreased the travel time reliability significantly. For instance, the congested state became more dominant during evening peak time, and BTI increased up to 178%. The percentage increase of BTI due to incidents was 58%. Similarly, the value of PTI increased up to 6.92 at peak time due to incidents, and the percentage increase of PTI was 52%.

A good correlation between four reliability measures (PTI, BTI, TTI & C_v) could be observed as depicted in figure 4-10. As given in table 4-5, the correlation coefficients between each reliability measures were 0.90, 0.72, 0.88, and 0.84 respectively, for BTI - C_v, PTI - C_v, PTI -TTI, and PTI – BTI respectively.

The overall conclusion drawn is that the occurrence of incidents significantly impacted the traffic congestion and travel time reliability. The selected reliability indicators perform well and correlate representing the travel time reliability on Coronation Drive.

This research has a practical significance as it provides a comparative overview of the different reliability measures. The practical significance of different indicators were identified which is valuable for the transport authorities to identify vulnerable routes on their networks. It can also be used as an operational performance measure. This study proposes to use the outcome of this research in traveller information systems, to supply with reliable travel time information to travellers. For researchers, it provides an insight on the different reliability measures that can be used for research, integrating reliability with modelling, network analysis and route choice.

More empirical research is necessary with respect to the impact of other sources of congestion, which described in chapter 2.

