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SYSTEMS PLANNING OFFICE

on Project

"Comparison of Methods for Measuring Travel Time at Florida Freeways and Arterials"

FDOT Contract BDV32-977-02

July 2014

by

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DISCLAIMER

METRIC CONVERSION CHART

U.S. UNITS TO METRIC (SI) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

METRIC (SI) UNITS TO U.S. UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

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16. Abstract

Travel time is an important performance measure used to assess the traffic operational quality of various types of highway facilities. Previous research funded by the Florida Department of Transportation (FDOT) on travel time reliability developed, implemented, and evaluated tools for estimating travel time reliability for freeways and arterials. These efforts also compared the model-estimated travel times to field-measured travel times using various sources of data. Given the variety and diversity of travel time measurement methods, it is important to evaluate the accuracy of the data obtained by each of them and to develop recommendations regarding their suitability in the validation of travel time estimation models as well as in the development of real-time travel time reliability metrics.

The main objective of this research was to collect field data along several freeways and arterials and to evaluate the travel time measurements obtained by STEWARD, INRIX, BlueTOAD, and HERE. The research team collected data with the use of an instrumented vehicle on five freeway segments and two arterial segments in Florida. The field-measured travel times were statistically compared with the travel times provided through the methods listed above.

The results of the statistical comparison suggest that the HERE traffic data provide better freeway travel time estimates, compared to the remaining methods. HERE traffic is more accurate for oversaturated conditions. On the other hand, when analyzing uncongested freeway segments, STEWARD, INRIX, and BlueTOAD performed better than HERE traffic. Lastly, analysis at the arterial sites suggested that none of the methods was accurate, although the sample size was relatively small, especially during the oversaturated runs.

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EXECUTIVE SUMMARY

Travel time is an important performance measure used to assess the traffic operational quality of various types of highway facilities. Previous research funded by the Florida Department of Transportation (FDOT) on travel time reliability developed, implemented, and evaluated tools for estimating travel time reliability for freeways and arterials. Previous research efforts have also compared the model-estimated travel times to field-measured travel times. To perform these comparisons, various sources of data have been used. Given the variety and diversity of data collection methods, it is important to evaluate the accuracy of the data obtained by each of them and to develop recommendations regarding their suitability in the validation of travel time estimation models as well as in the development of real-time travel time reliability metrics.

The objectives of this research were to: a) identify the locations and times when travel time data are collected by each method, b) collect field data along the selected freeways and arterials using an instrumented vehicle, c) statistically compare the field measured travel times with the travel times collected by various methods.

The available travel time data collection methods evaluated in this study are STEWARD, INRIX, BlueTOAD, and HERE traffic. STEWARD travel times were available for the majority of the freeway segments in Florida. INRIX data were available for several freeways and arterials in Florida; however, these data did not cover the entire data collection period as these were available only for a limited time period (until September 2013). BlueTOAD travel times are only available in the Jacksonville area (freeways and selected arterials). HERE data cover the majority of the freeways and specific arterial segments in Florida; however, travel time data prior to October 2013 are not available.

Travel time data were obtained at five freeway segments (both directions) and two arterial segments (both directions) under varying traffic conditions. At least five travel time measurements were obtained at each location. The travel time data were collected using an instrumented vehicle equipped with a GPS. The data collection recorded speeds as well as video of the surroundings and prevailing conditions during the data collection.

Two statistical comparison methods were used. The first method constructed a confidence interval which was specified by a maximum relative error. The second statistical method was based on a selected acceptable range for the absolute percent error. A statistical analysis by facility type and by congestion level was also developed.

The results of the statistical comparison suggest that the HERE traffic data provided better freeway travel time estimates, compared to the remaining methods. HERE traffic is more accurate for oversaturated conditions. On the other hand, when analyzing uncongested freeway segments, STEWARD, INRIX and BlueTOAD performed better than HERE traffic. Lastly, analysis at the arterial sites suggested that none of the methods was accurate, although the sample size was relatively small, especially during the oversaturated runs.

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1. INTRODUCTION

1.1 Background

Travel time is an important performance measure used to assess the traffic operational quality of various types of highway facilities. National and state efforts associated with travel time reliability have focused on the prediction of travel time as well as the travel time distribution and various travel time reliability-related measures. Previous research funded by the Florida Department of Transportation (FDOT) on travel time reliability developed, implemented, and evaluated tools for estimating travel time reliability for freeways and arterials. These tools and models can estimate travel time reliability along freeway and arterial sections of the Strategic Intermodal System (SIS) as a function of various changes in the system, such as incident removal times and work zone policies, as well as selected ITS programs and initiatives. Previous research efforts have also compared the model-estimated travel times to field-measured travel times.

To perform these comparisons, various sources of data have been used. One of those sources is STEWARD, which is a central data warehouse developed by the University of Florida to assemble and archive data from Traffic Management Centers (TMCs) around the state and to provide various summary data reports. STEWARD assembles flow and speed data, and thus travel times are based on spot speed measurements. A second source of travel time data is BlueTOAD (Bluetooth Travel-time Origination And Destination) devices. This advanced traffic monitoring technology can detect anonymous Bluetooth signals from passing vehicles. Matching of subsequent detections by BlueTOAD devices along the road through rigorous filtering and integrated processing can be utilized to obtain the respective travel times. A third source of data is from INRIX, a company which provides real-time or archived travel time data. The exact source of the data and the related algorithms are proprietary. A fourth source is Nokia/ NAVTEQ, also known as HERE, which provides real-time or archived travel time data. The HERE data include real-time data from GPS, smart phones, consumer sources, and commercial sources. The travel time estimation algorithms based on these data are proprietary.

Given the variety and diversity of data collection methods it is important to evaluate the accuracy of the data obtained by each of them and to develop recommendations regarding their suitability in the validation of travel time estimation models as well as in the development of real-time travel time reliability metrics.

1.2. Objectives

The main objective of this research is to collect field data along several freeways and arterials and evaluate the travel time measurement methods outlined above with respect to their accuracy.

1.3. Report Organization

The next section presents an overview of the data collection and statistical analysis methods used in this project. Chapter 3 describes the study sites selected and summarizes the data collection effort using our instrumented vehicle. Data were collected at freeway and arterial locations with under-saturated as well as over-saturated conditions and varying weather conditions. Chapter 4 presents the data analysis which includes the statistical comparison of the travel time data vs. the field values obtained and the formulation of the final recommendations related to the use of the travel time databases examined. The last chapter summarizes the research findings.

2. OVERVIEW OF DATA COLLECTION AND ANALYSIS METHODS

This chapter provides a summary of the travel time measurement methods evaluated in this study, the data collection plan using our instrumented vehicle, and the statistical methods used for the comparison.

2.1. Description of Travel Time Measurement Methods

The travel time measurement methods evaluated in this project are STEWARD, INRIX, BlueTOAD, and HERE traffic data.

STEWARD

In STEWARD, travel time data are obtained from FDOT's SunGuide system through a variety of data sources, such as various detector types. Smoothed speed data are gathered from detectors to generate travel time (TVT) data. A smoothed rolling average for speed and travel time is used to calculate the average speed of each link that composes the TVT link. From these speeds the time to traverse each link is computed and then the sum of the parts is the travel time over the TVT link. Figure 2.1 depicts the travel time calculation method used by STEWARD.

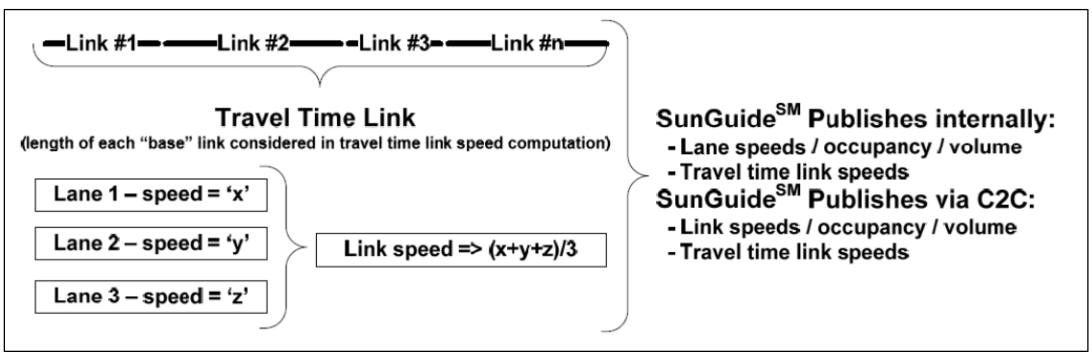


Figure 2.1. SunGuide computation of travel time link speeds (Source: SunGuide-UTVT-2.0.1)

The travel times at each link are calculated using the following steps:

1. The speed for each lane that is part of the link is first calculated. The link speed is then the average of the lane speeds as shown in Figure 2.2.

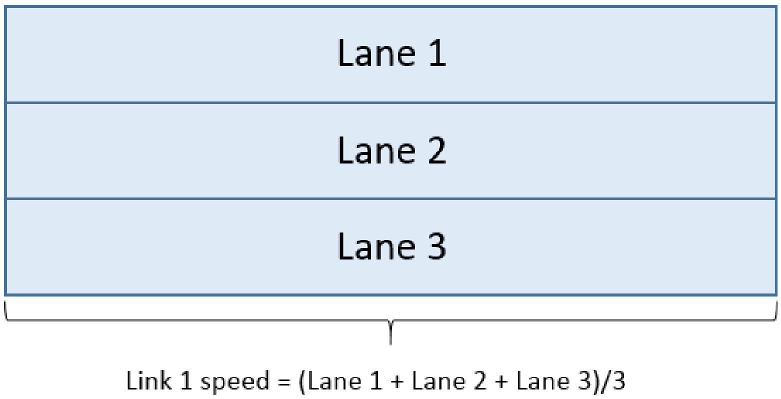


Figure 2.2. TSS link speeds (Source: SunGuide-UTVT-2.0.1)

2. To calculate the travel time for a travel time link, each individual link's travel time is calculated and aggregated as follows (Figure 2.3):
   a. If the link reports a speed that is either greater than the speed limit or 0, the speed limit is substituted for the speed.
   b. Each travel time link is also bound by the upper and lower bounds that are set for that link.

