Travel Time Reliability and Level of Service

Marlene Beverley Russell
Louisiana State University and Agricultural and Mechanical College, mruss26@lsu.edu

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_theses
Part of the Civil and Environmental Engineering Commons

Recommended Citation
Russell, Marlene Beverley, "Travel Time Reliability and Level of Service" (2014). LSU Master's Theses. 3747.
https://digitalcommons.lsu.edu/gradschool_theses/3747

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Master’s Theses by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
TRAVEL TIME RELIABILITY AND LEVEL OF SERVICE

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Civil Engineering

in

The Department of Civil and Environmental Engineering

by

Marlene Russell
B.S., University of the West Indies, 1998
August 2014
ACKNOWLEDGEMENTS

I would like to thank Professor Sherif Ishak for guiding me throughout my study and for generously providing my funding during this Master’s degree program. I would also like to thank my other committee members Dr Guo and Dr Elseifi for their feedback and suggestions.

Special thanks to Julius Codjoe for his help, encouragement and support. Thanks also to fellow students for all the help and fund memories.

I am deeply grateful to my family and friends for all their love and support.
## TABLE OF CONTENTS

ACKNOWLEDGEMENTS........................................................................................................ ii

LIST OF TABLES................................................................................................................ iv

TABLE OF FIGURES............................................................................................................. v

ABSTRACT............................................................................................................................ vi

1. INTRODUCTION ............................................................................................................. 1
   1.1 Problem Statement..................................................................................................... 2
   1.2 Objectives .................................................................................................................. 4

2. LITERATURE REVIEW ................................................................................................. 5
   2.1 HCM’s Level of Service (LOS) ................................................................................ 5
   2.2 Travel Time Reliability Measures with LOS ......................................................... 8
   2.3 Determining Route Choice with TTR ................................................................. 16
   2.4 Review of TTR Applications ........................................................................... 17
   2.5 A LOS Case Study ............................................................................................ 18
   2.6 The Travel Time Index versus the Buffer Index ............................................. 20
   2.7 Relation between Average Travel Speed and Travel Time ............................ 21

3. STUDY AREA AND TRAFFIC DATA ............................................................................ 22
   3.1 Source of Data ...................................................................................................... 22
   3.2 Missing data and outliers .................................................................................... 23
   3.3 Assessment of study area ................................................................................. 24
   3.4 Assessing Travel Time Reliability on the I-12 .................................................. 25

4. METHODOLOGY ............................................................................................................ 27
   4.1 Formulation of New Buffer Index ....................................................................... 27
   4.2 Comparison of new with existing Buffer Index ............................................... 30
   4.3 Reporting TTR and LOS from existing traffic data ........................................... 33

5. RESULT AND ANALYSIS ............................................................................................ 34
   5.1 Reporting TTR and LOS: Step 1 ....................................................................... 34
   5.2 Reporting TTR and LOS: Step 2 ....................................................................... 36
   5.3 Reporting TTR and LOS: Step 3 ....................................................................... 37
   5.4 Reporting TTR and LOS: Step 4 ....................................................................... 40

6. CONCLUSIONS .............................................................................................................. 41
   6.1 Future Research .................................................................................................... 41

REFERENCES ..................................................................................................................... 43

VITA ........................................................................................................................................ 46
LIST OF TABLES

TABLE 1 Definition of LOS from the HCM................................................................. 5

TABLE 2 SHRP 2 L08 Project Team’s Freeway Reliability LOS defined by Travel Speed and TTI Ranges .................................................................................................................. 8

TABLE 3 Main TTR Measures Examined ..................................................................... 10

TABLE 4 Comparison of differences between new and existing BI based on speed ranges ...... 31

TABLE 5 Assessment of Segments 1, 2, 3 and 4 for year 2013/14 ........................................ 36

TABLE 6 Comparison of TTIs on the I-12 and from the SHRP 2 L08 Project Team’s Freeway Reliability LOS Definition .................................................................................................................. 37

TABLE 7 Comparison of TTI and BI for Segment 4 on the I-12 ........................................ 39
# TABLE OF FIGURES

FIGURE 1 Cumulative distribution of Travel Time for I-12 Walker to Juban (January 2012) ... 11
FIGURE 2 Cumulative distributions of ATT for I-12 Juban to Range (June 2012) ............... 19
FIGURE 3 Cumulative distributions of ATT for I-12 Range to Millerville (June 2012) .......... 19
FIGURE 4 Cumulative distributions of ATT for I-12 Millerville to Airline (June 2012) ......... 20
FIGURE 5 Sample of BlueTOAD data .................................................................................. 23
FIGURE 6 Map of I-12 from Walker South Road to Essen Lane .......................................... 24
FIGURE 7 Histograms of travel time on the I-12 Juban to Range (March 2011 and 2012) ...... 26
FIGURE 8 Histograms of travel time on the I-12 Juban to O’Neal (Jan 2011 and June 2011) ... 26
FIGURE 9 Histograms of travel time on the I-12 Juban to O’Neal (June 1st and 2011) ........... 26
FIGURE 10 Plot of new BI versus existing BI for 10 segments on the I-12 ............................. 32
FIGURE 11 Location of the four analysed segments on the I-12 ........................................... 35
FIGURE 12 Travel Time Index for segment 4 on the I-12 ...................................................... 40
FIGURE 13 Buffer Index for segment 4 on the I-12 .............................................................. 40
ABSTRACT

Travel time reliability (TTR) is familiar to travelers, and its indices are useful measures of the quality of a freeway’s service. Technical groups such as highway agencies are more familiar with a freeway’s level of service (LOS), but the LOS does not capture the variability in travel time. Similar to Pu (2011) this thesis introduces a modified buffer index (BI) incorporating a median rather than average travel time as a new travel time reliability measure. Current research by the SHRP 2 L08 Project Team defines freeway reliability LOS by determining equivalent travel time index for similar travel speed ranges shown on page 8 in TABLE 2. It is anticipated that the new index will be able to provide an additional model for defining LOS using TTR as a service measure on freeway corridors. Data from the BlueTOAD (Bluetooth Travel-time Origination and Destination) devices, which utilize Bluetooth technology, was used to develop a methodology to determine a LOS of the highway facility with the use of the new TTR index and a section of the I-12 highway was used for this study. The Wilcoxon Signed Ranked test was used to assess whether the difference between the median values of the new and existing BIs at various speed ranges are significant. From the Wilcoxon Signed Ranked test the difference between the new and existing BI was found to be significant for speed ranges \( s_r \geq 60 \text{mph} \), \( 50 \leq s_r \leq 59 \), \( 45 \leq s_r \leq 49 \), \( 40 \leq s_r \leq 44 \), \( 35 \leq s_r \leq 39 \), but not \( s_r < 35 \text{mph} \). However the BI was inconclusive in providing an accurate measure for defining LOS. This is due to the data showing an increasing linear upward trend from LOS A to LOS C but then starts decreasing linearly downwards from LOS D to LOS F. More analysis is needed at all the speed ranges and should be carried out on several segments along the I-12 corridor instead of one segment in order to obtain comprehensive results. Data, including volume data for an entire year is also needed to comprehensively analyse the LOS.
1. INTRODUCTION

There are several definitions of transportation system reliability based on various studies; that which focuses on the probability of trips that can be successfully carried out at the specified time (the travel time reliability); trips that can be successfully completed based on the remaining connectivity between an OD pair (connectivity reliability) and also trips that can be carried out at certain level of the link capacity (capacity reliability) (Bell and Iida, 2003). The focus of this thesis paper is on travel time reliability rather than capacity or connectivity reliability. Travel time reliability is one of the key performance measures used by a number of public agencies in the States (Texas Transportation Institute and Cambridge Systems, Inc, 2009). The Second Strategic Highway Research Program (SHRP 2) estimates reliability as one of the four transportation factors that need to be addressed when a highway capacity expansion decision is being made (Lint et al 2008).