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Appendices

Figure A-1**: Daily Travel Time Series for Coronation Drive (August 2013)**

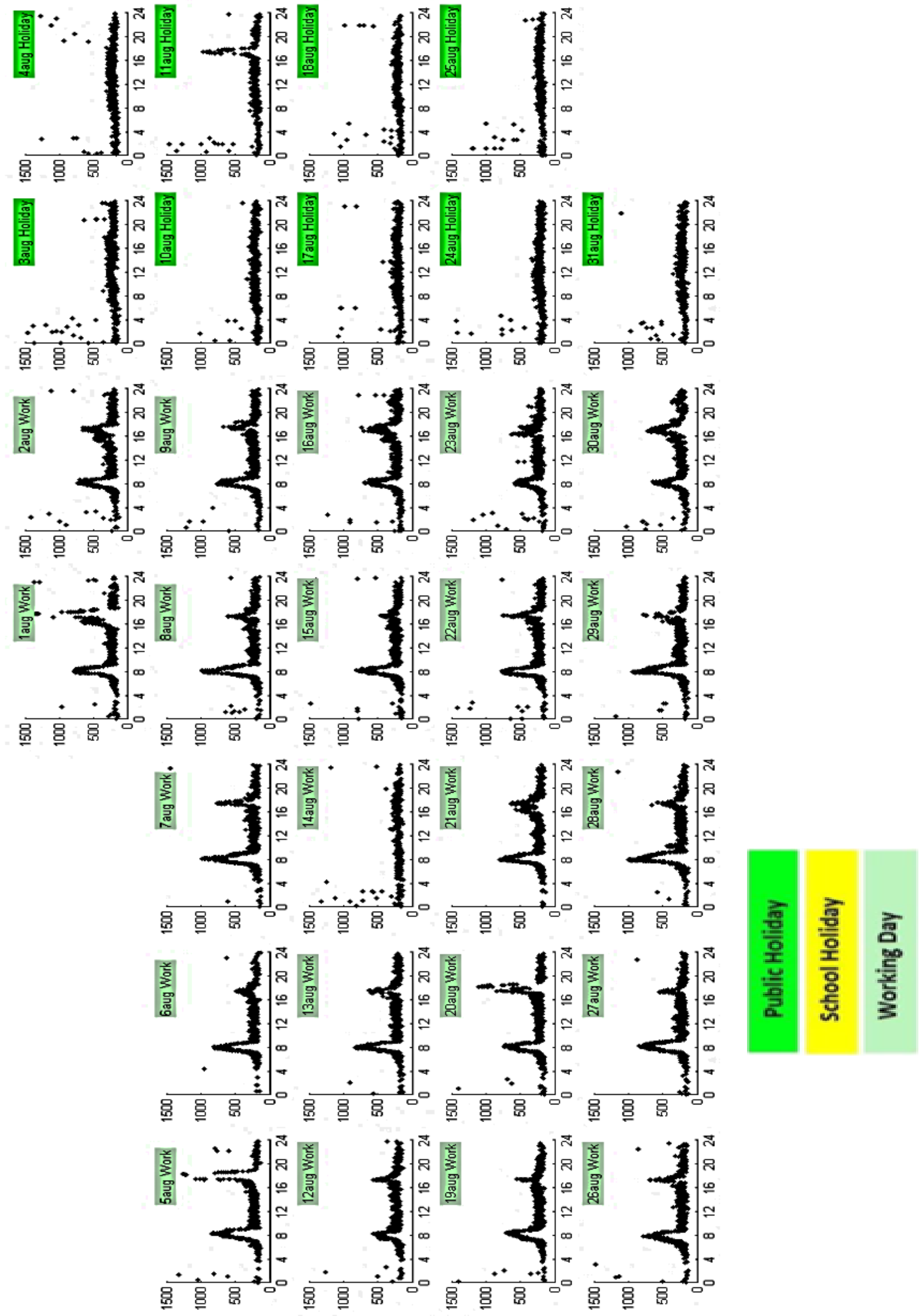