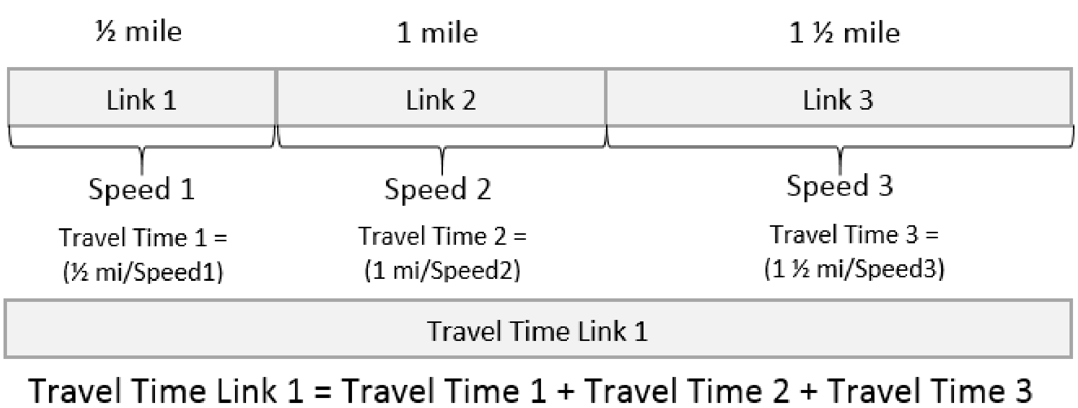


Figure 2.3. Travel time link calculations (Source: SunGuide-UTVT-2.0.1)

3. A system configuration parameter for the percentage of lanes with data is used to determine whether enough data exists to publish travel times for a particular travel time link (this method can be accurate if speeds are consistent between adjacent links):

a. If percent of lanes with data is less than this number, no travel times are published for the travel time link.
b. If percent of lanes with data is greater than this number, links missing data use the average speed across all links in the travel time link for calculating travel times.

The travel times in SunGuide are calculated and obtained through STEWARD in one-minute increments and are reported for freeway sections only. The coverage of travel times through SunGuide is limited to the locations where sensors are installed within each FDOT District.

INRIX

INRIX combines information from multiple probe technologies such as fleet-based GPS probe vehicles, data from existing fixed-sensor networks such as loop- or radar-based detection, historical traffic flow data from State DOTs, crowdsourcing, and fleet-based GPS probe vehicles. The data is then fused to provide real-time travel time estimates and incident information. Complete description of the algorithms used to estimate real-time travel times is not available since these algorithms are proprietary. An example illustration of the interface that INRIX provides is shown in Figure 2.4.

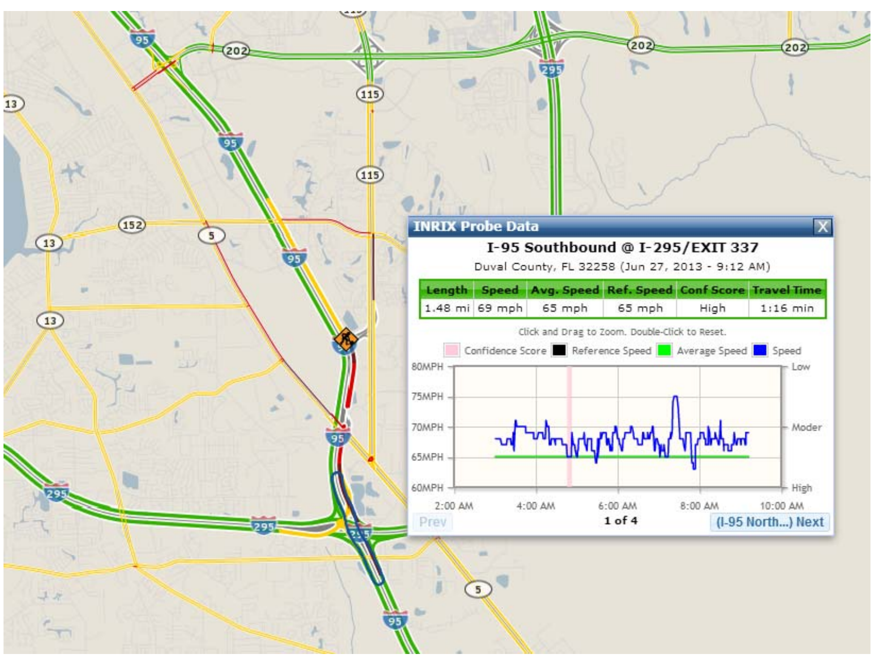


Figure 2.4. INRIX probe data travel time illustration along I-95 SB at Jacksonville, FL

The travel time information through INRIX is available at 1-minute intervals. In addition to the travel time, INRIX provides “Average speed”, “Reference speed”, and “Speed” for each segment. Average speed corresponds to the historical average mean speed for the roadway segment for that hour of the day and day of the week in miles per hour. Reference speed is the calculated “free-flow mean speed” which represents the 85th percentile observed speed for all time periods, with a maximum value of 65 mph. Speed is the current estimated space mean speed for the roadway segment in miles per hour. The number of readings recorded for each segment is considered when aggregating multiple segments together, allowing segments with consistent data coverage to be weighted more heavily than those with poor or inconsistent coverage.

The INRIX data also provide a “Confidence Score” and “the C-value”. The confidence score represents a qualitative assessment of confidence in the travel time estimates and may take the following three values:
30: high confidence based on real-time time data for a specific segment;
20: medium confidence based on real-time data across multiple segments and/or based on a combination of expected and real-time data;
10: low confidence based primarily on historical data.

The C-value indicates the probability that the current probe reading represents the actual traffic conditions based on current and historic trends. This value is presented only when the confidence score is 30 and it ranges from 0 (= low probability) to 100 (= high probability).

It should be noted that INRIX travel times for Florida were not available for dates after September 2013.

<u>BLUETOAD</u>

In Florida, BlueTOAD data are available only for specific freeway and major arterial segments of FDOT District 2 (Jacksonville area). Figure 2.5 is a snapshot of the speed map provided by BlueTOAD for the Jacksonville area. BlueTOAD is the only travel time measurement method that provides travel times for arterial streets. As it can be seen from this figure, the roadway network is color-coded based on the average speeds. However, some links are grey, indicating there are not enough Bluetooth pair data available to estimate travel time for the specific time interval.

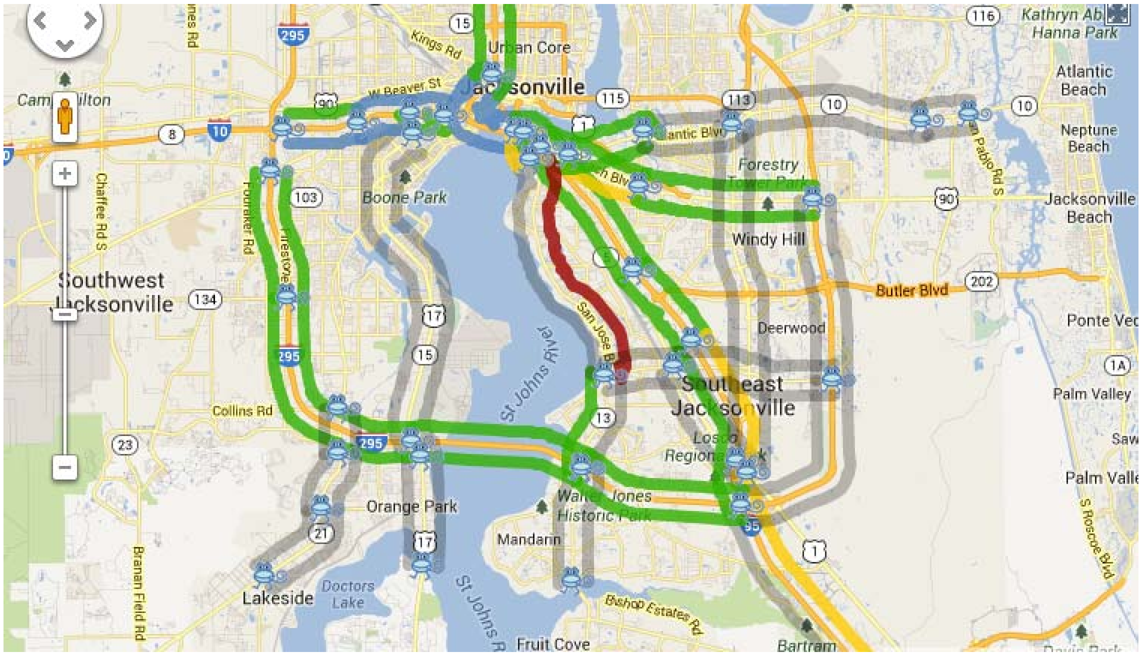


Figure 2.5. BlueTOAD speed map at Jacksonville, FL

BlueTOAD reports travel times and speeds in 5 or 15 minute intervals. The availability of travel time data depends greatly on the availability of Bluetooth devices such as phones, headsets, navigation systems and music players in the traffic stream. It is possible that not enough such devices are available, especially during low-volume periods, therefore the system is not able to calculate travel times.

Travel times and speeds from BlueTOAD are obtained through real-time analysis of multiple detection matches. BlueTOAD does not provide the raw travel time measurements, but filters and processes them before providing the estimated travel times.