Notwithstanding the importance of travel time reliability, it is being measured by researchers and planners in various ways. This is due to the classification of travel time reliability into two categories; one being performance-driven reliability measures, and the other being travelers’ response to reliability. Practical applications such as monitoring the performance of transportation systems are essentially carried out using performance-driven measures while on the other hand, response measures are used in research to combine uncertainty into travel demand or economic modeling to accurately reflect traveler’s choice behavior. Lomax et al (2003) were the earliest researchers to use travel time reliability measures as a practical performance measure. They recommended the use of the percent variation, misery index, and buffer time index and consequently the U.S. Department of Transportation (DOT) recommended 90th or 95th percentile travel time, buffer index, planning time index, and

It is generally considered that different travel time reliability measures are positively correlated, and hence an increase in one measure will lead to an increase in another. It has also been found that level of service (LOS) and travel time are related, but there is a need for a direct relationship to be established between travel time reliability and LOS for general road conditions. The relation between travel time and LOS shows that; under LOS A-E the travel time is low and consistent while under LOS F the travel time is 3 times longer than free flow traffic conditions and the standard deviation is also much greater (Chen et al, 2003). The LOS for freeways is given on a scale from A to F in the Highway Capacity Manual (HCM) based on density of vehicles per mile per lane (Transportation Research Board, 2010). This is a spatially localized measure and it is used to analyze the operation of specific locations, such as a weaving section (Cassidy and May, 1991) and to design freeways (Lin and Su, 1998). Level F is normally considered stop-and-go traffic which is unacceptable, while A-D are generally acceptable by drivers.

1.1 Problem Statement

Studies have shown that commuters and road users value travel time and travel time reliability. Travel time reliability (TTR), is familiar to travelers, and its indices are useful measures of the quality of a freeway’s service. Technical groups such as highway agencies are more familiar with a freeway’s level of service (LOS), but the LOS does not capture the variability in travel time. It is more related to technical aspects such as road design rather than
the user’s experience during their trip. There is a need for a model to determine LOS from existing TTR indices. This is because TTR is of equal importance to travelers and technical groups and as such there is a need to have a TTR index which can additionally be used to give an accurate indication of the LOS of the facility.

From studies into several TTR indices, the buffer index and the percent variation, which statistically is known as coefficient of variation, rose above others as the preferred travel time reliability indices, and have appeared to resonate with most audiences. However, for the buffer index previous studies have assumed for example Weibull and normal distributions of travel time reliability, but no verification was made with real-life traffic data, which directly impacts the accuracy of predicting reliability. In a study by Pu (2011) it is recommended that defining the Buffer Index on the basis of the median, rather than the average, will avoid underestimating the reliability in travel time, especially for heavily right-skewed travel time distributions. Similarly to Pu this thesis introduces a modified buffer index incorporating a median rather than average travel time as a new travel time reliability measure. Current research by the SHRP 2 L08 Project team defines freeway reliability LOS by determining equivalent travel time index for similar travel speed ranges as shown in TABLE 2 on page 8. Similar to the existing travel time index, it is anticipated that the new index will be able to provide an additional model for defining LOS using TTR as a service measure on freeway corridors. This model will be of benefit to road users by providing a reliable TTR index as well as to technical audiences who will additionally be able to determine a facility’s LOS by using the new TTR index.
1.2 Objectives

The primary goal of this study is to develop a model (methodology) to determine the level of service (LOS) of a highway facility based on a new travel time reliability (TTR) measure. To accomplish the goal, the specific objectives are:

- Develop a new TTR index by presenting a modified Buffer Index that can additionally be used to give an accurate indication of the LOS of the facility.
- Develop a methodology that can be used to determine the LOS of a facility with the use of the new TTR index consisting of a 4 step process that is outlined in section 4.3.

Suitable traffic data for the study was accessed from the BlueTOAD (Bluetooth Travel-time Origination and Destination) devices, which utilize Bluetooth technology. A section of the I-12 highway from the system interchange with US 447/Walker South Road to the interchange with US 3064/Essen Lane will be used for this study. An assessment was carried out to verify a segment that has good quality data available. This is the first step of the 4 step process. The other three steps involved carrying out mathematical calculations in Microsoft Excel 2010 to obtain the Travel Time Index and the modified Buffer Index of the highway facility. The Travel Time Index values were compared with that of the SHRP 2 L08 Project Team’s values from their Freeway Reliability LOS definition. Also the Buffer Index and the Travel Time Index values were compared and then the criteria for the new Buffer Index ranges corresponding to specific LOS ranges determined.
2. LITERATURE REVIEW

This chapter provided a review of level of service and travel time reliability measures. The first section reviewed the Highway Capacity Manual’s Level of Service (LOS) for a road segment. The second section reviewed travel time reliability measures and points out the suitability of these in measuring LOS. The third section reviewed travel time reliability for determining route choice. The fourth section briefly describes the applications of travel time reliability. The fifth section looks at a case study to evaluate the LOS of road network based on travel time reliability. The sixth section summarises the difference between the Travel Time Index and the Buffer Index. Finally the seventh section briefly describes the relation between travel time and average travel speed.

2.1 HCM’s Level of Service (LOS)

The Highway Capacity Manual Volume 2: Uninterrupted Flow (Transportation Research Board 2010) defines the LOS of a homogenous road segment on a scale from A to F based on vehicle density, defined in TABLE 1.

<table>
<thead>
<tr>
<th>LOS</th>
<th>Density (pc/mi/ln)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( \leq 11 )</td>
</tr>
<tr>
<td>B</td>
<td>( &gt;11 - 18 )</td>
</tr>
<tr>
<td>C</td>
<td>( &gt;18 - 26 )</td>
</tr>
<tr>
<td>D</td>
<td>( &gt;26 - 35 )</td>
</tr>
<tr>
<td>E</td>
<td>( &gt;35 - 45 )</td>
</tr>
<tr>
<td>F</td>
<td>( &gt;45 ) or ( v_d/c ) ratio &gt;1.00</td>
</tr>
</tbody>
</table>


In the HCM, the equation that is used to estimate the density of the traffic stream is;
\[ D = \frac{\mathcal{V}p}{S} \]  
(1)

where \( D \) = density (pc/mi/ln)

\( \mathcal{V}p \) = demand flow rate (pc/h/ln)

and \( S \) = mean speed of traffic stream under ideal conditions (mi/h).

But the HCM only uses the demand flow rate, \( \mathcal{V}p \) when the \( \mathcal{V}p/c \) ratio is less than or equal to 1.00. All cases in which this ratio is greater than 1.00 are LOS F and in these cases no speed/ or density can be estimated.

Chen et al (2003) proposed the following equation;

\[ K = \frac{O}{L} \]  
(2)

where density \( K \) is in miles per vehicle

\( O \) is vehicle occupancy

and average length \( L \) is in miles per vehicle and estimated with a g-factor algorithm (Jia et al 2001).

This study was able to find a link between LOS and travel time. They stated that the HCM’s six levels of service do not capture the variability of travel time and that the traveller best understands the level of service in terms of time and the journey taken. From tests carried out under each level of service they were able to plot the mean and standard deviation of travel time that help prove this relationship.

