ABSTRACT

CHASE JR., RICHARD THOMAS. Monitoring Freeway Reliability Utilizing Network-Wide Link-Based ITS Data. (Under the direction of Dr. Billy Williams).

This thesis examines a host of travel time reliability performance measures proposed in literature for five locations in the US. All reliability measures were calculated from INRIX space mean speed segment data, though it was identified that facility travel time estimation could be improved by using an algorithm to stitch pseudo-trajectories through data in order to report travel times from a driver’s perspective. Improvements gained using the stitching method were greater for shorter reporting intervals, longer facilities, heavy recurring congestion and facilities with recurring congestion occurring toward its downstream end. In order to effectively monitor reliability for key facilities, it is important to estimate actual travel time for the facility rather than assuming that the constituent segments are comonotonic and aggregating the segment distributions.

Temporal sampling by time of day has a large effect on the travel time reliability measures calculated. If only portions of the day are used to create travel time distributions, the measures calculated from the sample will vary depending on the temporal characteristics of the segment. This means that distributions for a given time period are only valid when compared to the same time period, and even then effects like directional demand peaks can affect direct comparisons across segment types. Ideal comparisons of reliability measures should include all 24 hours of the day, and time of day analysis can identify time periods where management strategies can have the most effect on reliability. Capacity improvements on two facilities were shown to improve reliability by most measures, though the skew increased after the improvement due to non-recurring events providing larger deviations from the (reduced) mean.

Travel time reliability measures should provide additional information to decision makers, rather than restating typical performance measures. Most reliability measures are well
correlated to the average travel rate, and the Federal Highway Administration advises against using the four measures with the lowest correlation as they are statistical measures that non-technical decision makers may not understand. Detailed analysis of the relationships between each measure and the average travel rate concluded that skew may indicate segments or facilities with non-recurring congestion that is disproportionately larger than recurring congestion. No single measure appears to be ideal, and each measure is calculated from a part of or the entire travel time distribution. Though single measures can simplify decision making, it is recommended that full distributions be compared where appropriate. With increasing exposure to these distributions and careful explanations as to what they represent, decision makers can effectively prioritize traffic management and geometric improvements.
Monitoring Freeway Reliability Utilizing Network-Wide Link-Based ITS Data.

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Civil Engineering

Raleigh, North Carolina

2012

APPROVED BY:

_______________________________  ______________________________
Billy Williams                       Nagui Roupail
Committee Chair

______________________________
George List
DEDICATION

To my #1 son!
The author was born in Raleigh, NC on November 16, 1987. He completed his undergraduate degree in Civil Engineering at North Carolina State University in May 2010 and began graduate school there immediately after. In the fall of 2012, Thomas will be attending the University of Florida to pursue his PhD degree.
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I would like to thank the following people for their support:

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- My parents for their unrelenting support.
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1. INTRODUCTION

1.1 Problem Statement

The Federal Highway Administration (FHWA) defines travel time reliability as “a consistency or dependability in travel times, as measured from day to day or across different times of day.” [1] FHWA goes on to encourage all transportation operations and management agencies to adopt travel time reliability measures, but current research has only increased the number of reliability measures without coming to a consensus on a single optimal measure. Additionally, agencies must have a consistent dataset informing the reliability measures with clarity in what is being calculated. The reliability measures that an agency uses must be distinct from average measures that are currently used and easily estimated in planning or an analytical operational analysis. Finally, measures must be easily understood by non-technical decision makers.

1.2 Literature Review

The key to correctly interpreting travel time data is to first understand what the source is reporting. Typical Intelligent Transportation Systems equipment has been utilized to estimate average traffic stream travel times either indirectly through point sensors or directly through link-based detection. Early ITS equipment incorporated point based detection from inductive loops, and most advances in ITS technology focused on point based detection until recent decades. [2] While loops, video detection, radar and other point based detection systems can now provide very accurate traffic data, many of the technologies require significant equipment and construction costs. Many different methods for estimating travel times from point based detection systems have been developed, but the speeds reported by these systems are time mean speeds, instead of space mean speeds that are directly related to travel time. [3] More recent technology has focused on link based detection, including Bluetooth, cell phone tracking, and GPS probe networks. These methods typically only collect a sample of the traffic stream, but they also utilize technology already in vehicles to
minimize cost. In North Carolina, a GPS probe network maintained by INRIX covers all
freeway miles in the state, providing speeds and travel times for links or “segments”. INRIX
is able to blend data from existing ITS equipment with GPS probes from commercial fleets
and consumer devices. [4]

While link based detection systems are able to provide direct travel time estimates for
individual links, estimating travel times for entire trips is not necessarily as simple as a sum
of the link travel times. Path travel time estimates from point based systems have developed
significantly from a simple extrapolation method [5], but link based detection provides
unique issues with the introduction of sampling. Path, or route, travel time estimates allow
agencies to monitor critical stretches of the freeway network rather than only monitoring
disaggregate links.

Travel Time Reliability has its roots in both network planning [6] and transit applications [7],
but the tremendous amount of traffic data agencies are collecting have allowed for increasing
usage in monitoring operations of freeways and arterials as well as multimodal applications
[8]. Recent research for freeway applications has identified multiple measures of travel time
reliability. [9] Additional research has analytically compared a host of measures for an
assumed travel time distribution [10], analyzed individual measures across temporal domains
[11] and applied individual measures to a statewide freeway network [12].

Significant ongoing research is sponsored by the Strategic Highway Research Program
focused on Travel Time Reliability. A comprehensive list of reliability-focused sponsored
projects includes many that will improve the understanding of reliability in operational and
management agencies and enable more consistent usage of measures and monitoring
methods. [13]

1.3 Research Objectives

The objective of this thesis is to provide a consistent method for calculating and interpreting
travel time reliability measures. This includes identifying drawbacks in the raw travel time
collection methods, understanding reliability in a segment or link perspective compared to a facility or path, and proposing a core set of travel time reliability measures that provide new information to decision makers and can be easily understood by both users and operators of transportation facilities.

1.4 Organization of Thesis

This thesis is organized into 6 chapters. The first chapter explains the motivation for the research, a literature review, and the research objectives. The second chapter provides a scope of the study locations included in the thesis and a description of the data sources used for each procedure. The third chapter describes reliability reporting on a facility level compared to reporting reliability for segments that make up a facility. The fourth chapter outlines the differences in reliability measures reported over multiple temporal domains. The fifth chapter describes reliability performance measures that are typically calculated, provides a statistical analysis, and identifies measures that are consistent across spatial and temporal domains. Finally, the sixth chapter includes a summary of the findings, recommendations and future work.
2. DATA SOURCES AND STUDY LOCATIONS

2.1 Travel Time Data

All segment travel times were collected from the Regional Integrated Transportation Information System (RITIS), which archives one-minute aggregation period travel times from the INRIX probe vehicle network as a part of the I-95 Corridor Coalition Vehicle Probe Project. [14] INRIX uses GPS probes to collect speed information on over 1 million miles of roads across the United States. [4] Traffic data are reported for TMC codes defined by TeleAtlas and Navteq. TMC segment data are calculated in real time by INRIX and archived by INRIX and RITIS. More information on all variables that INRIX provides is included in Appendix A from the I-95 Interface Guide. [15]

INRIX reports both segment travel time and segment speed. However, the GPS probe data utilized estimates a segment space mean speed with a sample of speeds during a reporting interval within a segment and calculates travel times based on the integer space mean speed estimated. Therefore, all travel rates used for analysis were calculated directly from the reported space mean speeds rather than travel times to minimize any rounding errors.

Supplemental Bluetooth travel time data was also collected for two facilities to compare different methods for estimating facility travel time. Two different types of Bluetooth devices were used, one made by Traffax, Inc. [16] and the other made by DigiWest [17].

2.2 Segment-based Travel Time Sections

Segment-based analysis was performed at 5 locations: 1) I-40 in NC, 2) I-64 in VA, 3) I-95 in FL, 4) I-95 in DE, PA and NJ, and 5) I-395 in VA and DC. 15 minute INRIX data was collected over the time spans indicated in Table 1. In the case of I-64 in Virginia, only 5 segments report travel time for the entire year so reliability measures for the remaining segments have a much lower sample size.
Figure 1 shows all five locations and Figures 2-6 show each location in detail. Both rural and urban freeway segments were included as the methods can measure both types.

Table 1: INRIX Segment Sample Size (15 minute)

<table>
<thead>
<tr>
<th>Study Location</th>
<th>Freeway Miles</th>
<th># Segments</th>
<th>Start Date</th>
<th>End Date</th>
<th>Possible</th>
<th>Actual</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>141.44</td>
<td>131</td>
<td>1/1/2010</td>
<td>12/31/2011</td>
<td>9167904</td>
<td>8984517</td>
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</tr>
<tr>
<td>2</td>
<td>221.33</td>
<td>212</td>
<td>1/1/2011</td>
<td>12/31/2011</td>
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<td>2206518</td>
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<tr>
<td>3</td>
<td>280.88</td>
<td>297</td>
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<td>12/31/2011</td>
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<td>5183541</td>
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<tr>
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<td>12/31/2011</td>
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<tr>
<td>5</td>
<td>23.61</td>
<td>115</td>
<td>1/1/2011</td>
<td>12/31/2011</td>
<td>4018560</td>
<td>4003035</td>
<td>99.6%</td>
</tr>
</tbody>
</table>

2.3 Facility-based Travel Time Routes

10 facilities were identified that were contained in the segments identified in the previous section. Each facility experiences recurring congestion and was defined to contain most recurring congestion without queues building past the upstream segment. One minute INRIX data was downloaded for each segment within the routes over the time spans in Table 2.