Figure A-2: **Daily Travel Time Series for Coronation Drive (September 2013)**

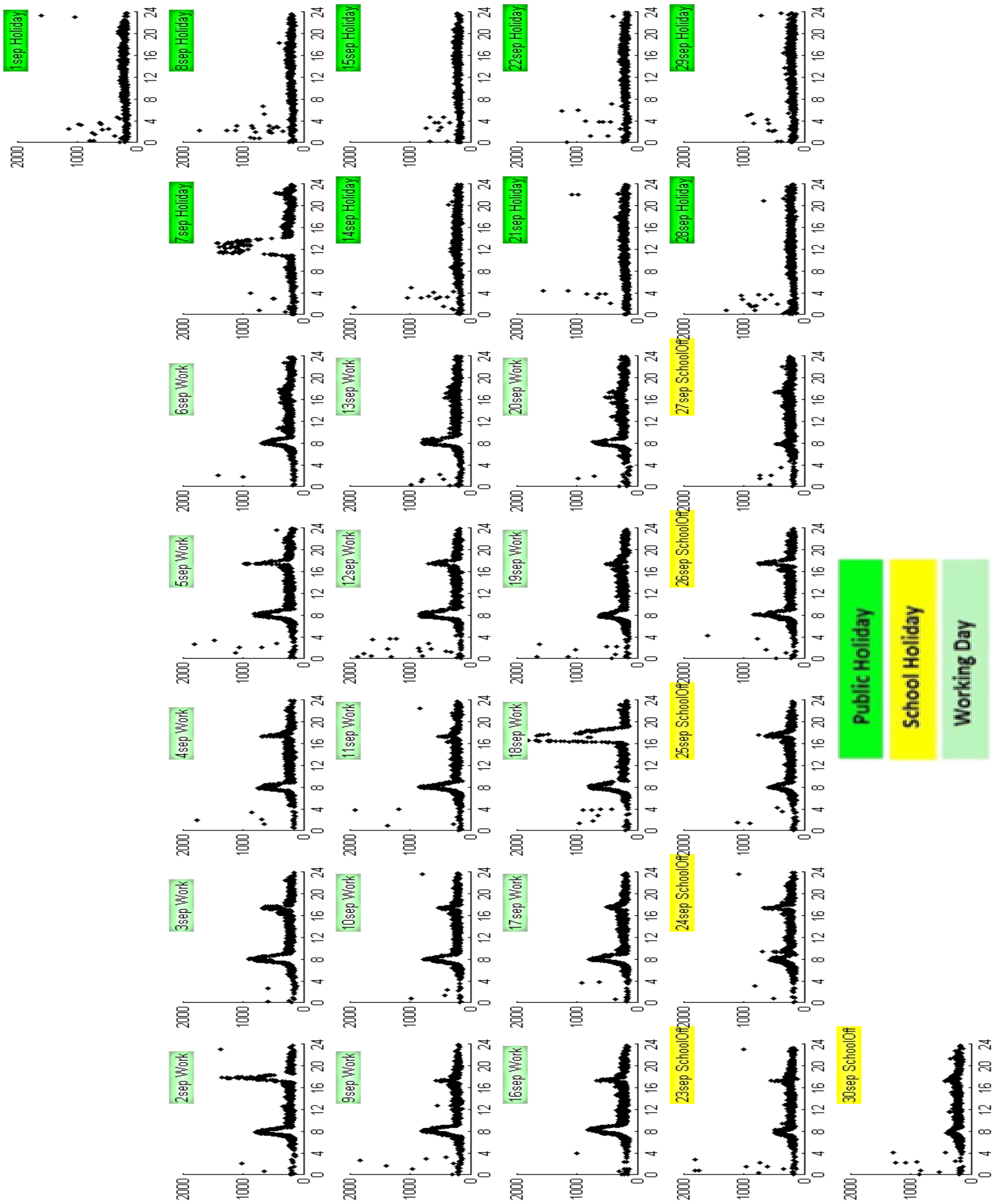