Ni et al (2012) pointed out that the model now employed by the HCM to predict what they state as “conditions where speeds begin to decline slightly with increasing flow” in LOS D is not “slightly” declining but is instead piecewise. Ni proposes a Longitudinal Control Model
(LCM) that is free of piecewise constraints and may give better measures for highway LOS, given by the following equation;

$$v = v_f \left[ 1 - e^{(1 - k^*/k)} \right] \quad (3)$$

where $v$ is traffic space-mean speed, $v_f$ is free flow speed, $k$ is traffic density and

$$k^* = 1/(\gamma v^2 + \tau v + l)$$

($\gamma$ = aggressiveness = 0.0307s$^2$/m, $\tau$ = perception reaction time = 1.25s, $l$ = vehicle length = 3.95m)

The authors recognize that there may have to be further exploration and analysis of equation 3 as the parameters in the equation such as $\gamma$ (aggressiveness), $\tau$ (perception reaction time) and vehicle length $l$ may need to be looked at in more detail. However, the LCM model does estimate travel time based on traffic speed as a function of traffic flow assigned to a route.

Within the reviewed literature, the SHRP 2 L08 Project team (2012) are currently conducting research aiming to incorporate travel time reliability measures into the Highway Capacity Manual. The team as their main research objectives are: (a) determining how data and information on the impacts of differing causes of non-recurrent congestion can be incorporated into the performance measure estimation procedures in the HCM, and (b) developing methodologies to predict travel time reliability on select freeways such as freeway facilities and urban streets. For instance, the project team proposes to determine equivalent travel time index for similar travel speed ranges (TABLE 2). These travel speeds are analogous to space mean speed and are determined over the whole freeway segment. They propose that travel speed ranges be produced for freeways similar to that done for urban streets. The travel speed ranges or LOS ranges are based on percentages of the free flow speed similar to that done for urban streets.
However, it may be necessary to extend the number of LOS ranges for oversaturated conditions because of the insensitivity of travel speeds to a wide range of density and v/c values (current LOS A through D).

TABLE 2 SHRP 2 L08 Project Team’s Freeway Reliability LOS defined by Travel Speed and TTI Ranges

<table>
<thead>
<tr>
<th>LOS</th>
<th>Travel Speed* and Equivalent TTIs</th>
<th>Percent of Trips in Each LOS Range, Weekdays, 4:30 – 6:00 PM</th>
<th>Seattle, I-405</th>
<th>Atlanta, I-75, Northside</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&gt;=60 (TTI &lt;= 1.083)</td>
<td>27.7% 1.6% 0.4% 15.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>50—59 (1.083 &lt; TTI &lt;= 1.300)</td>
<td>71.9% 48.3% 6.6% 80.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>45—49 (1.300 &lt; TTI &lt;= 1.444)</td>
<td>0.3% 12.0% 3.2% 1.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>40 – 44 (1.444 &lt; TTI &lt;= 1.625)</td>
<td>0.0% 9.3% 8.5% 0.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>35 – 39 (1.625 &lt; TTI &lt;= 1.857)</td>
<td>0.1% 11.0% 14.4% 0.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>&lt; 35 (TTI &gt; 1.857)</td>
<td>0.0% 17.8% 66.8% 1.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean TTI</td>
<td>1.016 1.352 1.984 1.050</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*could also be defined as percentages of free flow speed; travel speed is the space mean speed over the facility.

2.2 Travel Time Reliability Measures with LOS

Pu (2011) investigated the analytic and quantitative relationships between travel time reliability measures. Pu expresses a subset of reliability measures in terms of the shape parameter and/or the scale parameter of the lognormal distribution on the assumption of lognormal distributed travel times and the use of percent point distribution. The paper listed those reliability
measures that are encouraged (or discouraged) by various sources in the past decade as shown in TABLE 3 and illustrated in FIGURE 1 such as the FHWA (2006), the NCHRP Report 618 (2008) and SHRP 2 (2008). It was shown that the buffer index and the planning time index are the most encouraged on the list. Pu recommended the use of the coefficient of variation as a good proxy or representation for a number of other reliability measures including planning time index, median-based buffer index and skew statistics since amongst various factors, its magnitude relative to other measures are rather stable. This is not the case with the standard deviation statistics and is therefore not recommended as a proxy. But it was suggested that there might be a way to replace standard deviation with coefficient of variation (ratio of standard deviation to the mean) in the assessment of the value of reliability. Other findings are that the buffer index and percent of on-time-arrival should be defined based on median, rather than average to avoid underestimating reliability. The paper found that travel time reliability generally deteriorates as traffic congestion increases as shown by the relationship between reliability measures and the travel time index. This reliability measure therefore may be suitable to measure LOS since under free flow conditions the LOS is maximized at its optimum potential, but if the maximum travel time increases above this, i.e. the travel time index is an increasing positive number, it indicates congestion i.e. drivers may not be able to drive at optimum speed hence the LOS is decreasing.
<table>
<thead>
<tr>
<th>TTR measure</th>
<th>Definition</th>
<th>Recommendation of measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>95\textsuperscript{th} or other Percentile travel time</td>
<td>This measures the delay occurring during the heaviest traffic days on a particular route.</td>
<td>Its use as a TTR measure is recommended by the FHWA Guide (2006)</td>
</tr>
<tr>
<td>Buffer index</td>
<td>This is a measure of the additional time a driver takes to complete the journey over the time taken for normal conditions. It is defined as the difference between the 95\textsuperscript{th} percentile travel time and the average travel time, and then divided by the average travel time.</td>
<td>This TTR measure is widely encouraged by various sources such as Lomax et al (2003), FHWA Guide (2006), NCHRP Report 618 (2008), SHRP 2 (2008)</td>
</tr>
<tr>
<td>Planning time index</td>
<td>This measures the total travel time (including buffer time) and is calculated usually as the 95\textsuperscript{th} percentile travel time over free-flow travel time expressed as a ratio.</td>
<td>This TTR measure is encouraged by various sources such as FHWA Guide (2006), NCHRP Report 618 (2008), SHRP 2 (2008)</td>
</tr>
<tr>
<td>Percent variation</td>
<td>This measures the ratio of the standard deviation to the mean, ie the coefficient of variation, expressed as a percentage. It expresses the relationship between the amount of variation and the average travel time in a percentage measure.</td>
<td>Its use as a TTR measure is recommended by Lomax et al (2003), and NCHRP Report 618 (2008).</td>
</tr>
<tr>
<td>Travel time index</td>
<td>This measures the actual average travel time over free-flow travel time expressed as a ratio.</td>
<td>Its use as a TTR measure is neither encouraged nor discouraged</td>
</tr>
</tbody>
</table>
FIGURE 1 Cumulative distribution of Travel Time for I-12 Walker to Juban (Jan 2012)

The TTR measures examined can directly be calculated from FIGURE 1. The red arrow in FIGURE 1 represent the 95th percentile travel time and has a value of 3.5 minutes for this segment on the I-12 between Walker South Road and Juban Road. The blue arrow represents the mean or average travel time and has a value of 3.05 minutes, while the yellow arrow represents the free flow travel time and has a value of 2.98 minutes. Therefore the buffer index is 15% and the planning time index is 1.17 minutes along this segment of the I-12 between Walker and Juban for the period January 2012.

Susilawati et al (2010) investigated the use of the Buffer time index and the Planning index as the performance measures in ten selected corridors of the Adelaide road network in Australia. These indices were obtained based on eight years consecutive travel time data and a GPS probe vehicle survey system gathered the travel time data for three different times of day,
AM peak, off peak and PM peak. The findings reveal that the buffer time index as well as the planning index may not be enough to represent the travel time reliability because of the significant variation of the 95th percentile and mean travel time. It showed that there were also many differences in buffer time index results among the corridors and for some the differences are much larger than others. This shows though that this reliability measure may be suitable to measure LOS as the buffer time index is a measure of the additional time a driver takes to complete the journey over the time taken for normal conditions. It may be possible to establish a relationship between the percentage increase of time against the normal time as a measure of LOS and so if the buffer time increases the LOS decreases.