HERE Traffic

HERE traffic was established in 2012; the brand was previously known as NAVTEQ and Nokia Location & Commerce since 1985. The data available through HERE include speeds, volumes, travel times, incidents, and an assessment of the quality of data (Turner et al., 2011a). HERE employs data obtained from various sources such as state sensor data, probe vehicle data, GPS data and historic data, and performs big data analytics to derive its maps. The exact algorithms that are used in HERE are not published. The travel time data obtained from HERE are in 5-minute increments. Traffic data are reported at the road link level at Traffic Message Channel (TMC) segments. The length of these TMC segments varies significantly – their starting and ending point is located at physical or logical geometric changes (e.g., interchanges). The research team did not find any documentation in the published literature of an evaluation of travel times obtained from HERE traffic. HERE traffic data became available in Florida after October 2013.

2.2. Data Collection Plan

2.2.1. Field Data Collection Using an Instrumented Vehicle

Travel time were collected with the use of an instrumented vehicle. The instrumented vehicle is a Honda Pilot SUV, owned by the University of Florida Transportation Institute (UFTI). The instrumented vehicle has a Honeywell Mobil Digital Recorder (HTDR400) system. This system has two wide coverage digital cameras, which capture front and rear images and record them in the hard drive of the HTDR400 system. A laptop is connected to the system and allows the display of the two cameras through the HTDR400 software. Figure 2.6 provides an internal view of the instrumented vehicle.

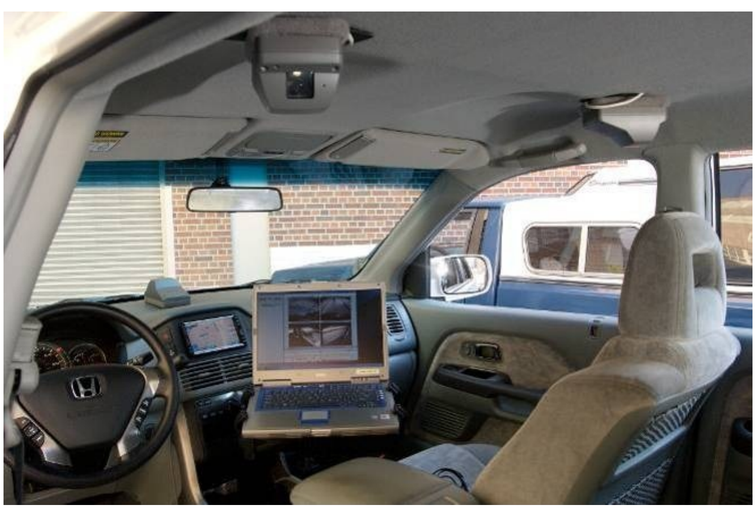


Figure 2.6. Inside view of the UFTI instrumented vehicle

When conducting travel time studies with instrumented vehicles, drivers are advised to "float" with traffic in an attempt to match the average speed of the surrounding traffic flow. A "rule of thumb" is to safely pass as many vehicles as pass the instrumented vehicle. This rule was adopted in this study to minimize the variability of test vehicle travel times, which reduces the required sample size. Although in this project only one test vehicle is used in each run, it is expected that with the proper implementation of the "floating car" method the obtained travel times are close to the ground truth values.

A portable GPS receiver is used for obtaining the travel route coordinates and the corresponding travel time of the vehicle. According to the manufacturer, the receiver's performance specifications are:

- Channels: 20
- Horizontal distance accuracy: ±3 m (±9.8 ft)
- Velocity accuracy: ±0.1 m/s (±0.33 ft/s)
- Reacquisition: 0.1 s
- Update rate: 1 Hz

These specifications are considered to be satisfactory for test vehicle studies (Turner et al., 2011).

The GPS data collected by the instrumented vehicle were analyzed using the TravTime™ software by GeoStats Services. This software includes a GIS component which is used for visual verification of the instrumented vehicle run and itinerary. The TravTime™ software estimates the travel time between any two points specified by the user. The program can also output additional performance measures such as travel time index (TTI), average speed, stopped time, and congested time.

2.2.2. Study Site Selection Criteria

Data were collected at both urban freeway segments and arterial segments. The data collection locations were determined by identifying overlapping sections from the various travel time data sources.

BlueTOAD data are available only for the Jacksonville area. INRIX data are also only available for the Jacksonville area. STEWARD data cover only freeway segments and not arterials. HERE traffic data were available for the majority of freeways and arterials in Florida. To evaluate the performance of the travel time measurement methods under varying traffic conditions, we selected locations that experience recurrent congestion. The final list of the data collection sites are provided in Table 2.1 and Table 2.2. Table 2.1 contains the urban freeway sections and Table 2.2 the arterial street sections. Detailed information on the data collected at those sites follows.

Table 2.1. Data collection sites on urban freeways

	Site	Description	Lanes	Length (m)	Location	STEWARD	INRIX	BlueTOAD	HERE	Field Data
1	I-295 NB	From I-95 to Roosevelt Blvd	3	7.89	Jacksonville	√	√	√	--	√
2	I-295 SB	From Roosevelt Blvd to I-95	3	7.89	Jacksonville	√	√	√	--	√
3	I-95 NB	From Acosta Expy to Kings Rd	3	2.9	Jacksonville	√	√	√	√	√
4	I-95 SB	From Kings Rd to Acosta Expy	3	2.9	Jacksonville	√	√	√	√	√
5	I-275 SB	From Bearss Ave to I-4	3	7.52	Tampa	√	--	--	√	√
6	I-275 NB	From I-4 to Bearss Ave	3	4.76	Tampa	√	--	--	√	√
7	I-4 EB	From 21st St. to I-75	4 → 3	7.16	Tampa	√	--	--	√	√
8	I-4 WB	From Hillsborough Ave to I-275	3 → 4	5.49	Tampa	√	--	--	√	√
9	I-75 NB	From US-301 to Fowler St.	3	4.75	Tampa	√	--	--	√	√
10	I-75 SB	From Fowler St. to US-301	3	6.45	Tampa	√	--	--	√	√

Table 2.2. Data collection sites on arterial streets

	Site	Description	Lanes	Length (m)	Location	STEWARD	INRIX	BlueTOAD	HERE	Field Data
1	SR-212 WB (Beach blvd)	From I-295 to University Blvd	2	4.9	Jacksonville	--	--	√	√	√
2	SR-212 EB (Beach blvd)	From University Blvd to I-295	2	4.9	Jacksonville	--	--	√	√	√
3	SR-13 NB (San Jose Blvd)	From I-295 to Gary St.	2	1.4	Jacksonville	--	--	√	--	√
4	SR-13 SB (San Jose Blvd)	From Gary St. to I-295	2	1.4	Jacksonville	--	--	√	--	√

2.2.3. Data Preparation

Given the variations of the exact measurement locations among the travel time measurement methods evaluated in this study, we considered only the common length of all methods as our benchmark section, as illustrated in Figure 2.7. In this way, the links obtained from any measurement method that correspond to the common length is aligned.

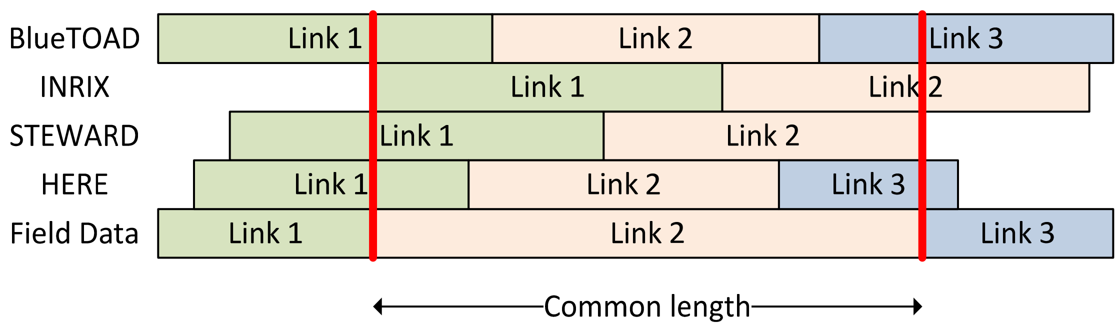


Figure 2.7. Illustration of common (benchmark) length for travel time comparison

Once the benchmark section length is defined, the link travel times (i.e., travel times for each specific link acquired by each measurement method, as shown in Figure 2.7) obtained from the various methods are converted to route travel times, so that these can be compared to the field-measured travel times. Route travel times correspond to the common length travel time, as shown in Figure 2.7, and are stitched using consecutive time intervals using link travel times, according to the method developed by Chase et al. (2012a). In order to replicate the drivers' experience, this stitching algorithm adds link travel times based on when a hypothetical vehicle would enter each subsequent link.

2.3. Travel Time Analysis Methods

Based on the literature review findings (complete description provided in Appendix A), two statistical analysis methods are deployed to conduct the comparisons. The first method is based on a reasonable expected maximum relative error, whereas the second method is based on the percent of travel time estimates that fall within a specific interval.