Table 2: INRIX Route Sample Size (1 minute)

<table>
<thead>
<tr>
<th>Route Numbers</th>
<th>Freeway Miles</th>
<th># Segments</th>
<th>Start Date</th>
<th>End Date</th>
<th>Possible</th>
<th>Actual</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2</td>
<td>26.89</td>
<td>44</td>
<td>1/1/2010</td>
<td>12/31/2011</td>
<td>46189440</td>
<td>45409576</td>
<td>98.3%</td>
</tr>
<tr>
<td>3,4</td>
<td>38.43</td>
<td>60</td>
<td>1/1/2011</td>
<td>12/31/2011</td>
<td>7516800</td>
<td>7440240</td>
<td>99.0%</td>
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<tr>
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<td>78</td>
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<td>1/1/2011</td>
<td>12/31/2011</td>
<td>16773120</td>
<td>16634144</td>
<td>99.2%</td>
</tr>
</tbody>
</table>
Figure 1: All INRIX Segment Study Areas
Figure 2: INRIX Segment Study Area 1
Figure 3: INRIX Segment Study Area 2
Figure 4: INRIX Segment Study Area 3
Figure 5: INRIX Segment Study Area 4
Figure 6: INRIX Segment Study Area 5
Route 1 and 2 are shown in Figure 7. Route 1 is on I-40 from US-1 to NC-147 near Raleigh, NC. The routes are approximately 13.5 miles long and contain 22 INRIX segments. Route 3 and 4 are shown in Figure 8. Route 3 is on I-64 from Greenbrier Parkway to the Hampton Roads Bridge Tunnel in the Hampton Roads area of Virginia. The routes are approximately 19 miles long and contain 31 INRIX segments. Route 5 and 6 are shown in Figure 9. Route 5 is on I-95 from Stirling Road to Linton Boulevard near Fort Lauderdale, FL. The routes are approximately 27 miles long and contain 39 INRIX segments. Route 7 and 8 are shown in Figure 10. Route 7 is on I-95 from I-495 in Wilmington, DE to I-76 in Philadelphia, PA. The routes are approximately 29 miles long and contain 50 INRIX segments. Route 9 and 10 are shown in Figure 11. Route 9 is on I-395 from I-95 to the Memorial Bridge near Washington, DC. The routes are approximately 8.5 miles long and contain 16 INRIX segments. Routes 9 and 10 are the only routes that experience recurring congestion building past the furthest upstream segment due to heavy congestion upstream and downstream of the facility.
Figure 8: Route 3 and 4 in Hampton Roads, VA on I-64
Figure 9: Routes 5 and 6 near Fort Lauderdale, FL on I-95
Figure 10: Routes 7 and 8 between Wilmington, DE and Philadelphia PA on I-95
In addition to the 10 routes analyzed at a 1 minute level, 3 additional routes were analyzed at 1, 5 and 15 minute aggregation levels to determine the how sensitive the differences in the two estimations were to different route characteristics and aggregation level.

Figure 12 contains maps of the three facilities and three reference points are numbered for comparison. Route A is a mixture of urban and rural interstate, 69.32 miles long on I-40 WB from I-95 to I-85 and contains 65 INRIX segments. The facility serves commuter traffic on interior sections, but typically only intercity traffic travels the entire facility. The facility encompasses all of Route B and a majority of Route C. The speed limit is 70 mph from the origin until approximately 17 miles into the facility, where the speed limit drops to 65 mph.
for the remainder of the facility. The travel time for the entire facility at the speed limit is 62.64 minutes.

Route B, an urban interstate route, is 14.72 miles long along I-40 WB from US-1 to NC-147 and contains 23 INRIX segments. The facility is primarily a commuter route that connects Raleigh, NC to Durham, NC and serves and passes through the Research Triangle Park, a major employment center in the area. The speed limit is 65 mph along the entire facility, and the travel time at the speed limit is 13.59 minutes. Route B contains all segments in Routes 1 and 2.

Route C, a rural interstate route, is 39.84 miles long on I-40 WB from NC-50/55 to I-440 and contains 17 INRIX segments. The facility crosses I-95 on the way to Raleigh, NC from southeastern North Carolina. The speed limit is 70 mph from the origin until approximately 30 miles into the facility, where the speed limit is 65 mph for the remainder of the facility, and the travel time at the speed limit is 34.53 minutes.

Temporary Bluetooth readers were placed at two locations indicated in Figure 12 on Route B by white circles with a dot in the center. At each location, two different readers were placed by the freeway, one pole-mounted and one placed on the ground. The readings from both types of readers were combined in to a single record for each location in order to maximize the possible matches between locations. The Bluetooth devices collected data from October 31, 2011 to January 6, 2012 except for short periods during battery charging. Segment travel times were downloaded for the same time period to compare estimation error for facility travel times in both directions.

For the facility characteristic sensitivity analysis, segment space mean speeds were collected for an 82.88 mile corridor of I-40 WB from NC-50/55 to I-85. Travel times were available in one-minute aggregation periods throughout 2010 with approximately 3.8% of missing records. One-minute travel times were also aggregated to five and fifteen-minute travel times using an average of available one-minute travel times. No sample size weighting could be done, because the probe sample size in each minute is the intellectual property of INRIX.
All space mean speeds were considered to represent all vehicles in the segment in the time period (i.e. 12:00:00-12:00:59 for one-minute aggregation or 12:00:00-12:14:59 for fifteen-minute aggregation).

![Sensitivity Analysis Routes](image)

**Figure 12**: Sensitivity Analysis Routes

### 2.4 Travel Time Reliability Performance Measure Definitions

Figure 13: Travel Time Reliability Performance Measures Overlaid on Travel Time Distribution shows a theoretical probability density function of travel rates for a section of freeway. Included are a majority of the performance measures described in the next subsections. While the figure shows actual travel times, these values can be normalized to travel rates in units of minutes per mile to compare segments and facilities of different lengths directly. All measures are calculated for the average traffic stream travel rates for a given time domain, as INRIX reports a single measure for each time period and not individual vehicle measures.
Figure 13: Travel Time Reliability Performance Measures Overlaid on Travel Time Distribution [18]
Travel Rate is one of two typical measures that normalize travel times. The second is the Travel Time Index [19], which is the observed travel time divided by the free flow travel time. The following equation calculates the Travel Time Index for a given Travel Rate:

\[
Travel \ Time \ Index = Travel \ Rate \left(\frac{\text{min}}{\text{mt}}\right) \times \frac{\text{Free \ Flow \ Speed \ (mph)}}{60 \text{ min/hr}}
\] (1)

2.4.1 Average Travel Rate

The average travel rate is calculated as a straight average of travel rates over the time domain. The average travel rate is not a true reliability measure, as it reports a nominal level of congestion as opposed to providing any information on the variation of travel rates. Travel time reliability measures that can be well predicted by the average do not provide new information to decision makers, so correlation tests will use the average travel rate as a baseline comparison to determine which reliability measures are providing unique information. The equation below was used to calculate average travel rates:

\[
\bar{\tau} = \frac{1}{N} \sum_{t=1}^{N} \tau_t
\] (2)

Where: \(\bar{\tau} = \text{Average Travel Rate} \)

\(\tau_t = \text{Travel Rate at time } t \)

\(N = \text{Total Observations in the time domain} \)

2.4.2 Standard Deviation

The standard deviation is a typical statistical measure used to quantify the variation in a distribution or dataset around the average. The FHWA advises against using the standard deviation as a reliability measure because it is more difficult for non-technical decision makers to understand [1], but it is included to compare reliability-focused measures to a traditional measure.
\[ s = \sqrt{\frac{1}{N} \sum_{t=1}^{N} (\tau_t - \bar{\tau})^2} \]  

Where: \( s \) = Standard Deviation of Travel Rate

2.4.3 Coefficient of Variation

The coefficient of variation is another typical statistical measure that can be used to compare distributions or datasets with different means. The coefficient of variation is discouraged for use as a reliability measure for the same reasons as the standard deviation [1]. The equation below shows how the coefficient of variation was calculated:

\[ \text{Coefficient of Variation} = \frac{s}{\bar{\tau}} \times 100 \]  

(4)

2.4.4 80th, 85th, 90th, 95th Percentile Travel Rate

Upper percentiles of travel time distributions, mostly the 95th percentile, are used for many reliability measures and typically indexed to median or average travel times. All travel rate percentiles were calculated in SAS. The following formulas describe how SAS calculates a given percentile from an ordered dataset:

\[ n \times p = j + g \]  

(5)

Where: \( n \) = Total observations in the dataset

\( p \) = Percentile to calculate / 100

\( j \) = Integer value of \( n \times p \)

\( g \) = Decimal value of \( n \times p \)

\[ \tau_p = (1 - g) \times \tau_j + g \times \tau_{j+1} \]  

(6)
Where: $\tau_p = p\times100$ Percentile Travel Rate

$\tau_j = j$th ordered observation

### 2.4.5 Average- and Median-based Buffer Index

Buffer Index measures were created to describe how much worse the 95th percentile travel rate is compared to typical travel rates. Early research focused on an average-based buffer index, but it has been shown that under highly skewed distributions, the buffer index based on the average can actually decrease as variability increases. [10] A buffer index based on the median has been used more recently that continues to increase as variation increases.