Higatani et al (2009) investigated the numerical characteristics of existing travel time reliability indices defined by the U.S. Department of Transportation (US-DOT). These travel time reliability measures are the planning time, planning time index, buffer time, and the buffer time index. The study for the research paper was carried out on the Hanshin Expressway network in Japan. A comparative evaluation of the performance among several radial routes was performed using these indices. The findings of the paper revealed that the reliability indices were able to capture various characteristics of travel time fluctuations but whereas average travel time shows two prominent peaks in a day, buffer time and buffer time index may not always have two similarly prominent peaks. They stated that this may be due to the instability of the length of congestion hours noted in the study. These reliability indices were found to be important measures in understanding the characteristics of traffic congestion of each route and hence these measures were shown to be suitable as measures of LOS. Furthermore the planning time is the total travel time (which includes buffer time) and is usually calculated as the ratio of the 95th percentile travel time over the free flow travel time and represents the worst level of congestion
at a given time of day in comparison with the free flow traffic condition. Another finding of the paper was that the buffer time and buffer time index profiles showed similar trends to Standard Deviation and Coefficient of Variation, respectively.

Li et al (2006) focused on analysing the travel time distribution properties and determining the factors which contribute to travel time variability from data gathered from the CityLink tollway in Melbourne Australia. The paper looked at the various components of travel time variability and explored their relationship and multiple regression analysis was used to quantify sources of travel time variability and their interaction effects. The analysis was then applied to two groups of data that were travel times in the morning and in the afternoon peak. The findings highlighted that the relationship between mean travel time and vehicle-to-vehicle variability (a component of the variance of travel time) indicated that the two are related in a small time interval (5 minutes). They showed that while the vehicle-to-vehicle variability explained about half travel time variability in the off-peak and morning peak period, it contributed comparatively little to afternoon peak travel time variability. Another finding revealed that the variability in the afternoon peak is predominantly caused by factors such as flow fluctuations, adverse weather, and incidents which was illustrated by the 90th percentile travel time difference being approximately 8 minutes in the peak period but no difference under free flow conditions. A 90th percentile travel time or 95th percentile travel time could be used as suitable measures for LOS as by definition these measures estimate how bad delay will be on specific routes during the heaviest traffic days.

Wakabayashi (2012) estimated travel time reliability for a newly opened expressway in Japan by comparing travel time reliability between two existing routes and the route under construction. A Multi-Hierarchical Stochastic (MHS) model for estimating travel time variation
under uncertainty was developed and the various inputs of the model were the network description data, the weathercast, and the travel time variation for a unit distance. The output is a Cumulative Distribution Function (CDF) for travel time variation between an OD pair. The travel time reliability and travel time variation indices assessed included the buffer time, buffer time index, planning time, planning time index, and the travel time variability index. The findings reveal that the planning time, planning time index, buffer time, and buffer time index have very different rankings because the planning time index and buffer time index are standardised indices. Also the study showed the buffer time index gives smaller values for more reliable routes but since the values are larger for routes with smaller average travel times this is a disadvantage of the buffer time index. However the comparative study revealed that every index exhibits its property depending on the route characteristics and this indicates that the combination of average travel time and appropriate travel time reliability index are essential for assessing truly reliable route in travel time.

Nam et al (2005) uses modal choice analysis to identify the importance of travel time reliability and to estimate the value of travel time reliability of transportation users. It used the Multinomial and the Nested Logit model structures as the best model representing trip behaviour without travel time reliability. A model with travel time reliability was also developed and the reliability indices used were standard deviation and maximum delay and these were measured based on triangular distribution. The findings revealed that from the comparison results between model with and without reliability for all tests conducted in the paper, model with reliability was better than that without reliability. It is stated that the travel time, standard deviation and maximum delay are quite significant figures in mode-choice decision and in addition the value of
time of the model with delay was much more reasonable than the one without delay when comparing with previous research.

Lyman et al (2008) as part of their study carried out an analysis of travel time reliability measures to be used as congestion measures in the Portland Oregon metropolitan region using data from 2004-2007 over a freeway segment, a corridor and an entire urban area. The case study tested several travel time reliability measures including travel time, 95th percentile travel time, travel time index, buffer index, planning time index, and congestion frequency. The paper investigated changes of travel time reliability over time and a case study compared rankings of freeways in Portland according to their travel time reliability ratings versus traditional congestion measures such as volume-to-capacity ratio, vehicle hours of delay, and mean speed. They recommend the use of reliability measures as well as the traditional congestion measures to give more informed planning decisions. The buffer index along with the travel time index were used to prioritize freeway corridors since they are subtle enough to give a percentage that travelers can relate to and is more likely than congestion frequency or the planning time index to reflect the kinds of decisions that travelers make.

Therefore the review of several papers have identified the buffer time index, travel time index, percent variation (coefficient of variation) and planning time index as relatively key to determine travel time reliability. The models that each research has developed appear to work satisfactorily at normal traffic flow conditions but become unstable, or uncertainties are identified when conditions are during peak periods or other incidents start to deteriorate normal traffic flow conditions. However overall it appears that the measures of travel time index, buffer index, planning time index, 95th percentile and percent variation (TABLE 3) are key to establishing relationships and models to measure travel time reliability.
2.3 Determining Route Choice with TTR

Recent analyses from the reviewed literature have suggested that travel time reliability is an important criterion for route choice decisions. But also long term data collection is needed to obtain distributions of travel times even though travel time reliability is an important measure of road network reliability. Stathopoulos and Karlaftis (2001) using real-time traffic data analysed the variations in traffic flow patterns for areas in Athens, Greece. The study revealed that traffic flow characteristics were the same for all weekdays but consisted of more variations during weekends and by time of day. Bates et al (2001) looked at the variations of travel time reliability using experimental data. Noland et al (1998) conducted a study whereby a model for simulating travel time uncertainty was produced. Scheduling choices based on traffic predictability were also validated that was derived from expected cost and average travel delay. These were studied from the user viewpoint.

The evaluation of travel time reliability based on the LOS of a whole road section is now possible. This was shown by Uno et al (2009) who revealed a methodology for evaluating the average travel time (ATT) and also the travel time reliability. Emam and Al-Deek (2006) used detector data to develop a methodology for evaluating travel time reliability employing a theoretical distribution based on traffic characteristics. Chen et al (2004) showed the effect on travel time of risk-taking route choice models and also the relationship between these models utilizing a risk-averse approach.

Using detector data it is now therefore possible to determine variances in travel times. However since a detector obtains traffic information at a single point whereas the LOS of the whole section may not be the same it is difficult to get accurate estimates. Studies have shown that the use of media access control (MAC) address of Bluetooth wireless enabled devices in
vehicles is seen as a cheaper and more reliable alternative for collecting travel time data. Tarnoff et al (2009) conducted a study and revealed that as well as providing accurate measurement of travel times and origin-destination data, the Bluetooth technology produces statistically viable data that can utilize sample sizes of 5% - 7% of the overall traffic stream. Day et al (2010) presented a study that also found similar results but with a larger sample size utilization of 10%.

2.4 Review of TTR Applications

The applications of travel time reliability can be summarised as follows;

- McLeod et al (2012) showed that the state of Florida have used a travel time reliability model on freeways to assist in planning extra resources to set project priorities which is a benefit to the highway authority.

- The study by Chen et al (2003) indicated the impact that incidents have on travel time reliability and that incident information can reduce travel time uncertainties, for example if incident information is available travel time savings can be made if assurance of the route is incident free.

- Liu et al (2007) examined the impact of cost and the ability to use express lanes to allow more certainty of travel time reliability, also that commuters expect to receive benefits by choosing to use express ways.

- Loustau et al (2010) examined the impact of incidents on the network of routes and was able to compare actual values with simulated values. Over time it was possible to identify the change of travel time reliability.

- Remais et al (2012) examined the impact of congestion by the measured congestion hours over short sections weighted against congestion hours over road segments of varying
length and establishing an average congestion per mile for an interstate route (Congestion Index).