2.3.1. Confidence Interval Method – Maximum Relative Error

For the confidence interval method considering the maximum relative error (Richardson and Smith, 2012), a reasonable expectation of 20% maximum relative error (e_{max}) is considered. Thus, the travel time measurement estimate should be no more than 20% from the population mean, in order to be classified as accurate: $\bar{X} - \frac{e_{max}\bar{X}}{2+e_{max}} \leq T \leq \bar{X} + \frac{e_{max}\bar{X}}{2+e_{max}}$ (Eq. 2. **1**)

$$\bar{X} - \frac{e_{max}\bar{X}}{2+e_{max}} \leq T \leq \bar{X} + \frac{e_{max}\bar{X}}{2+e_{max}} \quad \text{(Eq. 2. 1)}$$

Where:

e_{max} = maximum relative error (20%)

$\bar{X}$ = benchmark value

T = travel time measurement estimate

2.3.2. Accuracy Target Method – Absolute Percent Error

The accuracy target method, as described in Turner et al. (2011b), recommends evaluating the percent of travel time measurement estimates that fall within *X* of the benchmark, where *X* can be either a percentage or a confidence interval. The absolute error bias can be used to identify acceptable error levels:

$$|E_i| = |x_i - \mu_i| \quad \text{(Eq. 2. 2)}$$

Where:

E_i = error bias

$|E_i|$ = absolute error

μ_i = benchmark value for the i^{th} comparison (minutes or seconds)

x_i = the i^{th} travel time measurement method estimate (minutes or seconds)

The percent error and absolute percent error are:

$$X_i = \frac{x_i - \mu_i}{\mu_i} = \frac{E_i}{\mu_i} \quad \text{(Eq. 2. 3)}$$

$$|X_i| = \frac{|x_i - \mu_i|}{\mu_i} = \frac{|E_i|}{\mu_i} \quad \text{(Eq. 2. 4)}$$

The acceptable absolute percentage *X* used in this study is 20%.

A hypothesis test is constructed to evaluate the number of travel time estimates that are classified as accurate or inaccurate based on the process described above. In the hypothesis test, each time interval comparison counts as a Bernoulli trial where the outcome of the trial is success (accurate travel time estimate) or failure (inaccurate travel time estimate). The value of the probability of a trial being successful (p) is unknown, therefore the hypothesis test can be constructed to test whether this value exceeds some critical value. Therefore:

H_o: $p \leq c$

H_α: $p > c$

Where:

p = the probability of a trial being successful,

c = the critical quality threshold desired (e.g., 90%).

This test is also used to evaluate each measurement method considering all runs at all sites, each type of facility, and each type of traffic condition.

3. TRAVEL TIME FIELD DATA COLLECTION

For each data collection site, a brief description of the facility is provided along with information on the field data collection conditions and prevailing traffic conditions. The travel times collected with the instrumented vehicle, as well as the travel times obtained through INRIX, BlueTOAD, STEWARD and HERE traffic for the benchmark sections are also included.

3.1. I-295 NB/SB, Jacksonville, FL

The section is located along I-295 between I-95 and Blanding Blvd. The data collection was conducted on June 17th, 2013 from 3:30 pm to 6:30 pm. Six runs per direction were performed at the study section, which experiences congestion during the PM peak, as confirmed during the data collection. Figure 3.1 presents the starting (A) and ending (B) points of the sections where travel time information is available through the three different data sources (BlueTOAD, INRIX, and STEWARD). HERE traffic data were not available for this site at the time of the data collection.

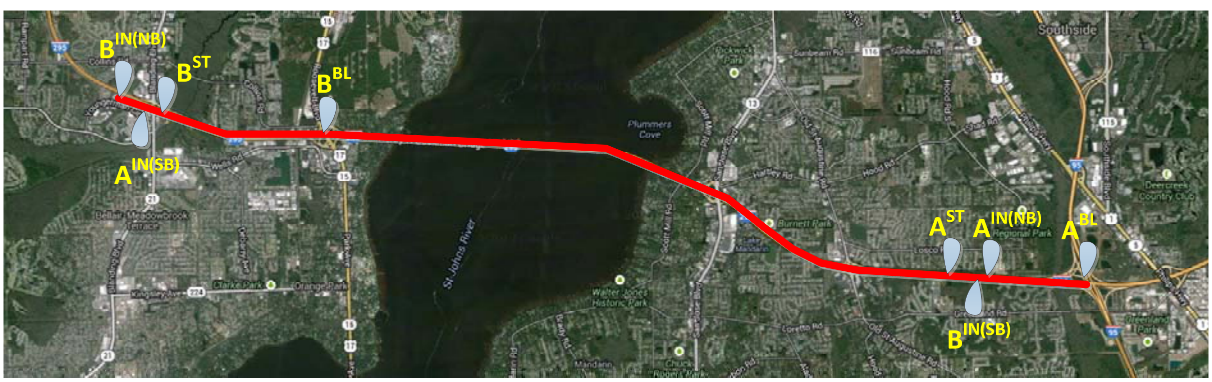


Figure 3.1. I-295 NB/SB study site

The length of the benchmark section along this corridor is 7.89 mi (both directions) and the coordinates of the starting and ending points are:

A^{ST} = 30.167930, -81.577773

B^{BL} = 30.191589, -81.705853

Table 3.1 presents the benchmark section travel times calculated through INRIX, BlueTOAD, STEWARD as well as the field-measured travel times for each of the six measurements. Table

3.1 also presents the corresponding travel times for the SB direction, although this direction did not experience considerable congestion.

Table 3.1. Travel times along I-295 study site (benchmark section)

		TRAVEL TIME (min)			
Run #	Field Start Time	STEWARD	INRIX	BlueTOAD	Field Data
I-295 NB					
1	3:51 pm	6.989	7.603	7.168	7.05
2	4:19 pm	7.366	7.689	7.377	8.82
3	4:51 pm	7.710	7.161	7.851	7.95
4	5:22 pm	8.266	7.080	8.738	11.48
5	5:59 pm	7.594	7.342	9.669	10.73
6	6:32 pm	7.000	7.202	7.269	7.62
I-295 SB					
1	3:37 pm	6.954	6.937	6.208	6.83
2	4:05 pm	6.941	6.881	6.620	7.05
3	4:37 pm	6.912	7.111	6.623	6.95
4	5:06 pm	6.917	6.989	6.548	7.15
5	5:44 pm	6.895	7.136	6.190	7.17
6	6:18 pm	6.991	7.127	6.572	7.33

The field travel times indicate that the instrumented vehicle encountered congestion during some intervals, as evidenced from field observations as well as higher field travel times. The source of congestion along the NB study section is located downstream of the junction of I-295 and I-95, and is caused by the merge of three lanes from I-95 with three lanes from I-295. Figure 3.2 shows the time-series plot of speeds at three detector stations in the vicinity of the bottleneck, using STEWARD data. Detector 220631 is located at the merge of I-295 with I-95 while the other two detectors are located downstream. As shown, the merge location experiences congestion starting at 4:45 pm which extends until 6 pm. The shaded area indicates the data collection period, which includes the congestion period.

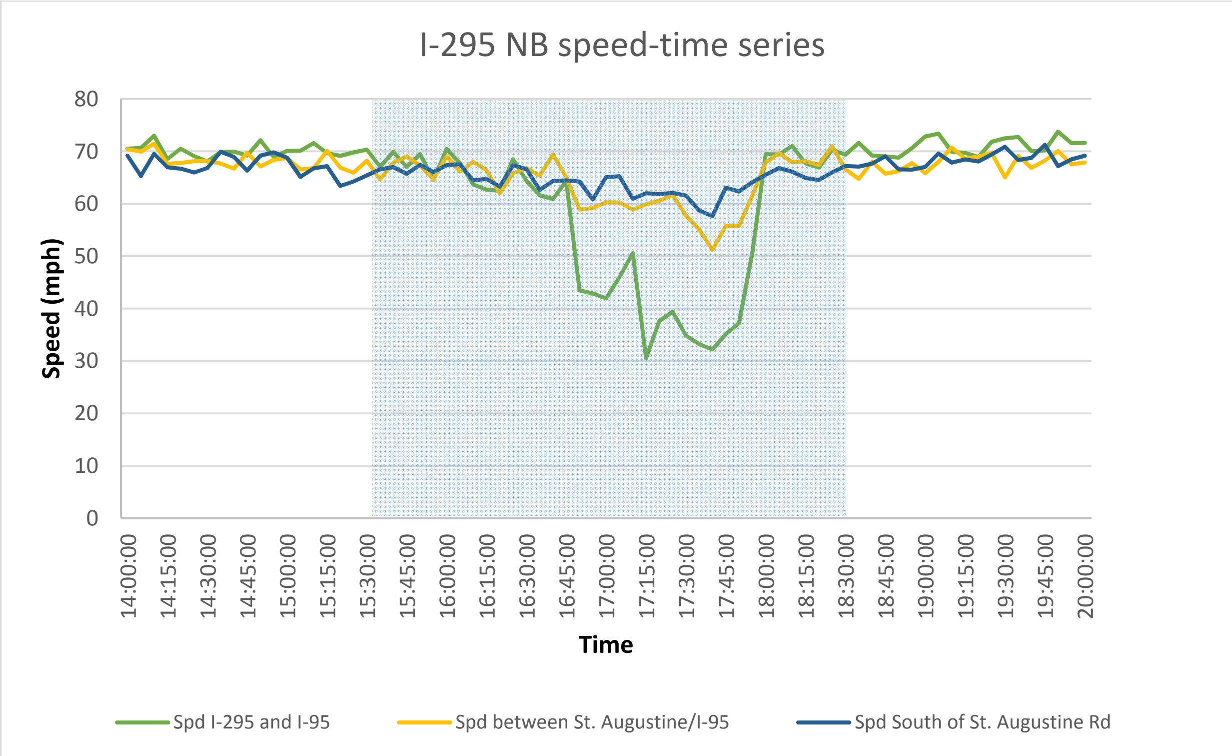


Figure 3.2. Time-series plot of speed at the study section along I-295 NB on June 17th, 2013

3.2. I-95 NB/SB, Jacksonville, FL

The section is located along I-95 between Acosta Expy and Kings Rd. The data collection was conducted on October 14th and 15th 2013, from 3:00 pm to 7:00 pm, and from 7:00 am to 11 am respectively. The segment experiences congestion during both am and pm peak periods. Ten runs per direction per peak period were performed at the study section. Figure 3.3 presents the starting (A) and ending (B) points of the sections where travel time information is available through three data sources (BlueTOAD, STEWARD and HERE).