Equation 7 shows the formula to calculate an average-based buffer index and Equation 8 shows the formula to calculate a median-based buffer index.

$$
\text{Average – based Buffer Index} = \frac{(95\text{th Percentile Travel Rate} - \text{Average Travel Rate})}{\text{Average Travel Rate}} \tag{7}
$$

$$
\text{Median – based Buffer Index} = \frac{(95\text{th Percentile Travel Rate} - \text{Median Travel Rate})}{\text{Median Travel Rate}} \tag{8}
$$

### 2.4.6 Misery Rate

The misery rate is a performance measure that quantifies how much delay the worst trips experience. Past research has identified the worst 5% of trips to the worst 20% of trips to include in the calculation, but the average travel rate of the worst 5% of trips was calculated for this thesis. The following equation shows how the misery rate was calculated for an ordered dataset.

$$
\text{Misery Rate} = \frac{1}{0.05N} \sum_{t=0.95N}^{N} \tau_t \tag{9}
$$

### 2.4.7 Semi-Standard Deviation

The semi-standard deviation is a one-sided statistic that measures deviations from a reference value. In the case of travel rate or travel time distributions, the reference value is typically
the free flow travel rate or travel time and the deviations are only calculated for observations where the travel rate or travel time is higher than free flow. Observations with faster space mean speeds than the free flow speed contribute 0 to the statistic. Equation 10 shows how the semi-standard deviation was calculated:

\[
\text{Semi-Standard Deviation} = \frac{1}{N} \sum_{t=1}^{N} [\max(\tau_t - \tau_{FF}, 0)]^2
\]  

(10)

2.4.8 Skew

The skew statistic is a statistical measure that measures the tendency of the deviations to be larger in one direction than in the other. Travel time and travel rate distributions are typically positively skewed and have tails to the right compared to space mean speed distributions which are typically negatively skewed and have tails to the left. Equation 11 shows how skew was calculated:

\[
Skew = \frac{n}{(n-1)(n-2)} \sum_{t=1}^{n} \left( \frac{\tau_t - \tau_s}{s} \right)^2
\]  

(11)

2.4.9 Failure Rate

The failure rate is the proportion of trips or time where travel occurs at a travel time or travel rate above a threshold or below an equivalent space mean speed. In this thesis, only speed data is available, so the rates are calculated as a proportion of time. The failure rate is analogous to typical engineering approaches to reliability, however the threshold for failure is not clear-cut as it is for a structural analysis. Two failure rates were calculated; one identifying the proportion of time the segment or facility had a space mean speed lower than 50 mph and one for the proportion of time the segment or facility had a space mean speed lower than 40 mph. The equation below shows how the failure rates were calculated:

\[
\text{Failure Rate} = \frac{f}{n}
\]  

(12)

Where: \( f \) = Number of observations with space mean speed below threshold
3. SEGMENT AND FACILITY RELIABILITY PERFORMANCE MEASURES

3.1 Segment Reliability Measurement

INRIX directly provides segment space mean speeds and travel times, so no adjustments are needed to calculate reliability. Proper filtering must be used, as data during full closures cannot be used in reliability calculation since speeds of 0 mph result in infinitely large travel times or travel rates. When using segment reliability measurements to prioritize management strategies or improvements, it is important to consider whether unreliability in the segment is due to a factor within the segment or in a downstream segment. If a segment directly downstream experiences high unreliability, congestion may back up into the upstream segment. In this case, it is possible that the reliability for the upstream segment could be improved by deploying a management strategy or capacity improvement in the downstream segment. It is important to note that ideally all observations of travel time, travel rate or space mean speed be assigned a weight based on the number of trips that traverse the segment, though it is not possible for the INRIX dataset without fusing additional ITS data or estimating traffic flow for each observation.

3.2 Facility Reliability Measurement

Facility travel times or space mean speeds from an ITS source can be interpreted in two distinct ways. The first is a typical snapshot of the facility operations that takes into account the operation of each constituent segment simultaneously. The second is to estimate travel times or space mean speeds in a way that mimics how drivers experience the facility. The next sections compare the typical “simultaneous” operational snapshot of the facility to travel times that were “stitched” through time. Both estimation methods are compared to observed Bluetooth travel times to identify which methods perform better compared to actual travel times.
3.2.1 Simultaneous Facility Travel Time Estimation

Simultaneous Facility Travel Times are estimated by summing all segment travel times for a given departure time. This approach has been used in research as well as the Highway Capacity Manual, where the Step 7 of the Freeway Facilities method aggregates segment performance measures for each time interval. [20] In the methodology, facility space mean speeds are calculated as a length-weighted average of segment space mean speeds. The facility space mean speed is then used to calculate facility travel time.

3.2.2 Stitched Facility Travel Time Estimation

An algorithm was developed to stitch, or walk, route travel times by creating a pseudo-trajectory through segment space mean speed data. This method is similar to one developed by Berkeley Transportation Systems [21], but instead of using the speed at the entry time of the segment, the space mean speed is continuously updated throughout the segment. The algorithm is equivalent to a phantom vehicle that travels at the continuously updated space mean speed of the segment it is driving on. Stitched travel times were reported based on the facility departure time, as this is a variable drivers control without having to know the dynamic traffic characteristics. Stitching can be performed at any aggregation interval and with segments of any length, though longer aggregation and longer facilities will smooth out shockwaves that the phantom vehicle experiences. While routes of any length can be calculated, it is important to consider if the facility is significant enough with a sufficient number of vehicles traversing the entire route.

Figure 14 visualizes the two different approaches to estimating facility travel times from 1 minute segment travel times that were performed for Route 1. All stitched pseudo-trajectories for a two hour period are shown in the background as thin lines, and for a single departure time indicated with an arrow, the simultaneous trajectory is shown as a solid bold line and the stitched trajectory is shown as a dashed bold line. The reference time for the segment travel times used in the simultaneous trajectory is equal to the departure time in all segments, shown as a solid grey line, while the reference time for the segment travel times in
the stitched trajectory is equal to the departure time plus the travel time to the current position therefore tracking an increase or decrease in subsequent segment travel time in changing conditions.

The key step of the algorithm is the 3rd inner loop that calculates segment travel time. The speed for the segment at the phantom vehicles current time (departure time + cumulative travel time) is checked for missing or 0 speed. Then there is a check if the phantom vehicle can complete travel on the segment before the next reporting interval. If travel on the segment cannot be completed before the next reporting interval, then the amount of time remaining in the reporting interval is added to the running total of segment travel time and the distance the phantom vehicle travels during that time at the reported space mean speed is added to the previous position on the segment. If it can, the travel time to complete travel on the segment is added to the running total of segment travel time from previous reporting intervals on the same segment and the current position on the segment is set to the end of the segment, and the total segment travel time is added to the cumulative facility travel time.
3.2.3 Estimated Facility Travel Times vs. Observed Facility Travel Times

Facility travel times are calculated for all departure times included in the Bluetooth dataset. The defined Route B contains the entire Bluetooth route, but an indexed travel time (Actual Travel Time/Free Flow Travel Time) is compared between each direction of travel. Mean Absolute Percentage Error (MAPE) and a 95% Confidence Interval (CI) are calculated for each estimation method, direction of travel, and during all times or only congested times where the observed facility travel time is at least 1.5 times higher than the free flow travel time.
MAPE is calculated with the following equation:

\[
MAPE = \frac{1}{N} \sum_{t=1}^{N} \left| \frac{ObsTTI_t - EstTTI_t}{ObsTTI_t} \right| \times 100
\]

Where: \(TTI = \frac{\text{Actual Travel Time}}{\text{Free Flow Travel Time}}\)

\(N = \text{Number of Observations}\)

\(ObsTTI_t = \text{Observed TTI at time } t\)

\(EstTTI_t = \text{Estimated TTI at time } t\)

A 95% CI around the MAPE is calculated with the following equation:

\[
95\% \text{ CI} = MAPE \pm t^* \left( \frac{s_{APE}}{\sqrt{n}} \right)
\]

Where: \(t^* = \text{Critical Value for } t \text{ Distribution with } n-1 \text{ Degrees of Freedom with } p = 0.025\)

\(s_{APE} = \text{Sample Standard Deviation of Absolute Percentage Error}\)

<table>
<thead>
<tr>
<th>Estimation Method</th>
<th>Direction</th>
<th>All Time Periods</th>
<th>Congested Time Periods Only</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MAPE and CI</td>
<td>Observations</td>
</tr>
<tr>
<td>Stitched</td>
<td>EB</td>
<td>6.40% ± 0.071%</td>
<td>30563</td>
</tr>
<tr>
<td>Simultaneous</td>
<td>EB</td>
<td>6.77% ± 0.085%</td>
<td>30563</td>
</tr>
<tr>
<td>Stitched</td>
<td>WB</td>
<td>6.30% ± 0.110%</td>
<td>13573</td>
</tr>
<tr>
<td>Simultaneous</td>
<td>WB</td>
<td>7.34% ± 0.165%</td>
<td>13573</td>
</tr>
</tbody>
</table>

Facility travel time error for estimation from both methods compared to Bluetooth travel times was calculated for each observed travel time. The estimation error was calculated
based on indexed travel times to account for minor facility length differences between the estimation facility and route between Bluetooth devices. The two Bluetooth devices for each origin and destination were placed at equal offsets from the freeway. The westernmost Bluetooth devices were placed on the outside shoulder of the eastbound lanes and the easternmost Bluetooth devices were placed in the median of the freeway. This resulted in more eastbound observations than westbound observations, as shown in Table 3.

For both sample periods and in both directions, the stitched method has a lower MAPE and a tighter 95% confidence interval. When all observations are included, a vast majority of the points are in the uncongested region. The pseudo-trajectory created from the stitched method still polls segment space mean speeds at later times farther in the facility, but since there is very little transition between the departure and arrival time the two methods will estimate more accurate and similar travel times during free flow conditions. The results for the congested time periods, where the observed travel times are at least 1.5 times longer than the facility free flow travel time, show wide margins of improvement for the stitched method compared to a typical simultaneous estimation method especially in the more congested westbound direction.