Figure A-3: **Daily Travel Time Series for Coronation Drive (October 2013)**

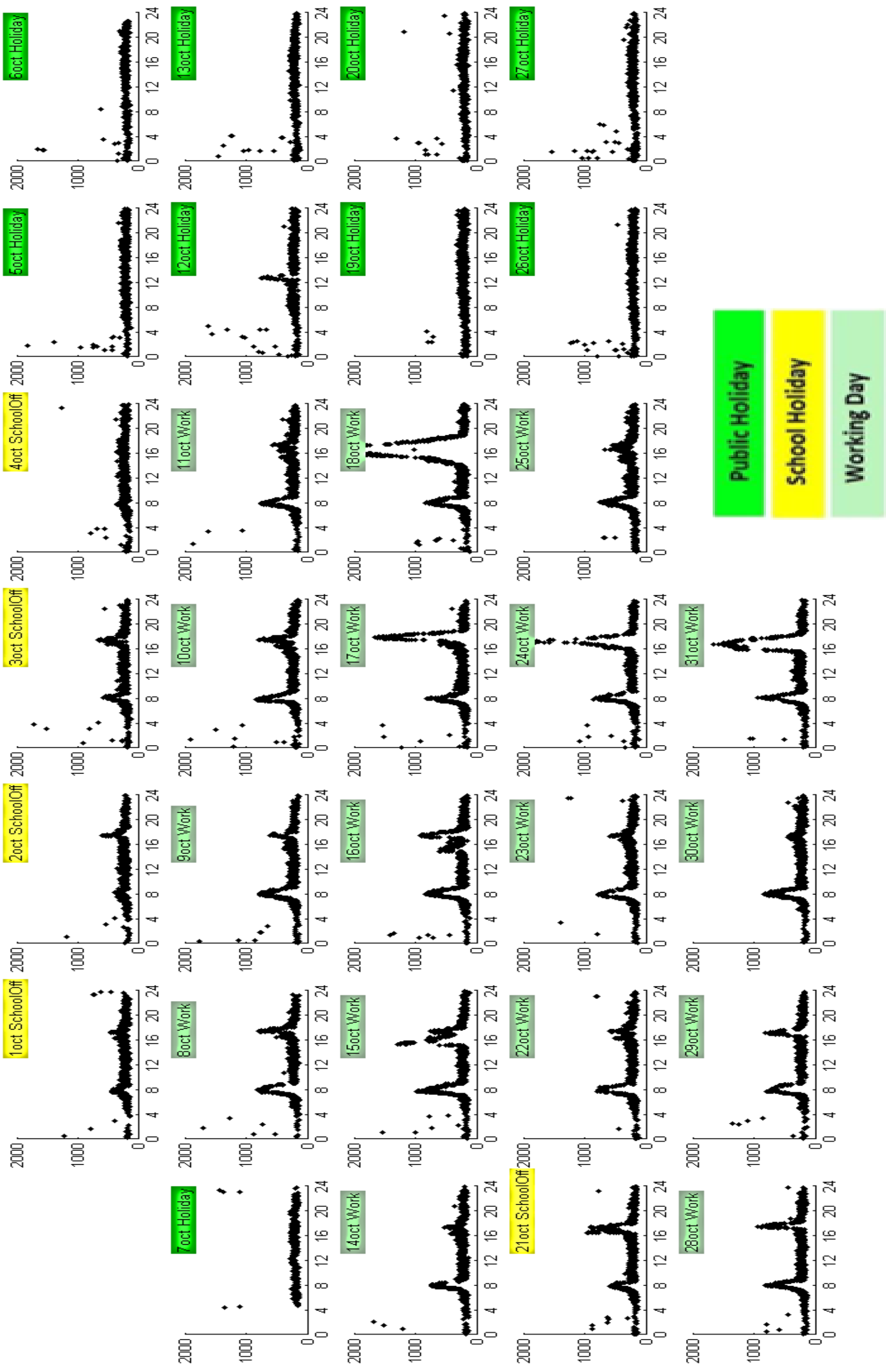

Figure A-4: **Daily Travel Time Series for Coronation Drive (November 2013)**