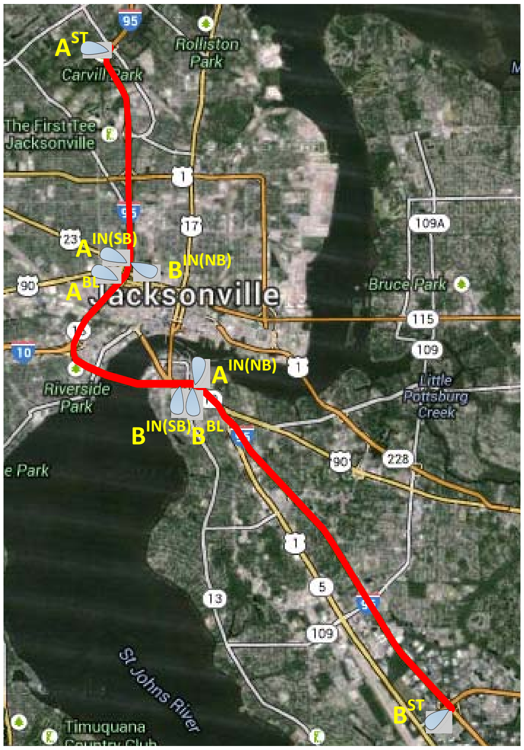


Figure 3.3. I-95 NB/SB study site

The length of the benchmark section for both directions along this corridor is 2.79 mi and the coordinates of the starting and ending points are:

A^{BL} = 30.33636, -81.66927

B^{BL} = 30.31419, -81.65864

The field measured travel times and the travel times obtained for the benchmark section through the three measurement methods are presented in Table 3.2 and Table 3.3.

Table 3.2. Travel times along I-95 NB study site (benchmark section)

Run #	Field Start Time	TRAVEL TIME (min)			
		STEWARD	HERE	BlueTOAD	Field Data
1	10/14/2013 3:46 pm	2.892	4.187	2.566	3.77
2	10/14/2013 4:02 pm	2.904	3.558	2.582	3.82
3	10/14/2013 4:18 pm	2.984	4.418	2.806	4.00
4	10/14/2013 4:35 pm	3.041	4.342	3.191	3.80
5	10/14/2013 4:50 pm	3.506	3.411	3.191	3.80
6	10/14/2013 5:07 pm	3.643	4.354	3.255	3.87
7	10/14/2013 5:26 pm	3.811	4.050	3.399	3.87
8	10/14/2013 5:44 pm	3.117	3.706	3.335	4.20
9	10/14/2013 6:00 pm	2.650	3.214	3.479	2.90
10	10/14/2013 6:12 pm	2.746	3.314	3.479	3.00
11	10/15/2013 7:44 am	3.756	3.086	*	3.13
12	10/15/2013 8:03 am	3.786	3.133	*	3.13
13	10/15/2013 8:20 am	3.731	3.170	*	3.38
14	10/15/2013 8:38 am	3.440	2.997	*	3.05
15	10/15/2013 8:55 am	3.563	3.355	2.646	2.85
16	10/15/2013 9:14 am	3.606	3.147	2.646	2.92
17	10/15/2013 9:31 am	3.614	3.306	2.646	3.00
18	10/15/2013 9:47 am	3.514	3.838	2.646	3.38
19	10/15/2013 10:02 am	3.052	3.441	2.710	3.15
20	10/15/2013 10:17 am	2.915	3.491	2.774	3.10

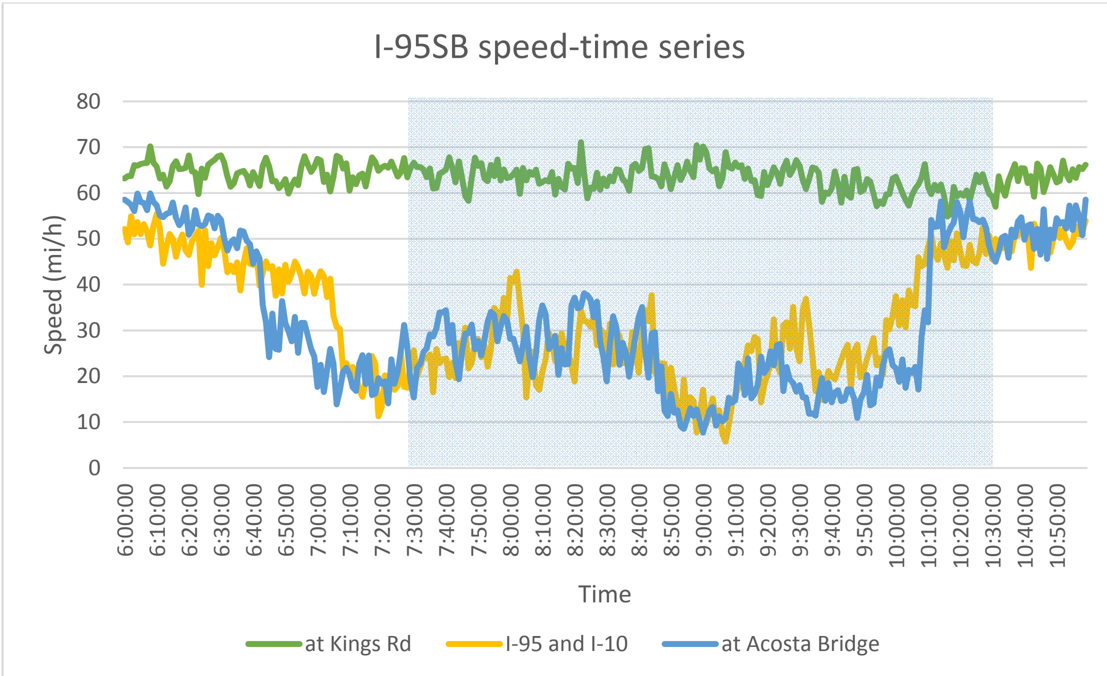
Notes:
* Not enough matches through BlueTOAD

Table 3.3. Travel times along I-95 SB study site (benchmark section)

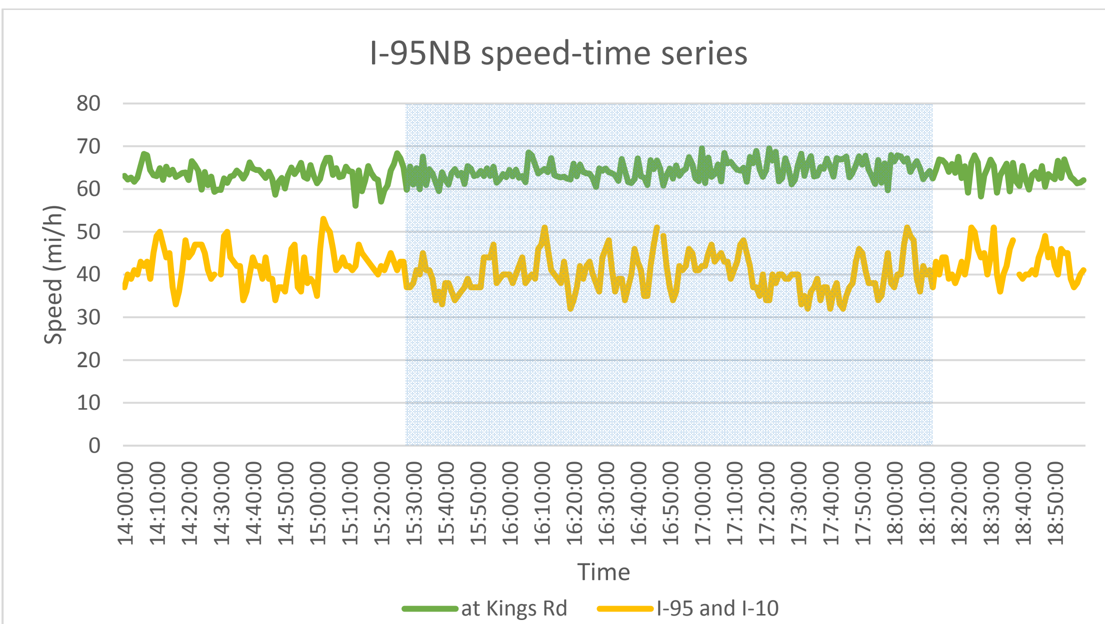
Run #	Field Start Time	TRAVEL TIME (min)			
		STEWARD	HERE	BlueTOAD	Field Data
1	10/14/2013 3:39 pm	2.810	3.185	2.549	3.28
2	10/14/2013 3:54 pm	2.716	3.187	2.566	3.05
3	10/14/2013 4:09 pm	2.739	2.987	*	3.02
4	10/14/2013 4:26 pm	2.740	3.175	2.566	2.90
5	10/14/2013 4:43 pm	2.831	3.288	2.437	2.97
6	10/14/2013 4:57 pm	3.056	2.890	*	3.08
7	10/14/2013 5:14 pm	4.739	3.485	2.437	3.02
8	10/14/2013 5:32 pm	6.081	4.176	2.437	4.37
9	10/14/2013 5:50 pm	4.370	4.445	*	3.62
10	10/14/2013 6:06 pm	3.021	3.160	*	2.83
11	10/15/2013 7:51 am	4.116	5.518	*	4.85
12	10/15/2013 8:10 am	4.003	5.277	*	4.95
13	10/15/2013 8:27 am	3.838	4.521	*	4.05
14	10/15/2013 8:44 am	3.675	7.832	2.758	7.50
15	10/15/2013 9:00 am	4.898	9.835	3.063	9.37
16	10/15/2013 9:20 am	3.418	4.993	*	4.95
17	10/15/2013 9:38 am	3.701	7.753	4.746	5.23
18	10/15/2013 9:53 am	3.577	6.594	4.762	5.40
19	10/15/2013 10:08 am	3.154	3.368	4.65	3.23
20	10/15/2013 10:23 am	3.008	3.412	4.65	3.22

Notes:
* Not enough matches through BlueTOAD

The SB direction experiences congestion during the am peak, while congested conditions occur in the NB direction during the pm peak. The entire stretch of the benchmark section experiences congestion during both peak periods. The speed-time series plots of Figure 3.4 show the congestion events for both directions. For the SB congested conditions occur along the Acosta Bridge and particularly, downstream of the I-10 interchange. Along the NB approach the average speeds at the interchange of I-95 and I-10 are reduced whereas uncongested conditions occur further downstream, towards the north end of the benchmark section.