In addition to the MAPE and CI for each combination of factors, the Travel Time Index for the two estimation methods and observations were plotted for large congestion events. Visual analysis was performed to identify temporal differences in the estimation methods that aggregate statistics do not distinguish.

For each direction, congested time periods were identified for visual analysis to display both estimation methods against observed travel times. All travel times were indexed to the free flow travel time (approximately 12 minutes in both directions) to account for minor facility length differences. As mentioned earlier, bias may be inherent in either source of travel time data and in most of the visual analyses outlier Bluetooth observations that were not filtered out by the IQ4 method employed by the software delivered by the device manufacturers were identified and labeled as filled circles. All displayed observations were identified as non-
outlier data by the manufacturer’s software without knowledge of the INRIX data or either estimation method results. Both estimation methods are informed by the same database of segment space mean speeds which have been shown to have latency issues and may have a vastly different composition of vehicles sampled compared to Bluetooth. [22]

The westbound facility experiences more severe recurring congestion. Figure 15 shows a congestion event that includes two collisions that occurred just as traffic demand was increasing during the PM peak period. All times reported are departure time for the routes. Both collisions occurred near the downstream end of the facility, causing maximum impact on facility travel times. Peak observed travel times with an index of approximately 6 correlate to a travel time of 70+ minutes to traverse a 13.3 mile facility. The extreme congestion exaggerates the differences between the two estimation methods and demonstrates the significant enhancements that the stitching methods provide. Other than a small lag (that could be due to lag in segment speed reporting), the stitched estimates fall extremely close to the observations while the peak of the simultaneous estimates is overestimated and lags significantly behind the observed peak.
Figure 15: Westbound Facility Travel Time Estimates and Observed Facility Travel Times

Figure 16 shows that the stitched estimation fits the transition from the peak travel time to an uncongested regime very well, in this case for the eastbound direction. However, in this case, the segment space mean speeds fluctuate greatly during the peak period, which throws off both estimation methods from the shape of the observed travel time profile. While neither method tracks perfectly, the stitched method also acts to smooth some of the wild segment speed fluctuations that cause large jumps in the simultaneous facility travel times.
3.2.4 Sensitivity Analysis of Estimation Methods to Facility Characteristics

Table 4 shows the statistics of the stitched and simultaneous facility travel times as well as the absolute differences for all weekday times in 2010. The free flow travel time is shown in parentheses next to each facility name. Any time periods where one or both methods did not report a travel time were not considered. Calculations were also performed on the AM peak periods and PM peak periods for weekdays in 2010. Mean, standard deviation and maximum travel times are reported for each method of all time periods in 2010. The mean, standard deviation and maximum absolute differences were calculated for each of the three time periods.

Table 4 shows that the mean travel time for all time periods does not change significantly when segment travel times are aggregated. This is expected, as the overall means are also
close to the free flow travel time since the facilities are in free flow conditions a majority of
the time. The mean absolute travel time difference for each facility increases when
examining the AM and PM peak periods. Route B and C both have diminishing mean
absolute differences in all time periods, while the mean increases from one-minute to five-
minute aggregation period in Route A. As the aggregation period increases, the amount of
time periods that the stitching method goes through decreases, and short facilities with travel
times shorter than the aggregation period (as in Route B at fifteen-minutes aggregation) have
stitched travel times identical to simultaneous travel times. The absolute difference is close
to 0 minutes in Route B with a fifteen-minute aggregation period, however travel times in the
congested period are larger than fifteen-minutes, so some stitching is performed that creates
different travel times from simultaneous travel times.

Average weekday facility travel time profiles are shown in Figure 17 for each aggregation
interval and method. All three facilities experience some level of recurring congestion at one
or two peak periods. Figure 17a compares methods and facilities at one-minute aggregation
for all weekdays in 2010. Routes A and C show a lag in the simultaneous method in
reporting a peak in travel time. Route A has a large peak in the AM period and a smaller
peak in the PM period, and both are reported approximately 30 minutes apart depending on
the method. The magnitudes of the average travel time in the AM peak for Route A appear
to be different between methods, but Figures 17b and 17c show that the difference appears to
be due to an artifact in the one minute data that does not occur in aggregated facility travel
times. In the case of Route C, a smaller AM peak is reported with no PM peak in travel
times. The different methods indicate a peak in facility travel time approximately 20 min
apart. Average weekday facility travel times calculated for Route B at one-minute
aggregation do not show any clear differences, even at or near the AM peak in travel times.
Table 4: 2010 Estimation Method Travel Times and Absolute Differences (Minutes)

<table>
<thead>
<tr>
<th></th>
<th>Route A (62.64)</th>
<th>Route B (13.59)</th>
<th>Route C (34.53)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Min</td>
<td>5 Min</td>
<td>15 Min</td>
</tr>
<tr>
<td>Stitched Mean</td>
<td>63.93</td>
<td>64.48</td>
<td>64.50</td>
</tr>
<tr>
<td>Stitched Std. Dev.</td>
<td>3.29</td>
<td>4.55</td>
<td>4.43</td>
</tr>
<tr>
<td>Stitched Max.</td>
<td>123.95</td>
<td>120.40</td>
<td>117.85</td>
</tr>
<tr>
<td>Simultaneous Mean</td>
<td>63.71</td>
<td>64.57</td>
<td>64.58</td>
</tr>
<tr>
<td>Simultaneous Std. Dev.</td>
<td>2.54</td>
<td>4.83</td>
<td>4.75</td>
</tr>
<tr>
<td>Simultaneous Max.</td>
<td>122.83</td>
<td>121.94</td>
<td>119.66</td>
</tr>
<tr>
<td>All-Absolute Difference Mean</td>
<td>1.71</td>
<td>1.95</td>
<td>1.58</td>
</tr>
<tr>
<td>All-Absolute Difference Std. Dev.</td>
<td>2.48</td>
<td>2.94</td>
<td>2.52</td>
</tr>
<tr>
<td>All-Absolute Difference Max.</td>
<td>60.62</td>
<td>57.12</td>
<td>46.16</td>
</tr>
<tr>
<td>AM-Absolute Difference Mean</td>
<td>3.18</td>
<td>3.73</td>
<td>3.05</td>
</tr>
<tr>
<td>PM-Absolute Difference Std. Dev.</td>
<td>4.19</td>
<td>4.55</td>
<td>3.89</td>
</tr>
<tr>
<td>PM-Absolute Difference Max.</td>
<td>50.06</td>
<td>44.77</td>
<td>37.82</td>
</tr>
<tr>
<td>AM-Absolute Difference Mean</td>
<td>2.40</td>
<td>2.83</td>
<td>2.27</td>
</tr>
<tr>
<td>PM-Absolute Difference Std. Dev.</td>
<td>3.33</td>
<td>4.01</td>
<td>3.45</td>
</tr>
<tr>
<td>PM-Absolute Difference Max.</td>
<td>60.62</td>
<td>57.12</td>
<td>41.97</td>
</tr>
</tbody>
</table>
All else being equal, facility travel times calculated using the stitching method will indicate congestion earlier than the simultaneous method as the downstream segment travel times are taken from time periods later than the facility departure time. Therefore, the lag in the simultaneous facility travel times seen in Route A and Route C are expected, while the lack
of lag in Route B merits in depth analysis. The lack of lag can be partially attributed to the creation of weekday averages, as the peak may not be consistently at the same time of day for each day of the week or throughout the year. However, this should not reduce lag as drastically as was found, so the segments that make up Route B were examined. It turns out the most highly congested segments occur near the beginning of the segment, so the stitched facility travel times experience the congestion at nearly the same time period as simultaneous facility travel times with the same departure time. Further analysis into the segments of Route A and C found that the most highly congested segments were located approximately 2/3 of the way through Route A and at the downstream end of Route C.

Figure 17b shows average facility travel times at five minute aggregation for all weekdays in 2010. Route A and Route C again display a difference between the time the peak average travel times occur similar to one-minute aggregation travel times, but the time between the peak of the stitched and simultaneous travel times decreased to approximately 20 and fifteen-minutes respectively. Route B maintains no noticeable difference in the time of the peak average travel time between the two methods. Similarly, Figure 17c shows the that Route A and Route C both have a one time period (fifteen-minute) difference in the time of the peak average travel time at fifteen-minute aggregation for all weekdays in 2010. Again, Route B does not display a difference in the time of the peak average travel time between the methods.

Further examination of the patterns displayed in Figure 17 indicates that the difference in time between the peak average travel time for the stitched and simultaneous method appears to be a function of the aggregation period, the facility length, and the location along the facility at which congestion occurs. Aggregating from one-minute segment travel times to fifteen-minute segment travel times decreases the time difference between the peaks, but both facilities that had a large time difference between peaks maintained at least one time period between the peaks of the stitched and simultaneous average facility travel times. The length of the facility also affects the time between peak average times, with a larger difference appearing in longer facilities compared to shorter facilities in the same aggregation.
period except in the case of fifteen-minute periods, where the aggregation and granularity of the averages leaves one time period between peaks. As seen in all aggregation periods, Route B does not have a large time difference between peaks due in most part to the fact that the most congested segments in the facility are located near the beginning of the facility. Route B and Route C have a single cluster of congested segments where a bottleneck often creates queues backing up into multiple segments. Route A encompasses the bottlenecks from both Route B and Route C.

3.3 Facility Travel Rate Distributions vs. Segment Travel Rate Distributions

Once cumulative distributions have been created for individual segments and individual observations are removed, aggregation of the segment distributions must assume that each segment is comonotonic. [23] This means that an observation at the 5th percentile for the first segment must occur at the same time as the 5th percentile for all other segments in the route, and all percentiles of the cumulative distribution for each segment can be summed to create the facility cumulative distribution.