- Mehran et al (2009) measured the impact of certain conditions on travel time reliability eg weather and accident on a section of a highway. The results showed that establishing impact relief can significantly improve travel time reliability and actions like opening of the hard shoulder at peak times both offered more capacity and reduce accident occurrences.

2.5 A LOS Case Study

Yamazaki et al (2012) described a method to evaluate the level of service (LOS) of road networks based on travel time reliability that was done using electronic toll collection data. In the study 15-min intervals of average travel time (ATT) was used as the representative value for evaluating the LOS of road sections. Also to identify periods of good or bad traffic conditions the study refers to the travel time distribution. Therefore cumulative travel time distributions of ATT every 15 min for different road sections was analysed for different sections of roadway. They suggested that a cumulative distribution located towards the left side of the graph with a steep slope shows a smooth and stable traffic service. However if it is located towards the right with a more gradual slope then this indicated a large variation in travel time and hence travel time reliability. Using the I-12 as an illustration of the methodology three graphs, FIGURES 2 to 4 show travel time distributions for June 2012 for three sections along this corridor. The shape of the cumulative distribution of the ATT for every 15-min interval during the morning (6:00 – 10:00) and evening (17:00 – 21:00) was found to be similarly located towards the left side of the graph revealing that travel time and its variation tends to be small at these times. In contrast to the distributions during the mid-daytime (12:30 – 14:30) that revealed a larger variation in travel
time and therefore lower travel time reliability as shown by the fact that the distribution was located towards the right and usually has a more gradual slope.

What this case study has demonstrated is that the travel time of a section of roadway and hence the travel time variable is a useful source for determining the level of service.

FIGURE 2 Cumulative distributions of ATT for I-12 Juban to Range (June 2012)

FIGURE 3 Cumulative distributions of ATT for I-12 Range to Millerville (June 2012)
2.6 The Travel Time Index versus the Buffer Index

When preparing a reliability measure the amount of time that should be budgeted for a trip is important. The process should account for variations such as month-to-month and time of day variations (knowledge of the month can determine when to travel as well as what time of day to travel) and variation in road section length (trip travel time rather than separate road sections are important). Below is a summary of two travel time reliability measures, the Travel Time Index and the Buffer Index after which a conclusion is drawn:

- Travel time index is a measure of the average travel time that would be experienced by the system users during the analysis period. While the Buffer Index is a measure of the amount of additional time (above the average) needed to include 95% of the travel data points.
- The travel time index measure provides information about user experience as well as system operating condition ie it reflects the average level of congestion and mobility
(Unit et al, 2001). It has also been pointed out in the literature that this index is a congestion intensity measure rather than a reliability measure.

- The Buffer Index is comparable across highway systems because it is standardized using minimum or average travel time (Wakabayashi, 2012). It has therefore been concluded that the Buffer Index can be used to compare the LOS between road sections of differing lengths.

What can be stated from the summary above is that the Buffer Index could be able to provide more information to the traveler in terms of travel time reliability and hence the level of service of a facility than the Travel Time Index.

2.7 Relation between Average Travel Speed and Travel Time

This section briefly demonstrates the relationship between travel time and therefore travel time reliability and average travel speed. Studies have shown that there is a strong correlation between a vehicle’s travel time and the average travel speed. One such study conducted by Martchouk et al (2010) demonstrated that during off-peak hours both speed and travel time are at their free flow values. However during peak hours the average speed then decreases to less than half of the free flow speed and travel time increases by up to 4 times the free flow value. Conversely though at night average speed is observed to be lower than free flow speed but travel time is still close to its free flow value. Since at night there are less vehicles contributing to the average segment speed, a single vehicle that is travelling at a lower speed than the main traffic stream can greatly reduce the average speed.
3. STUDY AREA AND TRAFFIC DATA

The first section of the chapter introduces the data used in the study and the collecting procedures. The second section briefly looks at ways of dealing with missing data. The third section describes details of the study area. The fourth section assesses travel time reliability on the I-12 by comparing graphical results of travel time.

3.1 Source of Data

BlueTOAD devices have been installed and activated along a 14.5 mile section of the I-12 corridor in East Baton Rouge and Livingston Parishes of Louisiana since November 2010. They operate on Bluetooth technology to detect and match Bluetooth enabled devices in vehicles travelling along the study route. These Bluetooth enabled devices include cell phones, headsets, music players and navigation systems. It is assumed that not every vehicle will have these devices but taking a sample of vehicles is considered to be representative of the entire traffic stream. There is one BlueTOAD device at the westbound I-12 / Juban Road interchange (IC) and another at the westbound I-12 / South Range Avenue IC, 2.4 miles apart. The media access control (MAC) address of Bluetooth enabled devices in vehicles are detected as they get into the detection zone of the Juban Road intersection. The information captured when these are matched at the South Range Avenue intersection detection zone is sent to TrafficCast’s processing units. The MAC addresses are stripped, travel time and speed data are calculated, and then all abnormal readings are filtered out before the processed data is sent to the BlueTOAD user interface (BlueTOAD website). A screenshot of the collected data is shown in FIGURE 5.
3.2 Missing data and outliers

The reasons for the missing data could include malfunction of the data recording mechanism or data entry error. It can be inferred that these data are missing at random and as such there are several ways of dealing with this such as: 1. listwise deletion (complete case analysis) – delete cases with missing values on any variable in the analysis. 2. mean substitution – substituting a mean for the missing data. 3. multiple imputation – using a variety of advanced techniques, e.g. Markov Chain Monte Carlo (MCMC) simulation, to estimate missing values that creates multiple versions of the same data set that explores the scope and effect of the missing data.

For this study, there were no missing data encountered. However, for speeds that averaged 100mph or higher these will be discarded as outliers since such values are highly unlikely to be sustained for 5 minutes or 15 minutes during peak periods, and therefore denotes a detector malfunction.

FIGURE 5 Sample of BlueTOAD data
3.3 Assessment of study area

The I-12 corridor in East Baton Rouge and Livingston Parishes of Louisiana is approximately 86 miles (138 km) in length and traverses an east-west direction from the I-10 in Baton Rouge to an interchange with both I-10 and I-59 in Slidell. The I-12 is predominantly 2 lanes in each direction except for the section between the interchange with the I-12 / US 3245/O’Neal Lane and the I10 / I-12 where there are 3 lanes in each direction. Attention was focused on the section from the system interchange with US 447/Walker South Road to the interchange with US 3064/Essen Lane shown in FIGURE 6, a distance of approximately 14.5 miles. Assessments to conduct the methodology were carried out at 12 different segments along the I-12 that had data available at different periods between October 2013 and March 2014.

FIGURE 6 Map of I-12 from Walker South Road to Essen Lane

Bluetooth travel time data for this thesis is grouped into 5-min intervals and the average travel time (ATT) over each 5-min interval is used as a measure to represent traffic conditions. In
this study the 5-minute interval is used because of the importance of the time-dependent changes in traffic conditions and the corresponding LOS. This means therefore that the use of shorter unit time intervals to calculate travel times is more viable.

3.4 Assessing Travel Time Reliability on the I-12

Since the travel time index is calculated as the ratio of the mean travel time to the estimated free flow travel time, a plot of mean travel time will look exactly like one of the travel time index (Lyman and Bertini, 2008). Hence travel time and travel time reliability on the I-12 can be assessed by comparing graphical results of the travel time over a two year period (yearly variation), different dates during the year (seasonal variation) and at different times during the day (daily variation).

FIGURE 7 shows the mean travel times for a 24 hour period collected for selected Tuesdays, Wednesdays, and Thursdays in March 2011 and March 2012 on I-12 Juban Road to South Range Avenue. These weekdays were chosen since they represent the typical commuting days for travelers. This shows how travel time varies year to year along the same section of roadway as can be seen from a fluctuation in mean travel time between I-12 Juban to Range obtained in March 2012 and in March 2011.