(a)



(b)

Figure 3.4. Time-series plot of speed at the study section along (a) I-95 SB during the AM peak on October 15th, 2013, and (b) I-95 NB during the PM peak on October 14th, 2013

3.3. I-275 NB/SB, Tampa, FL

The section is located along I-275 between Bearss Ave. and I-4. This site experiences congestion during the am peak periods in the SB direction. The data collection was conducted on July 31st, 2013 from 6:30 am to 10:00 am. Six runs were performed in the NB and seven in the SB. Figure 3.5 presents the starting (A) and ending (B) points of the sections where travel time information is available through STEWARD.

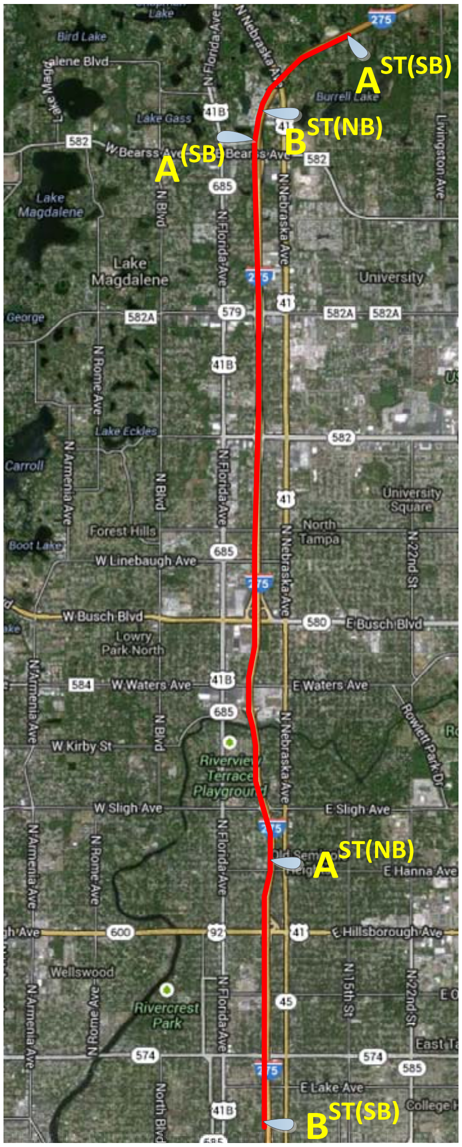


Figure 3.5. I-275 NB/SB study site

The length of the SB benchmark section along this corridor is 7.52 mi and the coordinates of the starting and ending points are:

A^{SB} = 28.08181, -82.45498

$B^{ST(SB)}$ = 27.97172, -82.45374

The length of the NB benchmark section is 4.8 mi and the start/end coordinates are:

A^{NB} = 28.01655,-82.45477

B^{NB} = 28.08569,-82.45457

Table 3.4 presents the route travel times calculated through STEWARD and HERE as well as the field-measured travel times for each of the measurements for the NB and SB directions.

Table 3.4. Travel times along I-275 study site

Run #	Field Start Time	TRAVEL TIME (min)		
		STEWARD	HERE	Field Data
I-275 NB				
1	6:56:00 AM	5.239	4.673	4.62
2	7:21:00 AM	5.110	4.537	4.88
3	7:53:00 AM	5.117	4.917	4.97
4	8:29:00 AM	5.157	4.740	4.95
5	8:59:00 AM	5.157	5.141	4.97
6	9:23:00 AM	5.059	4.727	4.88
I-275 SB				
1	6:41:00 AM	8.092	11.967	11.65
2	7:06:00 AM	12.412	16.294	11.57
3	7:33:00 AM	15.527	16.898	16.92
4	8:05:00 AM	15.313	22.514	21.25
5	8:42:00 AM	14.356	16.575	13.90
6	9:11:00 AM	8.084	7.850	7.78
7	9:33:00 AM	7.957	8.011	7.62

During the am peak period the SB direction is mostly congested. Figure 3.6 shows the time-series plot of speed along the study section of I-295 SB at specific locations during the data collection day. It appears that congestion starts at the downstream end of the section, close to the interchange with Martin Luther King Junior Blvd. The congestion propagates further upstream and reaches Fletcher Ave, which is fairly close to the beginning of the benchmark section. The shaded area shows the travel time period, which coincides with the oversaturated period.

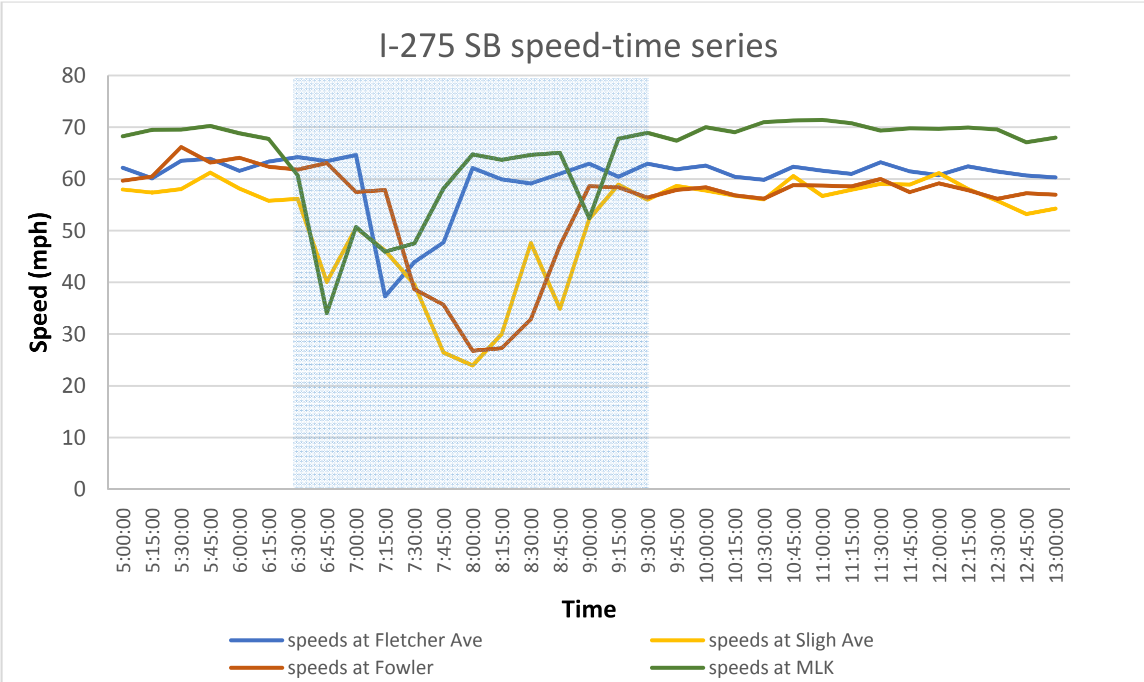


Figure 3.6. Time-series plot of speed at the study section along I-275 SB on July 31st, 2013

3.4. I-75 NB/SB, Tampa, FL

The section is located along I-75 in Tampa, between Fowler Rd and SR 60/Adamo Drive. This site experiences congestion during the pm peak periods in the SB. Data were collected on July 30th, from 3:00 pm to 6:30 pm. Five runs were performed along the SB and NB directions. Figure 3.7 presents the starting (A) and ending (B) points of the sections where travel time information is available through STEWARD.

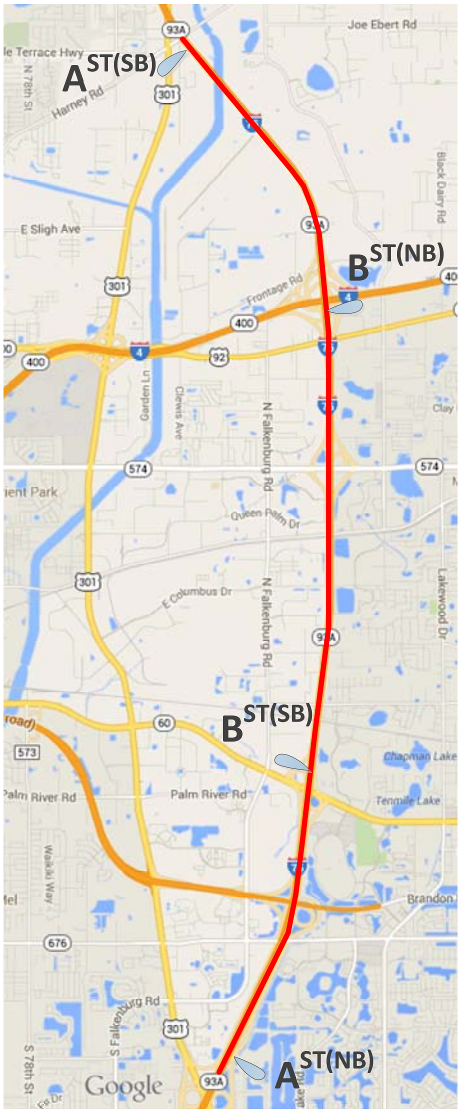


Figure 3.7. I-75 NB/SB study site

The SB section is 6.45 miles long. The NB section is 6.9 miles long. The coordinates of the starting (A) and ending (B) points of the benchmark sections at the SB and NB directions are:

$A^{ST(SB)}$ = 28.0308,-82.3441 $A^{ST(NB)}$ = 27.9040,-82.34280

$B^{ST(SB)}$ = 27.9422,-82.3299 $B^{ST(NB)}$ = 28.0000,-82.32650

Table 3.5 presents the route travel times calculated through STEWARD, HERE as well as the field-measured travel times for each of the measurements for the I-75 NB and SB directions.