Figure 18 shows this assumption for Route 1 at all time periods in 2010. For each percentile, the cumulative travel time is estimated for the facility by adding each segment travel time at the same percentile. The distributions created under the assumption of comonotonicity can be directly compared to the simultaneous estimate as they will be equal if all segments are comonotonic, while the stitched estimates will still be different as the segments are not analyzed at the same time. Figure 19 then compares this estimated facility travel time to the facility travel times estimated by the stitching and simultaneous method in 2010. While the observed Bluetooth travel times were collected for this route, the sample was collected only over a small portion of 2011. Table 5 shows the percent difference in the travel rate at important percentiles of the cumulative distribution. While the differences are lower near the median of the distribution, the assumption of comonotonicity is conservative at the highest percentiles which can have large effects on measures that are calculated from the entire distribution.
While there are techniques available to only update certain percentiles or other statistical measures for individual segments or facilities without keeping all observations, aggregating directly to facility measures from disaggregate segment measures is not advised for measures that take into account the entire travel time distribution. Instead, facility travel times should be calculated and then used to update facility measures directly for key facilities that require regular monitoring.
Figure 18: Estimating Facility Travel Time Distribution from Segment Distributions (Route 1)
Figure 19: Comparison of Facility Travel Time Distribution Estimation (Route 1 2010)

<table>
<thead>
<tr>
<th>Facility</th>
<th>5%</th>
<th>15%</th>
<th>50%</th>
<th>85%</th>
<th>95%</th>
<th>99%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route 1 2010 Stitched</td>
<td>-2.96%</td>
<td>-2.02%</td>
<td>-0.25%</td>
<td>-1.72%</td>
<td>-3.60%</td>
<td>17.86%</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------------</td>
<td>-------------------------</td>
<td>---------------------</td>
<td>-------------------------</td>
<td>-------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Route 1 2010 Simultaneous</td>
<td>-3.29%</td>
<td>-2.16%</td>
<td>-0.25%</td>
<td>-1.73%</td>
<td>-4.76%</td>
<td>16.24%</td>
</tr>
<tr>
<td>Route 1 2011 Stitched</td>
<td>-2.94%</td>
<td>-1.57%</td>
<td>0.14%</td>
<td>0.24%</td>
<td>-1.42%</td>
<td>-4.64%</td>
</tr>
<tr>
<td>Route 1 2011 Simultaneous</td>
<td>-3.29%</td>
<td>-1.75%</td>
<td>0.17%</td>
<td>0.26%</td>
<td>-1.54%</td>
<td>-5.65%</td>
</tr>
<tr>
<td>Route 2 2010 Stitched</td>
<td>-3.09%</td>
<td>-1.74%</td>
<td>-0.05%</td>
<td>-4.69%</td>
<td>-4.91%</td>
<td>29.59%</td>
</tr>
<tr>
<td>Route 2 2010 Simultaneous</td>
<td>-3.37%</td>
<td>-1.87%</td>
<td>0.00%</td>
<td>-5.21%</td>
<td>-7.29%</td>
<td>28.24%</td>
</tr>
<tr>
<td>Route 2 2011 Stitched</td>
<td>-3.08%</td>
<td>-1.75%</td>
<td>0.39%</td>
<td>0.04%</td>
<td>-7.09%</td>
<td>10.71%</td>
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<tr>
<td>Route 2 2011 Simultaneous</td>
<td>-3.39%</td>
<td>-1.90%</td>
<td>0.47%</td>
<td>0.13%</td>
<td>-7.83%</td>
<td>6.43%</td>
</tr>
<tr>
<td>Route 3 2010 Stitched</td>
<td>-4.10%</td>
<td>-1.08%</td>
<td>-0.71%</td>
<td>-4.09%</td>
<td>-1.29%</td>
<td>25.27%</td>
</tr>
<tr>
<td>Route 3 2011 Simultaneous</td>
<td>-4.17%</td>
<td>-1.10%</td>
<td>-0.70%</td>
<td>-4.69%</td>
<td>-3.11%</td>
<td>21.83%</td>
</tr>
<tr>
<td>Route 4 2011 Stitched</td>
<td>-4.24%</td>
<td>-1.05%</td>
<td>-0.26%</td>
<td>0.35%</td>
<td>-11.05%</td>
<td>28.21%</td>
</tr>
<tr>
<td>Route 4 2011 Simultaneous</td>
<td>-4.42%</td>
<td>-1.08%</td>
<td>-0.27%</td>
<td>0.25%</td>
<td>-11.57%</td>
<td>28.88%</td>
</tr>
<tr>
<td>Route 5 2011 Stitched</td>
<td>-5.05%</td>
<td>-2.27%</td>
<td>0.48%</td>
<td>0.11%</td>
<td>-10.95%</td>
<td>24.34%</td>
</tr>
<tr>
<td>Route 5 2011 Simultaneous</td>
<td>-5.82%</td>
<td>-2.55%</td>
<td>0.65%</td>
<td>0.23%</td>
<td>-11.71%</td>
<td>21.01%</td>
</tr>
<tr>
<td>Route 6 2011 Stitched</td>
<td>-4.74%</td>
<td>-2.27%</td>
<td>0.57%</td>
<td>-0.01%</td>
<td>-10.84%</td>
<td>22.06%</td>
</tr>
<tr>
<td>Route 6 2011 Simultaneous</td>
<td>-5.48%</td>
<td>-2.57%</td>
<td>0.73%</td>
<td>0.28%</td>
<td>-11.41%</td>
<td>17.44%</td>
</tr>
<tr>
<td>Route 7 2011 Stitched</td>
<td>-5.39%</td>
<td>-2.68%</td>
<td>-0.47%</td>
<td>-4.45%</td>
<td>-2.53%</td>
<td>39.93%</td>
</tr>
<tr>
<td>Route 7 2011 Simultaneous</td>
<td>-5.64%</td>
<td>-2.77%</td>
<td>-0.45%</td>
<td>-4.66%</td>
<td>-2.90%</td>
<td>40.01%</td>
</tr>
<tr>
<td>Route 8 2011 Stitched</td>
<td>-4.92%</td>
<td>-2.35%</td>
<td>-0.09%</td>
<td>-2.80%</td>
<td>-5.34%</td>
<td>30.30%</td>
</tr>
<tr>
<td>Route 8 2011 Simultaneous</td>
<td>-5.26%</td>
<td>-2.42%</td>
<td>-0.02%</td>
<td>-2.72%</td>
<td>-6.04%</td>
<td>28.06%</td>
</tr>
<tr>
<td>Route 9 2011 Stitched</td>
<td>-5.79%</td>
<td>-2.83%</td>
<td>-0.30%</td>
<td>-0.86%</td>
<td>0.72%</td>
<td>18.17%</td>
</tr>
<tr>
<td>Route 9 2011 Simultaneous</td>
<td>-5.81%</td>
<td>-2.83%</td>
<td>-0.35%</td>
<td>-1.64%</td>
<td>-0.08%</td>
<td>15.13%</td>
</tr>
<tr>
<td>Route 10 2011 Stitched</td>
<td>-4.33%</td>
<td>-1.56%</td>
<td>-0.25%</td>
<td>0.93%</td>
<td>-1.75%</td>
<td>11.70%</td>
</tr>
<tr>
<td>Route 10 2011 Simultaneous</td>
<td>-4.41%</td>
<td>-1.56%</td>
<td>-0.26%</td>
<td>0.88%</td>
<td>-2.85%</td>
<td>8.62%</td>
</tr>
</tbody>
</table>
4. TRAVEL TIME RELIABILITY MEASURES WITH VARIABLE TEMPORAL DOMAINS

4.1 Travel Time Reliability over 24 Hours vs. Peak Periods

Distributions of travel times or rates can vary greatly depending on the time of day included in analysis. Segments or facilities typically operate near free flow conditions most of the day, and only peak periods experience recurring congestion. Travel Time Reliability Measures were calculated for 8 selected time periods:

1. All Days, 24 Hours
2. Weekdays, 24 Hours
3. Weekdays, AM Peak Period (6AM-9AM)
4. Weekdays, PM Peak Period (4PM-7PM)
5. Weekdays, AM + PM Peak Periods
6. Weekdays, AM Peak Hour (7AM-8AM)
7. Weekdays, PM Peak Hour (5PM-6PM)
8. Weekdays, AM + PM Peak Hours

Figure 20 shows an example of cumulative travel rate distributions calculated for each time period for a segment that has high PM peak congestion. The segments were ranked by each reliability measure for each time period, and the rankings of each time period were compared to the rankings for all days and times. The root mean squared differences were calculated for each reliability measure and time period compared to time period 1, and are shown in the table below. All segments described in section 2.2 were included except for the reversible HOV lanes on I-395, as no measures can be calculated when the facility is closed.