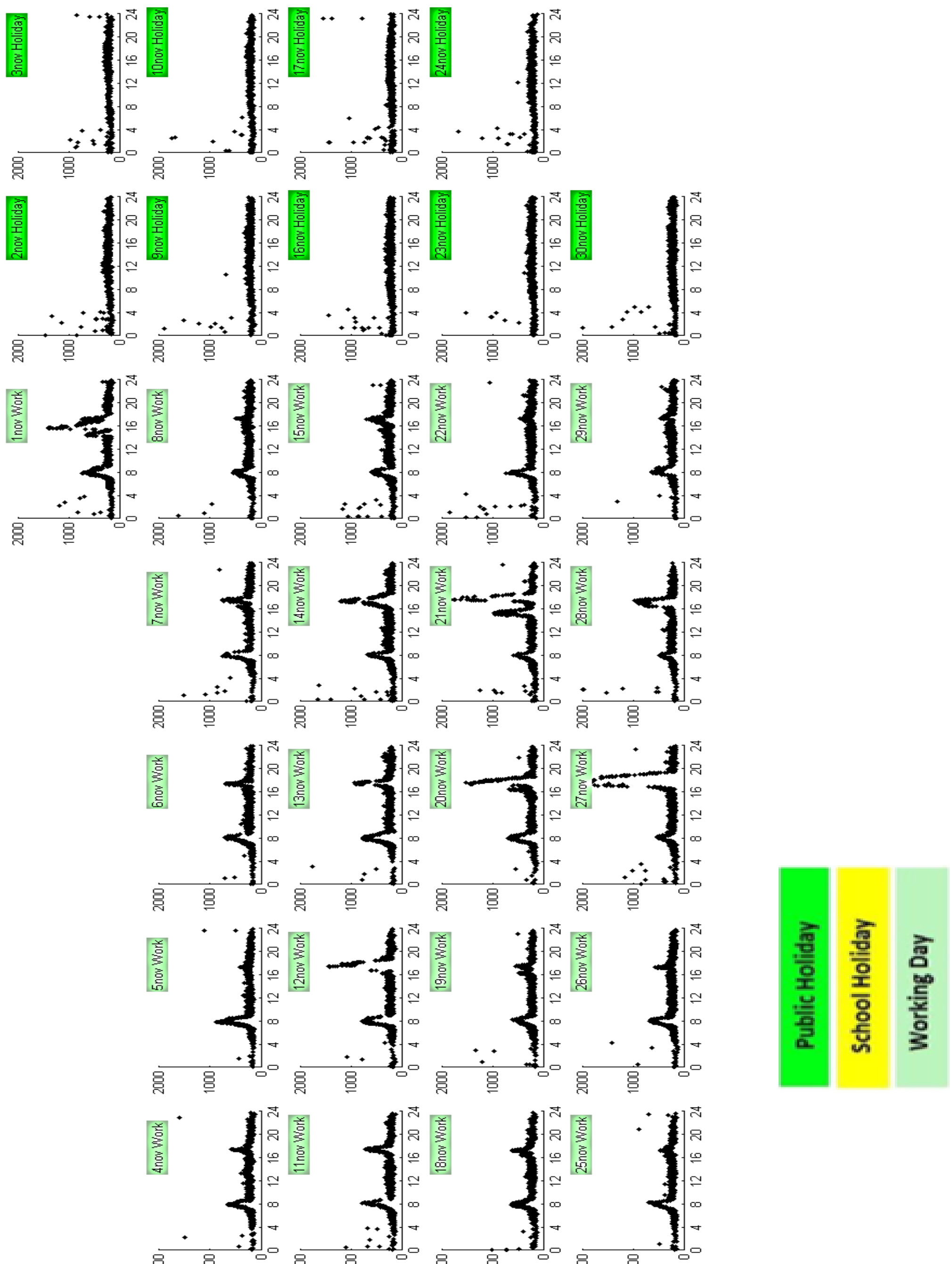

Figure A-5: **Daily Travel Time Series for Coronation Drive (December 2013)**

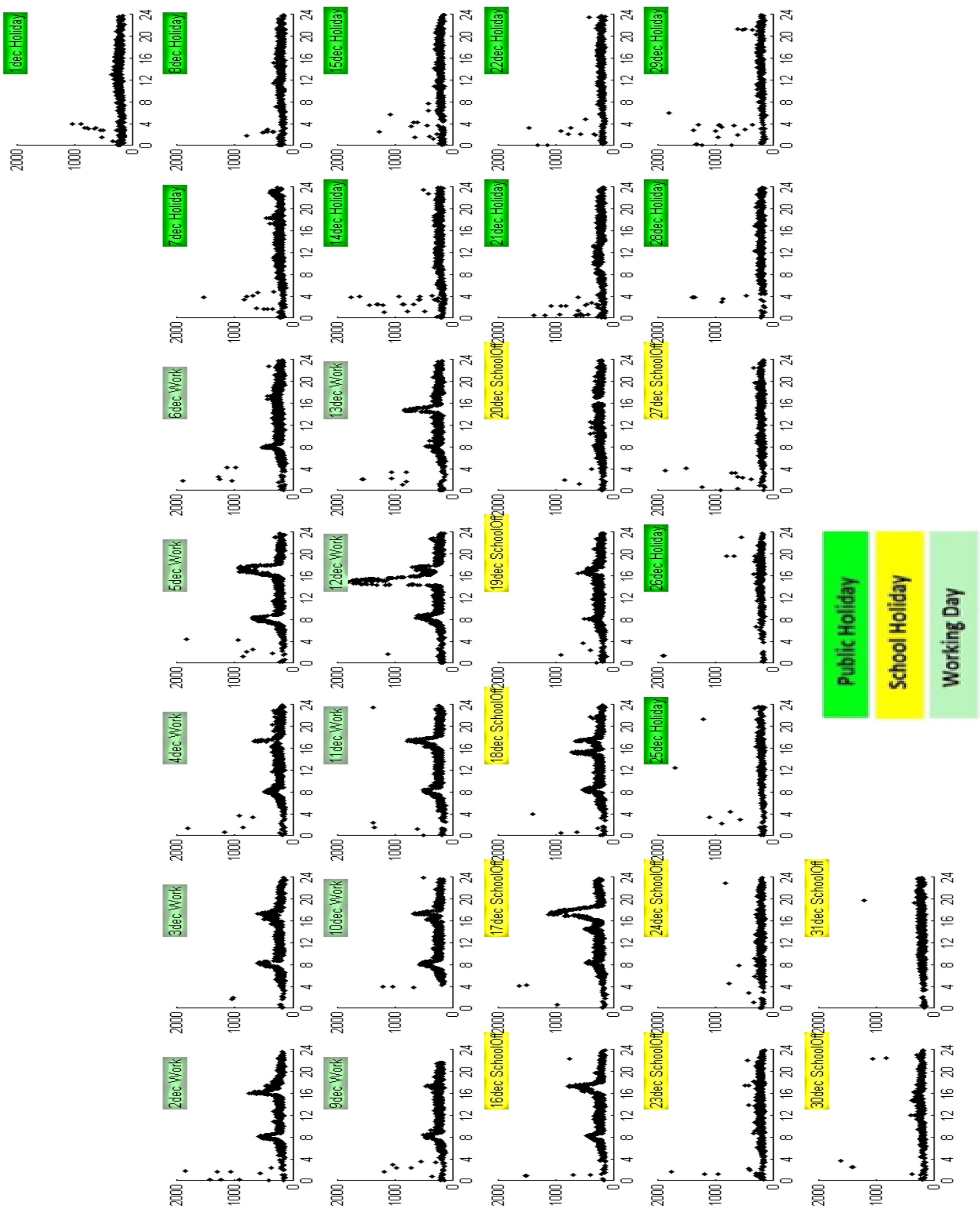