Table 3.5. Travel times along I-75 study site

Run #	Field Start Time	TRAVEL TIME (min)		
		STEWARD	HERE	Field Data
I-75 NB				
1	3:45 pm	6.230	5.979	5.75
2	4:16 pm	6.313	6.569	5.82
3	4:54 pm	6.228	6.471	5.58
4	5:33 pm	6.259	6.363	5.70
5	6:09 pm	6.157	5.736	5.62
I-75 SB				
1	3:29 pm	6.154	5.718	5.38
2	4:00 pm	6.145	6.038	5.77
3	4:38 pm	6.424	6.395	6.02
4	5:16 pm	6.208	6.008	5.57
5	5:50 pm	6.646	10.910	7.82

The pm peak period at the SB direction appears to be mostly congested. Figure 3.8 shows the time-series plot of speed along the study section of I-75 SB at specific locations during the data collection day. The congestion is located between the interchange with SR-60/Adamo Dr. and the interchange with Martin Luther King Junior Blvd. The upstream section appears to be free of congestion. The shaded area shows the travel time period, which coincides with part of the oversaturated period.

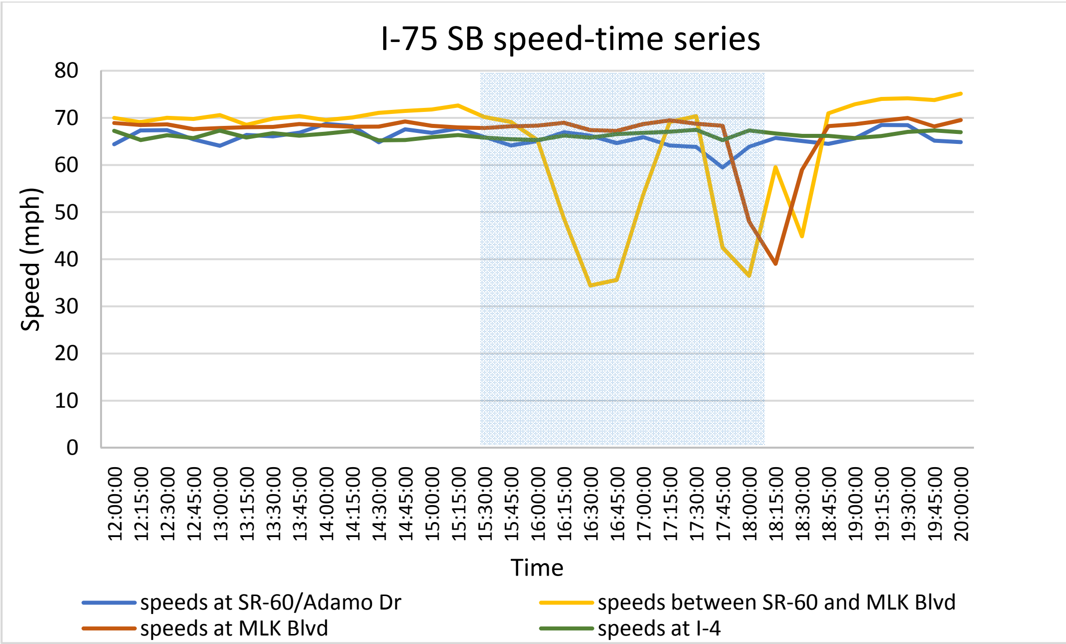


Figure 3.8. Time-series plot of speed at the study section along I-75 SB on July 30th, 2013

3.5. I-4 EB/WB, Tampa, FL

The section is located along I-4 east of Tampa, between I-75 and I-275. The roadway has for the most part 3 lanes per direction, and increases to 4 lanes per direction towards downtown Tampa. This site experiences congestion during the pm peak periods in the eastbound direction. The data collection was conducted on July 31st, from 3:30 pm to 6:30 pm. Seven runs were performed in both the EB and WB directions. Figure 3.9 presents the starting (A) and ending (B) points of the sections where travel time information is available through STEWARD and HERE traffic.

The common segment at the WB direction had to be adjusted to account for the HERE traffic links. The coordinates of the starting (A) and ending (B) points of the common sections at the EB and WB directions are:

$A^{ST(EB)}$ = 27.96443, -82.43401 $A^{ST(WB)}$ = 27.991830, -82.37145

$B^{ST(EB)}$ = 28.00138, -82.33064 $B^{ST(WB)}$ = 27.96549, -82.4347

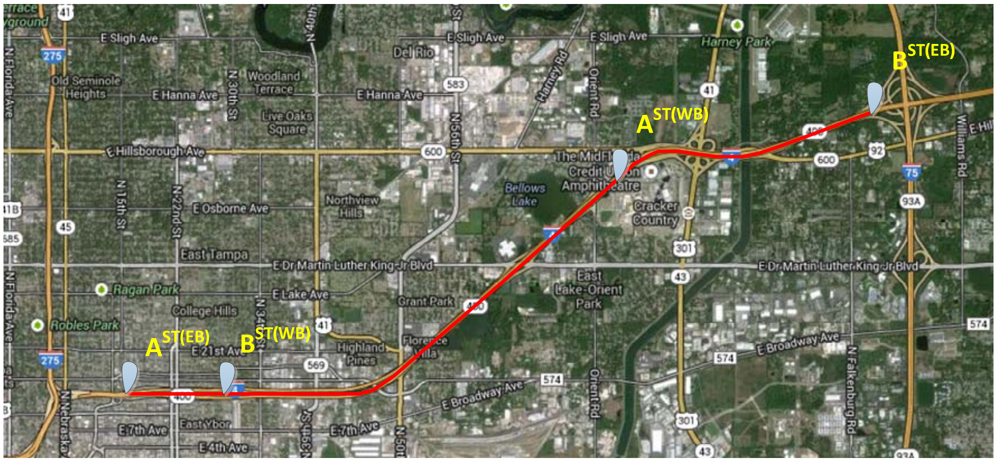


Figure 3.9. I-4 EB/WB study site

The EB approach section is 7.16 miles long and the WB approach section is 4.5 miles long. Table 3.6 presents the route travel times calculated through STEWARD and HERE as well as the field-measured travel times for each of the measurements for the I-4 EB and WB approaches.

Table 3.6. Travel times along I-4 study site

Run #	Field Start Time	TRAVEL TIME (min)		
		STEWARD	HERE	Field Data
I-4 EB				
1	3:23:00 PM	7.167	6.673	6.67
2	3:47:00 PM	7.315	7.008	6.57
3	4:15:00 PM	7.185	9.903	10.35
4	4:55:00 PM	7.207	8.896	8.38
5	5:25:00 PM	7.176	9.961	9.47
6	5:57:00 PM	7.133	10.514	10.65
7	6:25:00 PM	7.054	8.453	8.35
I-4 WB				
1	3:14:00 PM	3.937	4.145	4.17
2	3:38:00 PM	4.358	4.941	4.17
3	4:03:00 PM	4.510	4.441	4.48
4	4:43:00 PM	4.761	4.670	4.3
5	5:11:00 PM	4.581	4.407	4.18
6	5:45:00 PM	4.965	5.170	4.23
7	6:16:00 PM	4.383	5.927	4.32

The pm peak period at the EB direction appears to be mostly congested. Figure 3.10 presents the time-series plot of speed along the study section of I-4 EB at specific locations during the data collection day. The congestion is located primarily towards the I-275 interchange, and traffic conditions seem to improve towards I-75 at the EB direction. The shaded area in the graph represents the data collection period, which includes the congestion period along the EB approach.

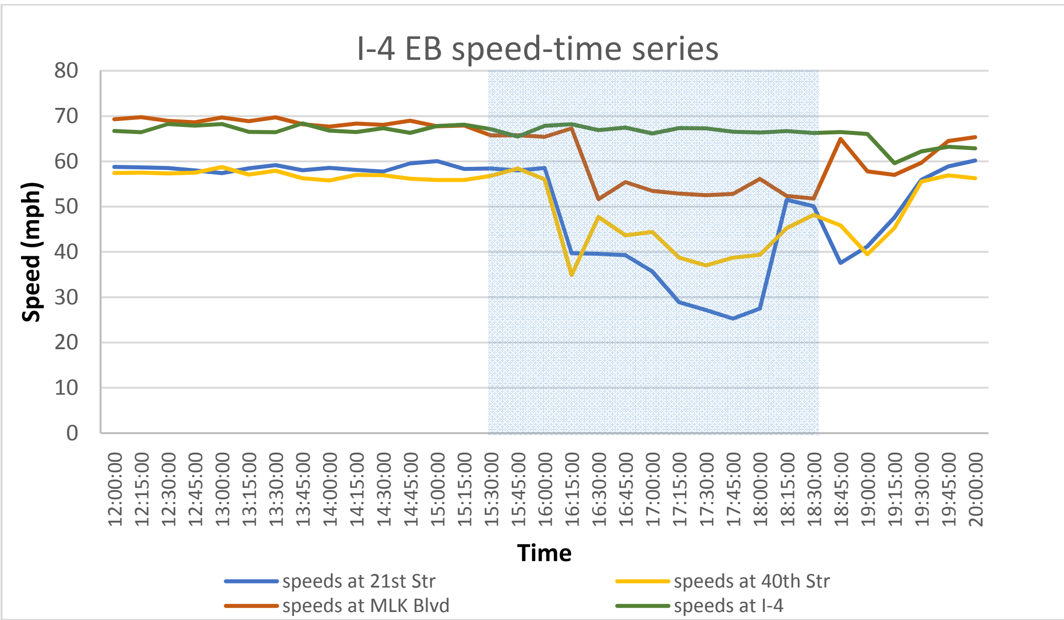


Figure 3.10. Time-series plot of speed at the study section along I-4 EB on July 31st, 2013

3.6. SR-13 NB/SB, Jacksonville, FL

This arterial section is located along SR-13 in Jacksonville between Emerson St and San Marco Blvd. The arterial has 2 lanes per direction and includes 4 signalized intersections. This site experiences congestion during the am peak periods in the northbound direction. The data collection was conducted on October 31st, from 7:00 am to 10:00 am. Five runs were performed in both the NB and SB directions. Figure 3.11 presents the starting (A) and ending (B) points of the sections where travel time information is available through BlueTOAD.