Root Mean Square Differences (RMSD) were calculated using the following equation:
Where: \( x_t = \) 24 Hour Performance Measure Value at time \( t \)

\[
RMSD = \sqrt{\frac{1}{N} \sum_{t=1}^{N} (x_t - y_t)^2}
\]  

(15)

\( y_t = \) Performance Measure Value for Comparison Time Domain at time \( t \)

Table 6 shows the root mean square differences for each time period and reliability measure compared to the first time period. For all reliability measures except the failure rate where space mean speed is below 40 mph and for the average travel time, the PM peak period or PM peak hour has the highest RMSD. For the failure rate where space mean speed is below 40 mph, the AM Peak Hour had the highest RMSD. When using one of these reliability measures, direct comparisons between measures calculated for a PM peak period or PM peak hour and measures calculated for a 24 hour time period will not be valid. Factors to convert selected time period measures to the equivalent 24 hour measure will only be appropriate if enough temporal characteristics of the segment are known to calculate the 24 hour measure directly.
<table>
<thead>
<tr>
<th>Comparison Time Period</th>
<th>Average Travel Rate</th>
<th>Standard Deviation</th>
<th>Coefficient of Variation</th>
<th>Skew</th>
<th>80th Percentile Travel Rate</th>
<th>85th Percentile Travel Rate</th>
<th>90th Percentile Travel Rate</th>
<th>95th Percentile Travel Rate</th>
<th>Semi-Standard Deviation</th>
<th>Failure Rate SMS&lt;50 mph</th>
<th>Failure Rate SMS&lt;40 mph</th>
<th>Median Buffer Index</th>
<th>Average Buffer Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.029</td>
<td>0.068</td>
<td>5.398</td>
<td>0.055</td>
<td>0.104</td>
<td>0.156</td>
<td>0.207</td>
<td>0.200</td>
<td>0.139</td>
<td>0.074</td>
<td>7.975</td>
<td>0.018</td>
<td>0.016</td>
</tr>
<tr>
<td>3</td>
<td>0.246</td>
<td>0.307</td>
<td>24.971</td>
<td>0.524</td>
<td>0.582</td>
<td>0.631</td>
<td>0.724</td>
<td>0.615</td>
<td>0.369</td>
<td>0.370</td>
<td>37.046</td>
<td>0.124</td>
<td>0.109</td>
</tr>
<tr>
<td>4</td>
<td>0.339</td>
<td>0.418</td>
<td>28.890</td>
<td>0.667</td>
<td>0.788</td>
<td>0.927</td>
<td>1.120</td>
<td>0.949</td>
<td>0.540</td>
<td>0.514</td>
<td>35.533</td>
<td>0.193</td>
<td>0.168</td>
</tr>
<tr>
<td>5</td>
<td>0.215</td>
<td>0.298</td>
<td>21.835</td>
<td>0.515</td>
<td>0.633</td>
<td>0.753</td>
<td>0.879</td>
<td>0.822</td>
<td>0.488</td>
<td>0.352</td>
<td>30.536</td>
<td>0.121</td>
<td>0.107</td>
</tr>
<tr>
<td>6</td>
<td>0.302</td>
<td>0.295</td>
<td>24.339</td>
<td>0.551</td>
<td>0.598</td>
<td>0.635</td>
<td>0.700</td>
<td>0.555</td>
<td>0.337</td>
<td>0.385</td>
<td>40.905</td>
<td>0.155</td>
<td>0.139</td>
</tr>
<tr>
<td>7</td>
<td>0.337</td>
<td>0.385</td>
<td>40.905</td>
<td>0.155</td>
<td>0.139</td>
<td>0.460</td>
<td>0.428</td>
<td>23.535</td>
<td>0.833</td>
<td>0.958</td>
<td>1.119</td>
<td>1.348</td>
<td>1.045</td>
</tr>
<tr>
<td>8</td>
<td>0.285</td>
<td>0.328</td>
<td>20.318</td>
<td>0.651</td>
<td>0.764</td>
<td>0.897</td>
<td>1.046</td>
<td>0.968</td>
<td>0.542</td>
<td>0.411</td>
<td>37.581</td>
<td>0.158</td>
<td>0.140</td>
</tr>
</tbody>
</table>
Figure 20: Cumulative Travel Rate Distribution for Segment 103N04121 near Philadelphia, PA
4.2 Travel Time Reliability by Time of Day

Typical traffic measures follow a daily pattern; however reliability can be greatly influenced by non-recurring events such as weather and incidents. Three reliability measures were selected to plot time of day reliability for segment travel rates: Semi-standard deviation, Skew and Standard Deviation. Reliability measures calculated with the small sample that a time of day analysis provides (N = number of days) can be greatly influenced by one or two outlier travel times. These three measures were chosen because they take into account each observation, rather than a single observation or only the worst observations and in the next chapter they are shown to have the lowest correlation to the average travel rate. Average travel rate was also included to represent recurring operations in comparison to the reliability measures. Each measure, including average travel rate, was normalized on a 0 to 1 scale to identify maximum and minimum values directly.

Figure 21 shows the time of day reliability measures and average travel rate for segment 102+04099 on I-95 NB near Fort Lauderdale, FL. The average travel rate for each 15 minute time period varies from 1.11 min/mi to 1.38 min/mi. Two of the reliability measures, the semi-standard deviation and standard deviation, show an AM and PM peak, while the skew has local peaks at multiple time periods. The maximum value for the each measure, other than skew, occurs at the same time as the average travel rate (9:15AM). The skew appears to be more sensitive to non-recurring congestion and does not appear to have a disparity in the local peak values between high and low demand time periods.

Figure 22 shows time of day reliability measures for segment 110N04121 on I-395 SB near Washington, DC. The average travel rate for each 15 minute time period varies from 0.98 min/mi to 1.11 min/mi and less congested than the previous segment analyzed. As a whole, the I-395 facility is very congested during peak times, with the southbound facility experiencing recurring congestion during the PM period. This segment, however, is directly downstream of an off-ramp to I-495 that acts as a bottleneck so that the traffic during the PM period is metered. Additionally, the skew identifies fewer local peaks indicating that the
non-recurring congestion is not as frequent on this segment compared to the previously analyzed segment.

Figure 23 shows time of day reliability measures for segment 110P04874 on I-64 WB near Hampton Roads, VA. This segment is located just upstream of the Hampton Roads Bridge-Tunnel, and incidents in the tunnel may contribute to the majority of the non-recurring congestion, while the bridge-tunnel also acts as a bottleneck that causes recurring congestion on this segment. The average travel rate for each 15 minute time period varies from 0.96 min/mi to 1.81 min/mi and experiences the highest recurring congestion of the segment shown in this section. Two peaks at 12:45 PM and 1:15 PM appear to have significantly high travel rates in the tail of the distribution, causing all three measures to reach a peak or near peak value. The skew decreases during the peak period, and this is the only measure shown that would indicate that the reliability improves during recurring congestion.

Figure 24 shows time of day reliability measures for segment 103N04108 on I-95 SB near Wilmington, DE. The average travel rate for each 15 minute time period varies from 0.94 min/mi to 1.77 min/mi. All reliability measures indicate that the facility is reliable for nearly all of the overnight and morning hours, though there are multiple local peaks for each measure during the day. During the peak PM period all measures except for skew indicate unreliability, but the peak standard deviation values occur earlier than the average travel rate. This may be indicative of a stochastic start of congestion that causes a high standard deviation but not as high average travel rate, while the three segments analyzed earlier had these measures peaking within the same time frame as the average travel rate.

Figure 25 shows time of day reliability measures for segment 125+04858 on I-40 WB near Raleigh, NC. The average travel rate for each 15 minute time period varies from 0.91 min/mi to 1.33 min/mi. This segment was under widening construction during 2010, and the reliability measures all show multiple local peaks throughout the day and overnight. In this segment, the semi-standard deviation and standard deviation peak later than the average travel rate indicating that while the time that congestion begins is fairly consistent, the time that congestion drops is stochastic.
Figure 21: Time of Day Reliability Measures for Segment 102+04099 on I-95 NB near Fort Lauderdale, FL
Figure 22: Time of Day Reliability Measures for Segment 110N04121 on I-395 SB near Washington, DC
Figure 23: Time of Day Reliability Measures for Segment 110P04874 on I-64 WB near Hampton Roads, VA
Figure 24: Time of Day Reliability Measures for Segment 103N04108 on I-95 SB near Wilmington, DE
Figure 25: Time of Day Reliability Measures for Segment 125+04858 on I-40 WB near Raleigh, NC
4.3 Travel Time Reliability during Construction and After a Capacity Improvement

Capacity improvements targeting recurring congestion have been shown to have very different effects on reliability based on the reliability measure used and how much the worst trips are improved by the improvement. For instance, a capacity improvement may significantly improve the average travel rate throughout the day, but the 95th percentile travel rate may remain unchanged if non-recurring events such as incidents cause similar travel rates after improvement. In this case, an average-based or even a median-based buffer index would show a decrease in reliability, or an increase in unreliability.

In 2011, a portion of Route 1 and 2 were widened from two lanes in each direction to three. Construction on the shoulder was present throughout 2010, while planned lane closures only occurred from 9 PM to 5 AM on weekdays to minimize congestion due to construction. The next sections compare reliability between these two years for the segments improved as well for the full facility.