To illustrate the seasonal variation in travel time FIGURE 8 shows the mean travel times for a 24 hour period collected for Tuesdays, Wednesdays, and Thursdays in January and in June of year 2011 on I-12 Juban Road to O’Neal Lane. It can be seen that journey times during the summer months (June) are much greater than those obtained during the winter months (January). It is likely this may be due to higher traffic volumes which creates congestion.

For an illustration of daily fluctuations FIGURE 9 shows the mean travel times for a 24 hour period collected for Wednesday June 1st 2011 and Thursday June 2nd 2011 on I-12 Juban
Road to O’Neal Lane. From these two graphs it can be seen that the daily traffic patterns are more or less similar for a 24 hour period.

FIGURE 7 Histograms of travel time on the I-12 Juban to Range (March 2011 and 2012)

FIGURE 8 Histogram of travel time on the I-12 Juban to O’Neal (January and June 2011)

FIGURE 9 Histograms of travel time on the I-12 Juban to O’Neal (June 1st and 2nd 2011)
4. METHODOLOGY

This chapter starts by explaining the formulation of the new Buffer Index in the first section. The second section compares the new Buffer Index and the existing Buffer Index by a statistical test. The third section reviews the steps needed to produce the TTR and LOS methodology.

4.1 Formulation of New Buffer Index

Buffer time is a travel time reliability measure recommended by the U.S. Department of Transportation (DOT), NCHRP, SHRP 2, and Lenox et al. It may relate particularly well to the way travelers make decisions. The buffer time uses minutes of extra travel time needed to allow the traveler to arrive on time (Chen et al, 2003). Therefore it would be the difference between the average and the upper limit of the 95% confidence interval as calculated from the annual average. The buffer index, another reliability measure, is defined as the difference between the 95th percentile travel time and the average travel time, and then divided by the average travel time. It represents the percentage of extra travel time that most travelers add to their trip to ensure on-time arrival and its value generally increases as reliability gets worse.

The buffer time is represented as follows:

Buffer time = 95th percentile travel time for a trip – average travel time

(4)

The buffer index is represented as follows:

\[ BI = \frac{95th \ percentile \ travel \ time – average \ travel \ time}{average \ travel \ time} \]  

(5)

where 95th percentile travel time indicates how bad delay will be on the heaviest travel days and is a translation of a standard “I can be late to work 1 day a month (1 day out of 20 work days) without getting into too much trouble” (Lomax et al, 2003).
Research carried out by Pu (2011) showed that the use of the median travel time compared to the mean or average travel time is more appropriate to calculate the buffer index, as well as the percent of on-time arrival, especially when travel time distributions are heavily skewed. With the assumption of lognormal distributed travel times and the use of the percent point function, several travel time reliability measures including the buffer index were formulated using the parameter(s) of the lognormal distribution; the travel time index, 95th percentile travel time, standard deviation, coefficient of variation, percent variation, skew statistics, planning time index, frequency of congestion, and percent of on-time arrival.

With respect to the shape parameter $\sigma$ of the lognormal distribution, the first derivative of all the travel time reliability measures was shown to have an increasing function except the average-based buffer index and average-based percent of on-time arrival, which increase first and then decrease. For the second derivatives of the reliability measures with respect to the shape parameter $\sigma$ it was found that all measures are convex except for the average-based buffer index (concave on $\sigma \in (0.645, 2.645)$), the frequency of congestion (concave), and the percent of on-time arrival (concave). Pu points out that it would be more convenient if one of the measures can be ‘representative’ or a ‘proxy’ for other measures with three main features. These are; 1) a well-defined traditional statistic so that it can be easily calculated with classical statistic methods (or software packages), 2) sharing the same varying direction (increasing or decreasing) with other measures when travel time distribution changes, and 3) the relative magnitude to other measures is relatively stable Pu (2011). He also found from his analysis that the average-based buffer index could potentially underestimate the unreliability when travel time distributions become heavily right-skewed (i.e. relatively large shape parameter $\sigma$ value). Also it could generate
unrealistic values if the shape parameter exceeds a certain value and hence in order to avoid this potential deficiency, median-based buffer index are recommended instead.

In a paper by Arezoumandi (2011) a new formulae to calculate the 95\textsuperscript{th} percentile of travel time was presented. He showed that the 95\textsuperscript{th} percentile of travel time is calculated in normal distribution as

\[ TT_{0.95} = \bar{x} + 1.645s \]  

(6)

where \( \bar{x} \) represents the mean and \( s \) is the standard deviation.

Similarly in lognormal distribution, the 95\textsuperscript{th} percentile of travel time using mean and standard deviation are calculated as

\[ TT_{0.95} = \bar{x} \ast \times s^{*1.6449} \]  

(7)

where

\[ \bar{x} \ast = \frac{\bar{x}}{\sqrt{1+(\bar{z})^2}} \]

\[ s^{*} = \exp\left(\sqrt{\log(1 + (\frac{s}{\bar{x}})^2)}\right) \]

therefore;

\[ \text{New } TT_{0.95} = \frac{\bar{x}}{\sqrt{1+(\bar{z})^2}} \times \left[\exp\left(\sqrt{\log\left(1 + \left(\frac{s}{\bar{x}}\right)^2\right)}\right)\right]^{1.6449} \]  

(8)

where \( \bar{x} \) represents the mean and \( s \) is the standard deviation.

The aim for this thesis is to incorporate the above formulae, equation 5 into the existing buffer index formulae, BI as follows;

\[ BI = \frac{95\text{th percentile travel time} - \text{average travel time}}{\text{average travel time}} \times 100\% \]
\[
\text{BI}_{\text{new}} = \frac{\text{New } \tt_{0.95} - \text{median travel time}}{\text{median travel time}} \times 100\% \tag{9}
\]

\[
\text{New Buffer Index} = \frac{\bar{y} \times \left[ \exp \left( \sqrt{n} \log \left( 1 + \left( \frac{s}{n} \right)^2 \right) \right) \right]}{\sqrt{\frac{1}{n} + \left( \frac{s}{n} \right)^2}} - \text{median travel time} \times 100\% \tag{10}
\]

4.2 Comparison of new with existing Buffer Index

In order to validate the formulated index, equation 10, a statistical test will be used to evaluate the significance of the difference between the new and existing Buffer Index (BI). This is done for all the speed ranges \( s_r \); \( s_r \geq 60 \text{mph}, 50 \leq s_r \leq 59, 45 \leq s_r \leq 49, 40 \leq s_r \leq 44, 35 \leq s_r \leq 39, s_r < 35 \text{mph} \). The Wilcoxon signed-rank test was used since this test has several advantages such as not requiring assumptions of normality, and it usually compare medians rather than means. This test is the nonparametric analogue to the paired t test.