Figure A-6: **Daily Travel Time Series for Coronation Drive (January 2014)**

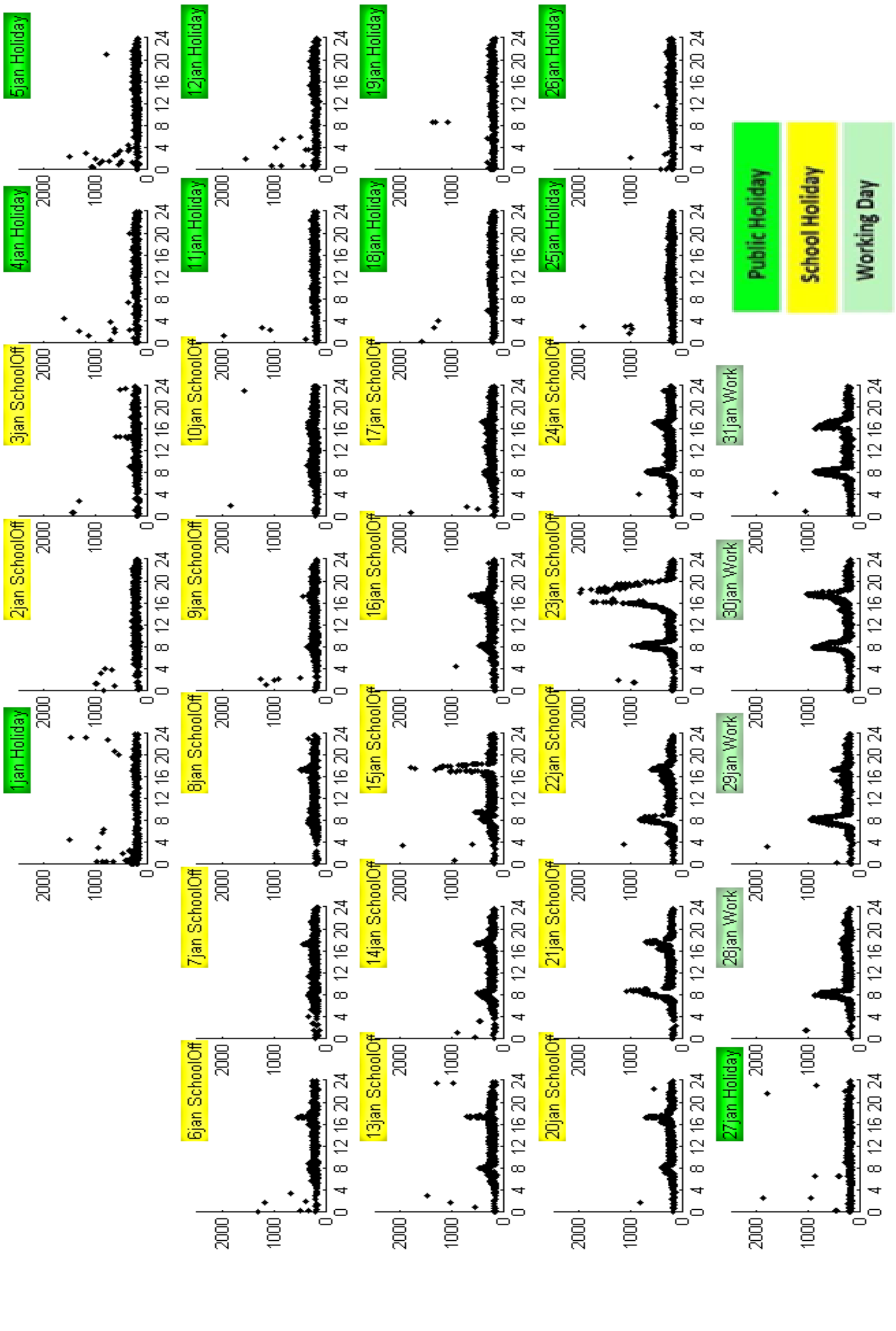

Figure A-7: **Daily Travel Time