4.3.1 Capacity Improvement Effects on Segment Reliability

Table 7 shows the percent change in five reliability measures for 10 segments that were widened from 2 mainline lanes to 3 mainline lanes in each direction. The decrease in the first four measures indicates that the improvements affect the tail of the travel time distribution, with the 95th percentile travel rate improving the most. Meanwhile, the non-recurring events have presumably not changed or gotten more frequent (construction does not affect weather and assuming a stable incident rate, incidents will increase if demand increases after to the widening) and the congestion due to these events deviates much more from the mean after construction as shown with the large increase in skew for all segments.
### Table 8: Percent Change in Facility Reliability Measures after a Capacity Improvement

<table>
<thead>
<tr>
<th>Facility</th>
<th>80th Percentile Travel Rate</th>
<th>85th Percentile Travel Rate</th>
<th>90th Percentile Travel Rate</th>
<th>95th Percentile Travel Rate</th>
<th>Skew</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route 1</td>
<td>-3%</td>
<td>-5%</td>
<td>-8%</td>
<td>-15%</td>
<td>128%</td>
</tr>
<tr>
<td>Route 2</td>
<td>-5%</td>
<td>-9%</td>
<td>-18%</td>
<td>-28%</td>
<td>44%</td>
</tr>
</tbody>
</table>
5. COMPARISON OF TRAVEL TIME RELIABILITY MEASURES

5.1 Correlation between Segment Reliability Measures and the Average Travel Rate

A correlation test was performed on reliability performance measures calculated for each segment across all times and days sampled. As stated earlier, reliability performance measures should provide new information to decision makers compared to standard mobility measures like the mean. Table 9 and Table 10 show the mean and standard deviation of each reliability measure across all segments. Table 11 shows the correlation coefficients for each combination of reliability measures and highlights four measures that are lowest correlated to the average travel rate: standard deviation, coefficient of variation, semi-standard deviation and skew.

| Table 9: Segment Reliability Measure Values: Mean and Standard Deviation |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                            | **Average Rate** | **Standard Deviation** | **Coefficient of Variation** | **80th PCTL** | **85th PCTL** | **90th PCTL** | **95th PCTL** |
| Mean Value                  | 0.991            | 0.298               | 28.5                        | 0.991          | 1.01          | 1.056         | 1.213         |
| Standard Deviation          | 0.126            | 0.271               | 22.917                      | 0.108          | 0.149         | 0.266         | 0.555         |

| Table 10: Segment Reliability Measure Values: Mean and Standard Deviation (cont.) |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                            | **Median BI** | **Average BI** | **Misery Rate** | **Semi Standard Deviation** | **Skew** | **Failure rate <50 mph** | **Failure rate <40 mph** |
| Mean Value                  | 0.257            | 0.19               | 1.719                      | 0.311                      | 28.59   | 0.05                | 0.023             |
| Standard Deviation          | 0.465            | 0.323              | 0.951                      | 0.291                      | 34.93   | 0.124               | 0.04              |

All four reliability measures identified by the correlation test are standard measures of variation, and literature advised against using these as they are not easily explained to a non-technical decision maker. A closer look into the relationships between each reliability
measure and the average travel rate can be found in the next section. Appendix B includes the relationships for the PM Peak Hour as a comparison. For the PM Peak hour, the four measures that show the lowest correlation to the average travel rate are coefficient of variation, median buffer index, mean buffer index and skew.
Table 11: Segment Reliability Measures Correlation Coefficients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Coefficient of Variation</th>
<th>80th PCTL</th>
<th>85th PCTL</th>
<th>90th PCTL</th>
<th>95th PCTL</th>
<th>Median BI</th>
<th>Average BI</th>
<th>Misery Rate</th>
<th>Semi stdev</th>
<th>Skew</th>
<th>Percent below 50mph</th>
<th>Percent below 40mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1</td>
<td>0.682</td>
<td>0.525</td>
<td>0.938</td>
<td>0.922</td>
<td>0.894</td>
<td>0.906</td>
<td>0.816</td>
<td>0.809</td>
<td>0.875</td>
<td>0.761</td>
<td>-0.229</td>
<td>0.86</td>
<td>0.914</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.682</td>
<td>1</td>
<td>0.973</td>
<td>0.476</td>
<td>0.505</td>
<td>0.567</td>
<td>0.705</td>
<td>0.718</td>
<td>0.691</td>
<td>0.862</td>
<td>0.992</td>
<td>0.14</td>
<td>0.449</td>
<td>0.67</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.525</td>
<td>0.973</td>
<td>1</td>
<td>0.314</td>
<td>0.334</td>
<td>0.394</td>
<td>0.544</td>
<td>0.578</td>
<td>0.554</td>
<td>0.752</td>
<td>0.946</td>
<td>0.227</td>
<td>0.301</td>
<td>0.527</td>
</tr>
<tr>
<td>80th PCTL</td>
<td>0.938</td>
<td>0.476</td>
<td>0.314</td>
<td>1</td>
<td>0.961</td>
<td>0.852</td>
<td>0.768</td>
<td>0.632</td>
<td>0.631</td>
<td>0.674</td>
<td>0.575</td>
<td>-0.211</td>
<td>0.893</td>
<td>0.838</td>
</tr>
<tr>
<td>85th PCTL</td>
<td>0.922</td>
<td>0.505</td>
<td>0.334</td>
<td>0.961</td>
<td>1</td>
<td>0.932</td>
<td>0.812</td>
<td>0.694</td>
<td>0.679</td>
<td>0.691</td>
<td>0.596</td>
<td>-0.195</td>
<td>0.848</td>
<td>0.859</td>
</tr>
<tr>
<td>90th PCTL</td>
<td>0.894</td>
<td>0.567</td>
<td>0.394</td>
<td>0.852</td>
<td>0.932</td>
<td>1</td>
<td>0.903</td>
<td>0.833</td>
<td>0.811</td>
<td>0.745</td>
<td>0.641</td>
<td>-0.178</td>
<td>0.766</td>
<td>0.866</td>
</tr>
<tr>
<td>95th PCTL</td>
<td>0.906</td>
<td>0.705</td>
<td>0.544</td>
<td>0.768</td>
<td>0.812</td>
<td>0.903</td>
<td>1</td>
<td>0.978</td>
<td>0.972</td>
<td>0.892</td>
<td>0.76</td>
<td>-0.177</td>
<td>0.724</td>
<td>0.887</td>
</tr>
<tr>
<td>Median BI</td>
<td>0.816</td>
<td>0.718</td>
<td>0.578</td>
<td>0.632</td>
<td>0.694</td>
<td>0.833</td>
<td>0.978</td>
<td>1</td>
<td>0.994</td>
<td>0.885</td>
<td>0.754</td>
<td>-0.161</td>
<td>0.59</td>
<td>0.822</td>
</tr>
<tr>
<td>Average BI</td>
<td>0.809</td>
<td>0.691</td>
<td>0.554</td>
<td>0.631</td>
<td>0.679</td>
<td>0.811</td>
<td>0.972</td>
<td>0.994</td>
<td>1</td>
<td>0.865</td>
<td>0.729</td>
<td>-0.161</td>
<td>0.6</td>
<td>0.822</td>
</tr>
<tr>
<td>Misery Rate</td>
<td>0.875</td>
<td>0.862</td>
<td>0.752</td>
<td>0.752</td>
<td>0.674</td>
<td>0.691</td>
<td>0.745</td>
<td>0.892</td>
<td>0.885</td>
<td>0.865</td>
<td>1</td>
<td>0.892</td>
<td>-0.211</td>
<td>0.636</td>
</tr>
<tr>
<td>Semi stdev</td>
<td>0.761</td>
<td>0.992</td>
<td>0.946</td>
<td>0.575</td>
<td>0.596</td>
<td>0.641</td>
<td>0.764</td>
<td>0.754</td>
<td>0.729</td>
<td>0.892</td>
<td>1</td>
<td>0.104</td>
<td>0.546</td>
<td>0.737</td>
</tr>
<tr>
<td>Skew</td>
<td>-0.229</td>
<td>0.14</td>
<td>0.227</td>
<td>-0.211</td>
<td>-0.195</td>
<td>-0.178</td>
<td>-0.161</td>
<td>-0.161</td>
<td>-0.211</td>
<td>0.104</td>
<td>1</td>
<td>-0.177</td>
<td>-0.211</td>
<td>-0.211</td>
</tr>
<tr>
<td>Percent below 50mph</td>
<td>0.86</td>
<td>0.449</td>
<td>0.301</td>
<td>0.893</td>
<td>0.848</td>
<td>0.766</td>
<td>0.724</td>
<td>0.59</td>
<td>0.6</td>
<td>0.636</td>
<td>0.546</td>
<td>-0.177</td>
<td>1</td>
<td>0.859</td>
</tr>
<tr>
<td>Percent below 40mph</td>
<td>0.914</td>
<td>0.67</td>
<td>0.527</td>
<td>0.838</td>
<td>0.859</td>
<td>0.866</td>
<td>0.887</td>
<td>0.822</td>
<td>0.822</td>
<td>0.849</td>
<td>0.737</td>
<td>-0.211</td>
<td>0.859</td>
<td>1</td>
</tr>
</tbody>
</table>
5.2 Visual Analysis of Relationships between Segment Reliability Measures and the Average Travel Rate

Further information on the relationships between each reliability measure and the average travel rate can be gleaned from a visual analysis of the scatter plots of each measure against the average for all segments.

5.2.1 Standard Deviation

Figure 26 shows the relationship between the standard deviation and the average travel rate. The two are loosely correlated (0.682 correlation coefficient) and have a linear relationship with scatter increasing as the average travel rate increases.

5.2.2 Coefficient of Variation

Figure 27 shows the relationship between the standard deviation and the average travel rate. The two are loosely correlated (0.525 correlation coefficient) and the coefficient of variation tends to increase linearly and displays increasing scatter as the average travel rate increases similarly to the standard deviation.

5.2.3 80th, 85th, 90th and 95th Percentile Travel Rate

Figure 28, Figure 29, Figure 30 and Figure 31 show the relationships between the 80th, 85th, 90th and 95th percentile travel rate, respectively, and the average travel rate. The correlation coefficients for each percentile are 0.938, 0.922, 0.894 and 0.906 respectively, indicating that all four are very well correlated to the average travel rate. All four relationships appear to have an exponential relationship with the average travel rate, while the values are more scattered in the upper average travel rates for the 90th and 95th percentile travel rates.
5.2.4 Average- and Median-based Buffer Index

Figure 33 and Figure 32 show the relationships between the average-based buffer index and median based buffer index, respectively, and the average travel rate. Both measures are loosely correlated to the average travel rate with correlation coefficients of 0.816 and 0.809 respectively. The average buffer index is flat for very low average travel rates, but increases exponentially after an average travel rate of approximately 1 min/mi. The median buffer index displays a similar pattern to the average buffer index.