The hypotheses for this test are as follows;

Ho: the median of the difference in BI new and existing is equal to zero

Ha: the median of the difference in BI new and existing is greater than zero

This is a one tailed test at the 5% significance level to show that the new buffer index is better than the old buffer index. This was conducted using the statistical computer programme SAS Enterprise Guide 9.2. TABLE 4 summarizes the results of the statistical test that is carried out on data for 10 segments on the I-12 namely;

- I-12 / S Range Avenue IC to I-12 / Juban Road IC (Eastbound)
- I-12 / Juban Road IC to I-12 / Walker South Road IC (Eastbound)
- I-12 / Sherwood Avenue IC to I-12 / Millerville Road IC (Eastbound)
- I-12 / Millerville Road IC to I-12 / S Range Avenue IC (Eastbound)
- I-12 / Sherwood Avenue IC to I-12 / Essen Lane IC (Westbound)
- I-12 / S Range Avenue IC to I-12 / Millerville Road IC (Westbound)
- I-12 / Essen Lane IC to I-12 / Sherwood Avenue IC (Eastbound)
- I-12 / Juban Road IC to I-12 / O’Neal Lane IC (Westbound)
- I-12 / O’Neal Lane IC to I-12 / Essen Lane IC (Westbound)
- I-12 / Essen Lane IC to I-12 / O’Neal Lane IC (Eastbound)

**TABLE 4 Comparison of difference between new and existing BI based on speed ranges**

<table>
<thead>
<tr>
<th>Speed range ($s_r$)</th>
<th>N (# of observations on the Difference = New BI – Existing BI)</th>
<th>Descriptive statistics</th>
<th>Test for location: $\mu_0=0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Median</td>
</tr>
<tr>
<td>$\geq60$ mph</td>
<td>10</td>
<td>2.479</td>
<td>2.32</td>
</tr>
<tr>
<td>50 – 59 mph</td>
<td>10</td>
<td>24.975</td>
<td>22.015</td>
</tr>
<tr>
<td>45 – 49 mph</td>
<td>10</td>
<td>66.263</td>
<td>59.19</td>
</tr>
<tr>
<td>40 – 44 mph</td>
<td>10</td>
<td>43.725</td>
<td>23.965</td>
</tr>
<tr>
<td>35 – 39 mph</td>
<td>10</td>
<td>12.418</td>
<td>12.555</td>
</tr>
<tr>
<td>$&lt;35$ mph</td>
<td>10</td>
<td>1.49</td>
<td>0.465</td>
</tr>
</tbody>
</table>

From the p-values, it shows that the data reject the null hypothesis, $H_0$ at a level of 0.05 except when the speed range is $s_r < 35$ mph. But for speed ranges $s_r \geq 60$ mph, $50 \leq s_r \leq 59$, $45 \leq s_r \leq 49$, $40 \leq s_r \leq 44$, and $35 \leq s_r \leq 39$ it can be concluded that the difference between the new and existing Buffer Indexes (BIs) are significant.
The new Buffer Index therefore gives different values to the existing and from the plot shown in FIGURE 10 it indicates that when using the median travel time there is a greater variability in the new Buffer Index values compared to the values obtained with the mean as in the existing Buffer Index. This is particularly the case within the speed ranges 40mph to 50mph. Also the new Buffer Index values are approximately 60% higher in this speed range.

It can be deduced that road users applying the existing Buffer Index to their journey may still risk arriving late. The new Buffer Index which utilizes the median travel time value could provide increased certainty to arrive on time, but up to 60% increase in travel time would be needed.

The greater variability occurs over the speed ranges of 40mph to 50mph and this could be due to the traffic lanes becoming congested with traffic possibly slowing and accelerating. Below this speed range (< 40mph) congestion is in place and above this range (> 50mph) traffic is more approaching free flow conditions. Therefore there is far more variability of traffic condition within the speed range of 40mph to 50mph, and a higher Buffer Index value should be used to make adequate allowance to guarantee reliable travel time.

FIGURE 10 Plot of new BI versus existing BI for 10 segments on the I-12
4.3 Reporting TTR and LOS from existing traffic data

The following is an outline of the steps required, ie the methodology to determine the travel time reliability and level of service on the I-12:

Step 1 - Obtain 5-minute interval traffic data (travel time, speed) for analysis period of specific highway corridor

Step 2 - For the specific data, compare values of existing Travel Time Index with the SHRP 2 L08 Project team’s values corresponding to each LOS to determine error rate

Step 3 – Calculate values for the new Buffer Index from equation 10 and compare values for new Buffer Index with existing Travel Time Index to determine new LOS ranges

Step 4 – Determine criteria for which new Buffer index ranges correspond to specific LOS ranges, i.e.

\[ \begin{align*}
    x_1 < \text{new Buffer Index} < x_2 \quad & \Rightarrow \text{LOS A} \\
    x_2 < \text{new Buffer Index} < x_3 \quad & \Rightarrow \text{LOS B} \\
    x_3 < \text{new Buffer Index} < x_4 \quad & \Rightarrow \text{LOS C} \\
    x_4 < \text{new Buffer Index} < x_5 \quad & \Rightarrow \text{LOS D} \\
    x_5 < \text{new Buffer Index} < x_6 \quad & \Rightarrow \text{LOS E} \\
    x_6 < \text{new Buffer Index} < x_7 \quad & \Rightarrow \text{LOS F}
\end{align*} \]
5. RESULT AND ANALYSIS

In this chapter the four steps outlined in section 4.3 are examined in detail. In the first step the segment to be used for the proposed model is chosen for analysis. In the second step the TTI values from the chosen segment on the I-12 is compared with the SHRP 2 L08 Projects Team’s TTI value from their Freeway Reliability LOS definition. In the third step the new BI values for the chosen segment is compared with the existing TTI values to determine new LOS ranges. Then the criteria for the new methodology is to be developed.

5.1 Reporting TTR and LOS: Step 1

For this part of the study, an initial assessment was carried out on 4 different segments along the I-12 for a 6 month period that had data available between October 2013 and March 2014 to determine which section had good quality data. These 4 segments, that is shown in FIGURE 11 were chosen since they were of suitable length, between 3.5 to 6.0 miles, for the data analysis while the other segments in the BlueTOAD database had shorter lengths and therefore not utilized. The chosen segments, that are divided into eastbound (EB) and westbound (WB) sections are as follows;

Segment 1: I-12 / Essen Lane IC to I-12 / O’Neal Lane IC (EB) = 5.7 miles
Segment 1: I-12 / O’Neal Lane IC to I-12 / Essen Lane IC (WB) = 5.7 miles
Segment 2: I-12 / O’Neal Lane IC to I-12 / Juban Road IC (EB) = 5.5 miles
Segment 2: I-12 / Juban Road IC to I-12 / O’Neal Lane IC (WB) = 5.5 miles
Segment 3: I-12 / Millerville Road IC to I-12 / S Range Avenue IC (EB) = 4.2 miles
Segment 3: I-12 / S Range Avenue IC to I-12 / Millerville Road IC (WB) = 4.2 miles
Segment 4: I-12 / Juban Road IC to I-12 / Walker South Road IC (EB) = 3.5 miles
Segment 4: I-12 / Walker South Road IC to I-12 / Juban Road IC (WB) = 3.5 miles

From the viewpoint of the availability of ideal travel time distribution, sufficient Bluetooth data should be available for the segment being analysed. From TABLE 5 the segment analysis revealed that segment 4, I-12 / Walker South Road IC to I-12 / Juban Road IC (WB) is the most suitable of the segments for analysis even though it has the shortest length of the four segments. This is due to the segment having the least amount of speed outliers and it also contains more number of travel time observations.