Series for Coronation Drive (February 2014)**

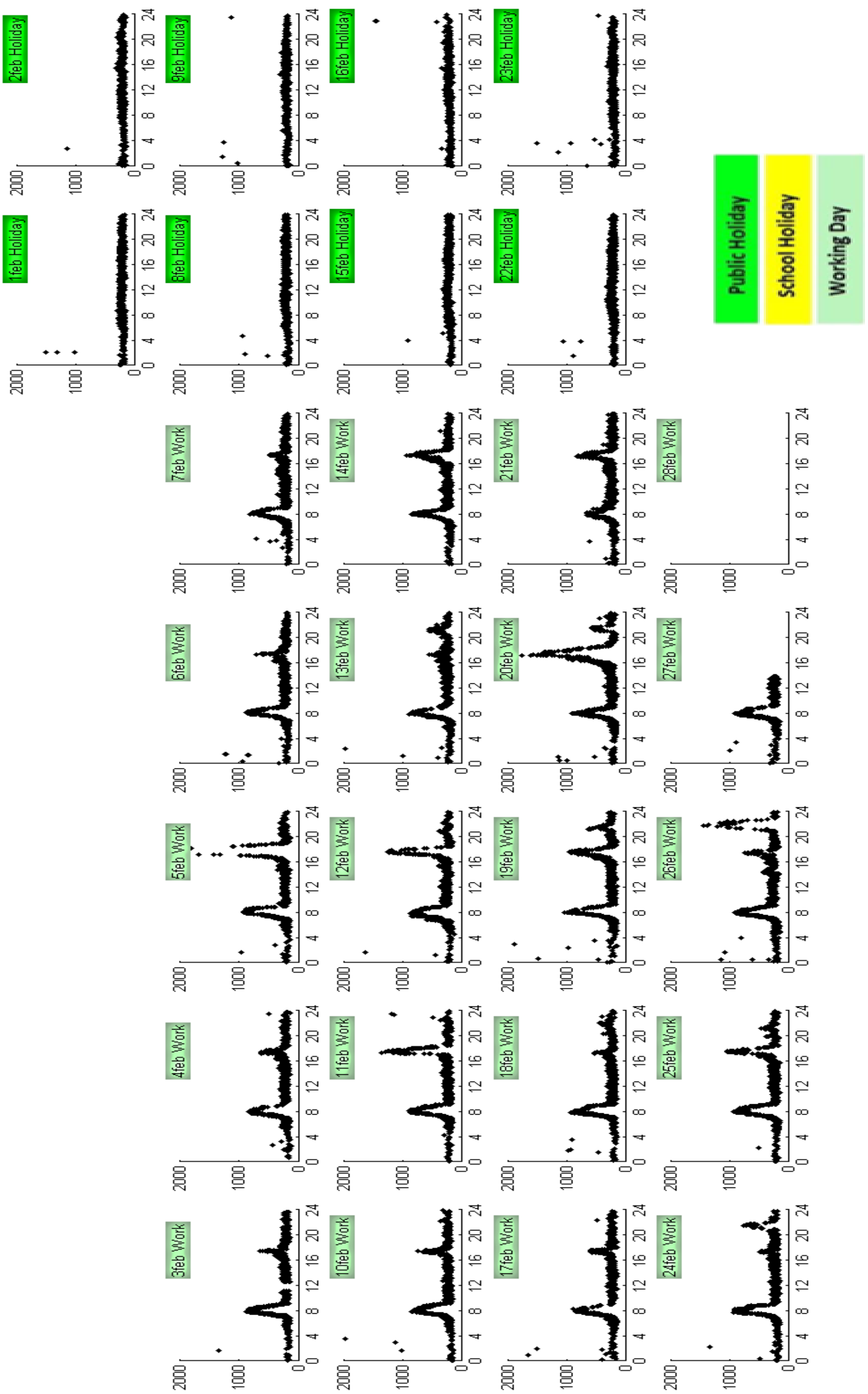

Figure A-8: **Daily Travel Time Series for Coronation Drive (March 2014)**