5.2.5 Misery Rate

Figure 34 shows the relationship between the misery rate and the average travel rate. The two are well correlated (0.875 correlation coefficient) and the relationship is linear with increasing scatter as the average travel rate increases.

5.2.6 Semi-Standard Deviation

Figure 35 shows the relationship between the semi-standard deviation and the average travel rate. The two are fairly correlated (0.761 correlation coefficient) and the relationship is linear, following a similar pattern to the standard deviation with increasing scatter for higher average travel rates.

5.2.7 Skew

Figure 36 shows the relationship between skew and the average travel rate. The correlation coefficient between these measures is the lowest for any reliability measure (-0.229) and has an inversely proportional relationship. The highest skew values identify segments with very low average travel rates as the least reliable. This makes sense if the hypothesis proposed in section 4.2 is true, that the skew identifies non-recurring congestion. These high skew and low average travel rate segments would have the skew value greatly affected by the outlying travel times from non-recurring congestion, while travel times during non-recurring congestion on segments with higher average travel rates do not deviate as far from the mean.
5.2.8  Failure Rate

Figure 37 and Figure 38 show the relationship between the failure rate and the average travel rate with a threshold of 50 mph and 40 mph, respectively. Both failure rates are well correlated with the average travel rate (0.860 and 0.914 correlation coefficients, respectively) and the 50 mph failure rate has an exponential relationship with the average travel rate, while the 40 mph failure rate relationship is more linear.
Figure 26: Segment Standard Deviation vs. Average Travel Rate
Figure 27: Segment Coefficient of Variation vs. Average Travel Rate
Figure 28: Segment 80th Percentile Travel Rate vs. Average Travel Rate
Figure 29: Segment 85th Percentile Travel Rate vs. Average Travel Rate
Figure 30: Segment 90th Percentile Travel Rate vs. Average Travel Rate
Figure 31: Segment 95th Percentile Travel Rate vs. Average Travel Rate
Figure 32: Segment Average Buffer Index vs. Average Travel Rate
Figure 33: Segment Median Buffer Index vs. Average Travel Rate
Figure 34: Segment Misery Rate vs. Average Travel Rate
Figure 35: Segment Semi-Standard Deviation vs. Average Travel Rate
Figure 36: Segment Skew vs. Average Travel Rate
Figure 37: Segment Failure Rate where Space Mean Speed less than 50 mph vs. Average Travel Rate
Figure 38: Segment Failure Rate where Space Mean Speed less than 40 mph vs. Average Travel Rate
6. CONCLUSIONS

This thesis examined a host of travel time reliability performance measures proposed in literature for five locations in the US. All reliability measures were calculated from INRIX space mean speed segment data provided through the I-95 Corridor Coalition. Segment-based reliability measures were calculated from 15 minute data while facility-based reliability measures were calculated from 1 minute data. It was identified that facility travel time estimation could be improved by using an algorithm to stitch pseudo-trajectories through data in order to report travel times from a driver’s perspective compared to a typical simultaneous route travel time. Improvements gained using the stitching method were greater for shorter reporting intervals, longer facilities, heavy recurring congestion and facilities with recurring congestion occurring toward its downstream end. In order to effectively monitor reliability using measures that incorporate the entire travel time distribution for key facilities, it is important to estimate actual travel time for the facility rather than assuming that the constituent segments are comonotonic and aggregating the segment distributions.

Temporal sampling by time of day has a large effect on the travel time reliability measures calculated. If only portions of the day are used to create travel time distributions, the measures calculated from the sample will vary depending on the temporal characteristics of the segment. This means that distributions for a given time period are only valid when compared to the same time period, and even then effects like directional demand peaks can affect direct comparisons across segment types. Ideal comparisons of reliability measures should include all 24 hours of the day, and time of day analysis can identify time periods where management strategies can have the most effect on reliability. Capacity improvements on two facilities were shown to improve reliability by most measures, though the skew increased after the improvement due to non-recurring events providing larger deviations from the (reduced) mean.
Travel time reliability measures should provide additional information to decision makers, rather than restating typical performance measures. Most reliability measures are well correlated to the average travel rate, and the Federal Highway Administration advises against using the four measures with the lowest correlation as they are statistical measures that non-technical decision makers may not understand. Detailed analysis of the relationships between each measure and the average travel rate concluded that skew may indicate segments or facilities with non-recurring congestion that is disproportionally larger than recurring congestion. No single measure appears to be ideal, and each measure is calculated from a part of or the entire travel time distribution. Though single measures can simplify decision making, it is recommended that full distributions be compared where appropriate. With increasing exposure to these distributions and careful explanations as to what they represent, decision makers can effectively prioritize traffic management and geometric improvements.
REFERENCES


Transportation Administration, 1978.


APPENDICES
Appendix A: INRIX Variable Definitions

Excerpt from I-95 VPP Interface Guide [15]:

“The TMC element includes the specific traffic data attributes requested in the API call. Each TMCSetId references a list of roadway segments for which information is to be provided. Each roadway segment is defined by its unique 9 character TMC location code (the next section on Location Referencing will describe these codes in great detail). For each TMC location code in a given TmcSetId (e.g. all roads in Delaware), the response will contain a TMC attribute. The specific attributes will depend upon the specific API call, but will include all or some of the following:

- The *speed* attribute provides the current estimated space mean speed for the roadway segment in miles per hour.

- The *average* attribute is the historical average mean speed for the roadway segment for that hour of the day and day of the week in miles per hour.

- The *reference* attribute is the calculated “free flow” mean speed for the roadway segment in miles per hour (capped at 65 miles per hour). This attribute is calculated based upon the 85th-percentile point of the observed speeds on that segment for all time periods, which establishes a reliable proxy for the speed of traffic at free-flow for that segment.

- The *score* attribute is an indicator of data type. Three discrete values will be provided:
  - “30” – Real-time time data for that specific segment
  - “20” – Based on real-time data across multiple segments and/or based on a combination of expected and real-time data
  - “10” – Based primarily on historical data or road reference speeds
    - See prior comments specific to the planned additional parameter for the new C-Value (confidence value) for which the University of Maryland has written a white paper.

- The *travelTimeMinutes* attribute is the current estimate time it takes to traverse the roadway segment in minutes.
The C-Value

In December 2009 INRIX began publishing a C-Value, or confidence value, to I-95 users in the API data feed (it has been officially available since May 2009 within the archive data that is accessed via the I-95 Monitoring Site), the C-Value is separate from the score attribute. The C-Value is designed to provide supplemental information to the score attribute to best identify the type and confidence of the data being sent by INRIX. The below is a sample (with very few TMCs) that shows how the C-Value will be returned in an API response once enabled. The C-Value alone is not intended to convey whether the data is purely real-time, nor is it intended to map to specific thresholds relating to use. Rather, when used in conjunction with score, the C-Value allows agencies to make an independent determination as to the type and confidence of the data based on individual use cases. It is important to remember that the score is used to determine the type of data (a score of „30. represents pure real-time data), and the C-Value should be used to add commentary to the score, or a confidence of the real-time data. The coalition in joint effort with the University of Maryland has prepared a white paper specific to the C-Value and its suggested use. The bullets below are important to consider when using the C-Value:

- Real-time speeds have variability which is a function of driver behavior and congestion state
- A model of confidence must capture this variability and identify speed estimates which are inconsistent with expectations.
- Our model of „expectations. is based on three time-scales which are used within the INRIX calculation to produce the single C-Value, it is a blended calculation based on all three time-scales:
  - Short-Term:
    o -Probe data is a reliable estimator of current speeds if their density is sufficient:
    o -If sufficient real-time data points, then confidence value is 100
  - Mid-Term:
    o -Compute a model of speed distributions within the last 45 minutes
    o -Is the current speed probable given mid-term speeds?
    o -Confidence value is proportional to probability
  - Long-Term:
    o -Historic data can be used to create a very dense model of average behavior. Within a broader range, these speeds can validate current speeds
    o -If current speed is within confidence interval about the historic average, then confidence value is 100
- The C-Value is expected to be returned only when a sufficient amount of real-time data exists for which to calculate confidence (in other words, when „score. is 30)
• C-Value of 100 represents that there was: high data density + the current data is very consistent with the data over the past 45 minutes + current data is very consistent with the historical data
• The C-Value was jointly developed between INRIX and the University of Maryland, for which benchmarking has been done
• Validation testing by the University of Maryland has determined that there is a linear relationship between the C-Value and average error, the higher the C-Value the lower the average error (more in depth information about the testing and how an agency might utilize the new C-Value is under development by Coalition and UMD staff and will be forthcoming in a separate document)"
Appendix B: Performance Measure Relationships with Average Travel Rate: PM Peak Hour Only

Figure 39: Segment Standard Deviation vs. Average Travel Rate
Figure 40: Segment Coefficient of Variation vs. Average Travel Rate
Figure 41: Segment 80\textsuperscript{th} Percentile Travel Rate vs. Average Travel Rate
Figure 42: Segment 85th Percentile Travel Rate vs. Average Travel Rate
Figure 43: Segment 90th Percentile Travel Rate vs. Average Travel Rate
Figure 44: Segment 95\textsuperscript{th} Percentile Travel Rate vs. Average Travel Rate
Figure 45: Segment Average Buffer Index vs. Average Travel Rate
Figure 46: Segment Median Buffer Index vs. Average Travel Rate
Figure 47: Segment Misery Rate vs. Average Travel Rate
Figure 48: Segment Semi-Standard Deviation vs. Average Travel Rate
Figure 49: Segment Skew vs. Average Travel Rate
Figure 50: Segment Failure Rate where Space Mean Speed less than 50 mph vs. Average Travel Rate
Figure 51: Segment Failure Rate where Space Mean Speed less than 40 mph vs. Average Travel Rate