FIGURE 11 Location of the four analysed segments on the I-12
### TABLE 5 Assessment of Segments 1, 2, 3 and 4 for year 2013/14

<table>
<thead>
<tr>
<th>Segment</th>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time period</td>
<td>EB</td>
<td>10/1/13–03/30/14</td>
<td>10/1/13–03/30/14</td>
<td>10/1/13–03/30/14</td>
<td>10/1/13–03/30/14</td>
</tr>
<tr>
<td># of observation</td>
<td>218474</td>
<td>269863</td>
<td>231068</td>
<td>149396</td>
<td>184642</td>
</tr>
<tr>
<td># of days missing</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Missing travel time data</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td># of outliers (speeds &gt; 100mph)</td>
<td>67</td>
<td>480</td>
<td>13</td>
<td>164</td>
<td>12</td>
</tr>
<tr>
<td>Recommendation</td>
<td>Segment 4, westbound, has the least amount speed outliers and it also contains more number of observations therefore is the most suitable of the segments for analysis.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 5.2 Reporting TTR and LOS: Step 2

This step compares the Travel Time Index (TTI) values for the I-12 data with that of the SHRP 2 L08 Project team corresponding to each LOS to determine the error rate. The 6 month data for segment 4 was analyzed and the result is presented in TABLE 6. The error rate was calculated as 4.0% that was determined as follows;

\[
\text{Error rate at speeds between 60 and 35 mph} = \left( \frac{\text{Number of errors}}{\text{Total number of TTI observations}} \right) \times 100\%
\]

This indicates that there is a distinct difference between the TTI values obtained for the I-12 and that of the SHRP 2 L08 Project team values for similar speed ranges. The data obtained in both cases are for a 5-minute time interval.
TABLE 6 Comparison of TTIs on the I-12 and from the SHRP 2 L08 Project Team’s Freeway Reliability LOS definition

<table>
<thead>
<tr>
<th>SHRP 2 L08 Travel Speed and Equivalent TTI values based on data from Seattle and Atlanta</th>
<th>I-12 corridor TTI = (TT/free flow TT) = (TT/5.672min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>&gt;=60 (TTI &lt;= 1.083)</td>
</tr>
<tr>
<td>B</td>
<td>50—59 (1.083 &lt; TTI &lt;= 1.300)</td>
</tr>
<tr>
<td>C</td>
<td>45—49 (1.300 &lt; TTI &lt;= 1.444)</td>
</tr>
<tr>
<td>D</td>
<td>40—44 (1.444 &lt; TTI &lt;= 1.625)</td>
</tr>
<tr>
<td>E</td>
<td>35—39 (1.625 &lt; TTI &lt;= 1.857)</td>
</tr>
<tr>
<td>F</td>
<td>&lt; 35 (TTI &gt; 1.857)</td>
</tr>
<tr>
<td></td>
<td>Error Rate = 4.0%</td>
</tr>
</tbody>
</table>

5.3 Reporting TTR and LOS: Step 3

In this procedure the aim is to calculate values for new Buffer Index and show that this is another TTR measure that can be used instead of the Travel Time Index. The impact of accidents has not been considered in the study because the effect can be immensely irregular from a very minor incident which has a small impact on congestion and capacity to a large incident which can close the majority of the road space and have a major impact on congestion and capacity. The uncertain nature of these incidents changes driver’s normal behavior.

In TABLE 7 and FIGURE 12 the segment average TTI is low at high speed ranges but rises gradually as the speed deceases to 40mph and lower. This is giving an indication that unreliability is higher at lower travel speeds than at higher travel speeds. However what the
segment average BI shows in TABLE 7 and FIGURE 13 is low values at 40 to 44 mph and below, then higher values as the speed ranges increase until when it gets to around speed range 50mph to 59mph where the BI value starts to decline again. This is giving an indication that when traffic volumes approach the freeway capacity and congestion emerges traffic speed range will converge. This indicates that the majority of traffic travelling will be travelling at or around the same speed. The results obtained may be an indication of this when the speed range lowers to about 40mph and below, and is an indication of congestion developing or taking place. In this situation the BI values calculated become low, as shown at the speed ranges 40 to 44 and 35 to 39 and this condition does not follow the former TTI values which rise at the lower speed ranges. Therefore for the BI unreliability is higher at mid speed ranges than at higher speeds as well as lower speed ranges.

It could be stated that the lower BI indicate a smaller variability in the travel time and that this can occur at different speed values. Hence in free flow conditions of light traffic and no incidents along the network corridor therefore high speed can be maintained by the majority of motorists as reflected by the lower BI obtained at the greater than 60mph speed range. Conversely, similar BI values are obtained at lower speeds, where possibly congestion is evident and all motorists are constrained to the lower speed limit, in this case around 40mph and lower. The mid speed ranges of 45 to 49 and 50 to 59, produce higher BI values, and the values are close to each other in magnitude. These suggest that there is a greater variability in the travel time, and suggests that the freeway is carrying heavy traffic volumes close to its capacity. Therefore drivers are limited in selecting their desired speed due to the presence of heavier traffic because they are controlled by the traffic queues and conditions ahead.
It can be said therefore that the Buffer Index was inconclusive in providing an accurate measure for defining LOS due to the data showing an increasing linear upward trend from LOS A to LOS C but then starts decreasing linearly downwards from LOC D to LOS F. However it may be possible to conclude that the Buffer Index should be linked to a speed range. Therefore the lower values of BI may suggest a reliable travel time is available but at two levels:

- a reliable short travel time in free flow conditions
- a reliable longer journey time but in congested conditions

The higher BI values may suggest to road users that the journey time has a higher variability.

**TABLE 7 Comparison of TTI and BI for Segment 4 on the I-12**

<table>
<thead>
<tr>
<th>TTI (average)</th>
<th>Equivalent BI (average %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;=60 (TTI = 0.94)</td>
<td>&gt;=60 (BI = 13.53)</td>
</tr>
<tr>
<td>50—59 (TTI = 1.25)</td>
<td>50—59 (BI = 90.64)</td>
</tr>
<tr>
<td>45—49 (TTI = 1.55)</td>
<td>45—49 (BI = 93.49)</td>
</tr>
<tr>
<td>40 – 44 (TTI = 1.66)</td>
<td>40 – 44 (BI = 52.87)</td>
</tr>
<tr>
<td>35 – 39 (TTI = 1.85)</td>
<td>35 – 39 (BI = 34.39)</td>
</tr>
<tr>
<td>&lt;35 (TTI = 2.87)</td>
<td>&lt;35 (TTI = 24.72)</td>
</tr>
</tbody>
</table>
5.4 Reporting TTR and LOS: Step 4

The criteria for which new Buffer index ranges correspond to specific LOS ranges could not be conclusively determined. Recommendations for future work are highlighted in chapter 6.
6. CONCLUSIONS

The following is a summary of the main findings of the study:

- From the Wilcoxon Signed Rank test it can be concluded that the difference between the new and existing Buffer Indexes (BIs) is significant for all the speed ranges \( s_r \) examined ie \( s_r \geq 60 \text{mph}, 50 \leq s_r \leq 59, 45 \leq s_r \leq 49, 40 \leq s_r \leq 44, 35 \leq s_r \leq 39 \), except speed range \( s_r < 35 \text{mph} \).

- The BI values in relation to the TTI values are correlated for speed ranges above and equal to 60 to a value of 45 mph but below 45 mph it is not. It appears that this is due to the BI giving more indication of the variability in travel time.

- The Buffer Index was inconclusive in providing an accurate measure for defining LOS. This is due to the data showing an increasing linear upward trend from LOS A to LOS C but then starts decreasing linearly downwards from LOS D to LOS F.

- It is possible to conclude that the Buffer Index should be linked to a speed range. Therefore the lower values of BI may suggest a reliable travel time is available but at two levels:
  - a reliable short travel time in free flow conditions
  - a reliable longer journey time but in congested conditions

  The higher BI values may suggest to road users that the journey time has a higher variability.

6.1 Future Research

It is recommended that the following actions be performed in the future:

- Data for an entire 1 year period is needed to more accurately perform test.

- Volume data should also be provided to comprehensively carry out level of service analysis
• Analysis should be carried out on several segments along the I-12 corridor instead of one segment for section 5 of the study in order to obtain comprehensive results.
REFERENCES


VITA

Marlene Beverley Russell, born in St Elizabeth, Jamaica, received her bachelor’s degree at the University of the West Indies located in St Augustin, Trinidad in 1998. Thereafter, she joined the Ministry of Transport and Works in Kingston and worked as a Traffic Engineer for 18 months. She later worked in London, England in a similar capacity where she was placed on secondment within several London Boroughs in their Highways and Transportation Department. Marlene began her studies at Louisiana State University in August 2012. Her technical interests are traffic safety and highway design.