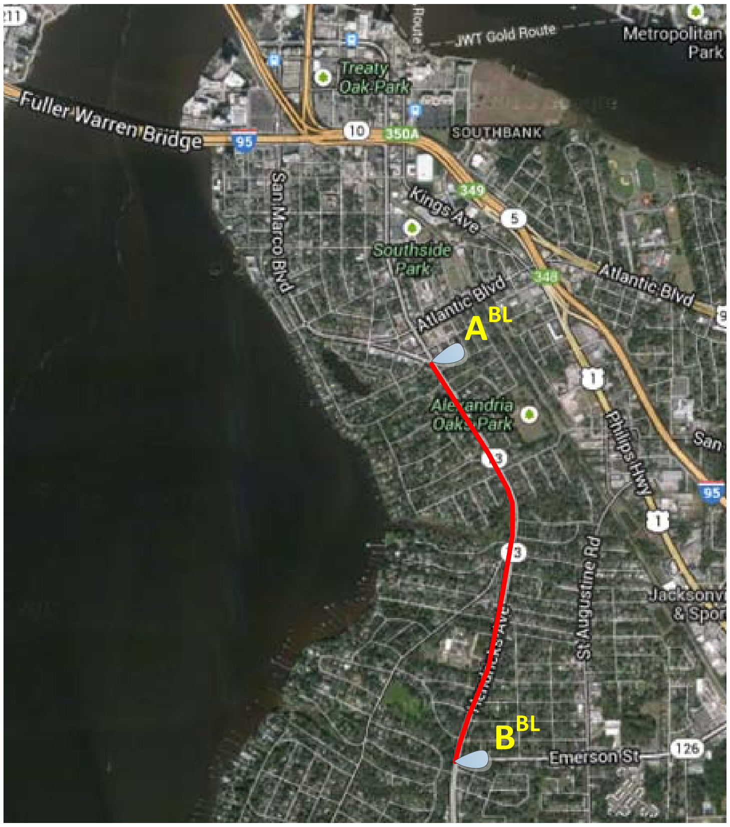


Figure 3.11. SR-13 NB/SB study site

The coordinates of the starting (A) and ending (B) points of the common sections (same for both NB and SB directions) are:

A^{BL} = 30.284687, -81.650892

B^{BL} = 30.303179, -81.652007

The arterial section is 1.4 miles long (for both directions). Table 3.7 presents the route travel times calculated through BlueTOAD as well as the field-measured travel times.

Table 3.7. Travel times along SR-13 NB/SB study site

		TRAVEL TIME (min)	
Run #	Field Start Time	BlueTOAD	Field Data
SR-13 NB			
1	6:54:00 AM	2.05	1.98
2	7:38:00 AM	2.45	2.78
3	8:29:00 AM	3.10	4.27
4	9:12:00 AM	2.58	1.80
5	9:49:00 AM	2.22	2.03
SR-13 SB			
1	7:03:00 AM	2.02	1.78
2	7:53:00 AM	2.12	3.00
3	8:39:00 AM	2.23	1.70
4	9:18:00 AM	2.41	2.17
5	9:56:00 AM	2.28	1.68

Figure 3.12 displays the average speeds along the study section for the SB and NB approaches. Given that sensor information is not available at arterial streets, the average speeds were obtained from BlueTOAD. The figure shows that the NB approach experiences congestion during the AM peak. The shaded area represents the data collection duration which includes the peak period.

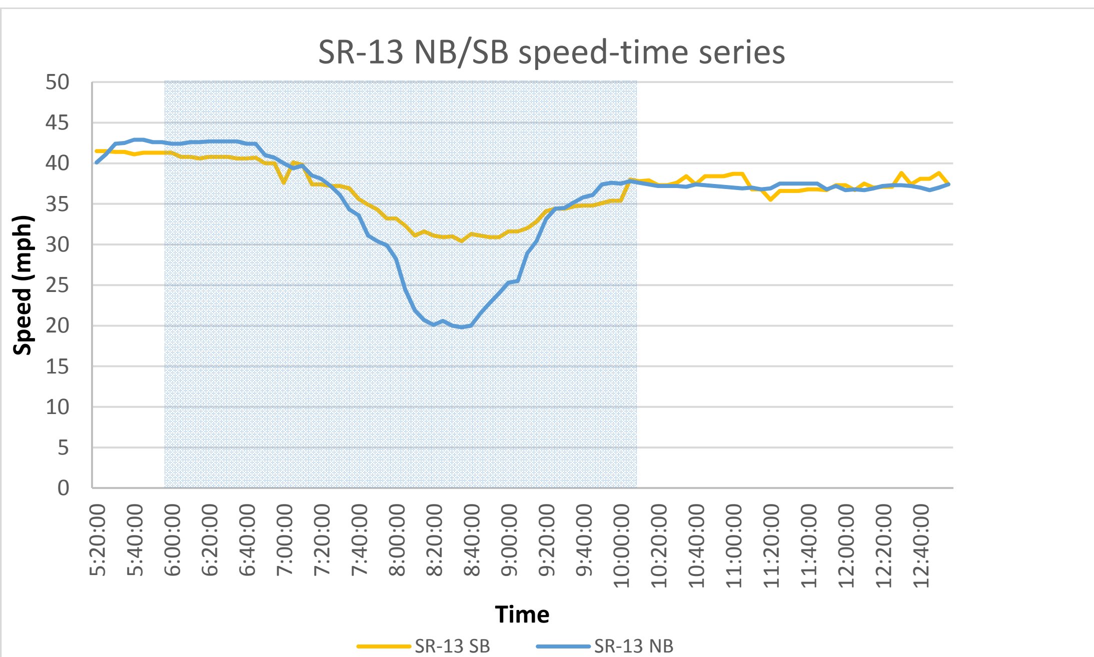


Figure 3.12. Time-series plot of speed at the study section along SR-13 NB and SB directions October 31st, 2013

3.7. SR-212 EB/WB, Jacksonville, FL

This arterial section is located along SR-212 (Beach Blvd) in Jacksonville between I-295 and University Blvd. The arterial has 2 to 4 lanes per direction, and includes 15 signalized intersections. This site experiences congestion during both peak periods. The data collection was conducted on December 5th, 2013 between 5:00 and 7:30 pm and December 6th, 2013 between 7:00 and 10:00 am. In total, eleven runs were performed in each direction. Figure 3.13 presents the starting (A) and ending (B) points of the sections where travel time information is available through BlueTOAD.

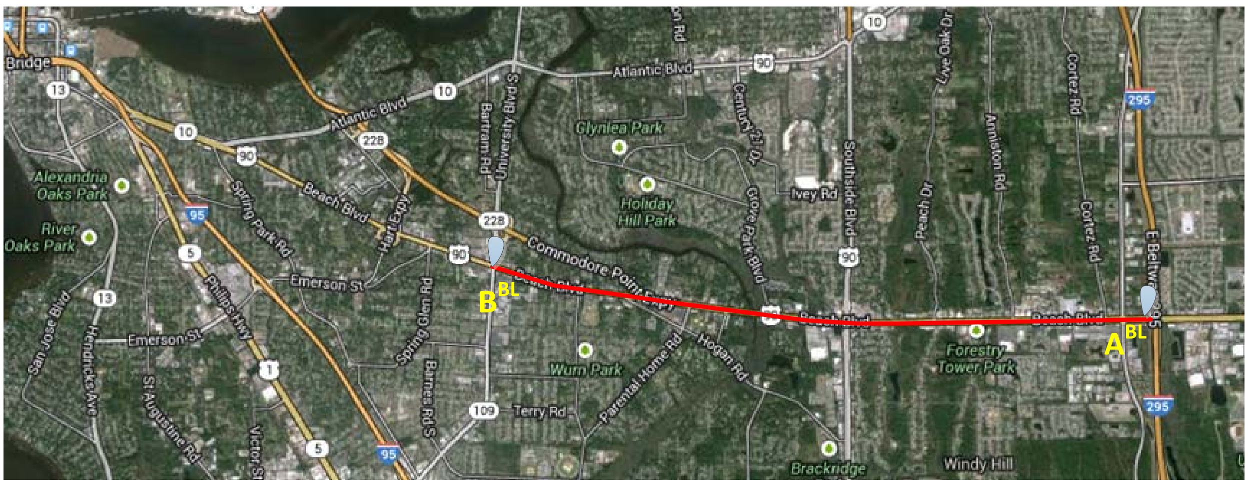


Figure 3.13. SR-212 EB/WB study site

The coordinates of the starting and ending points of the common sections (same for both EB and WB directions) are:

A^{BL} = 30.287068, -81.521730

B^{BL} = 30.292571, -81.601982

The arterial section is 4.9 miles long (same length for both directions).

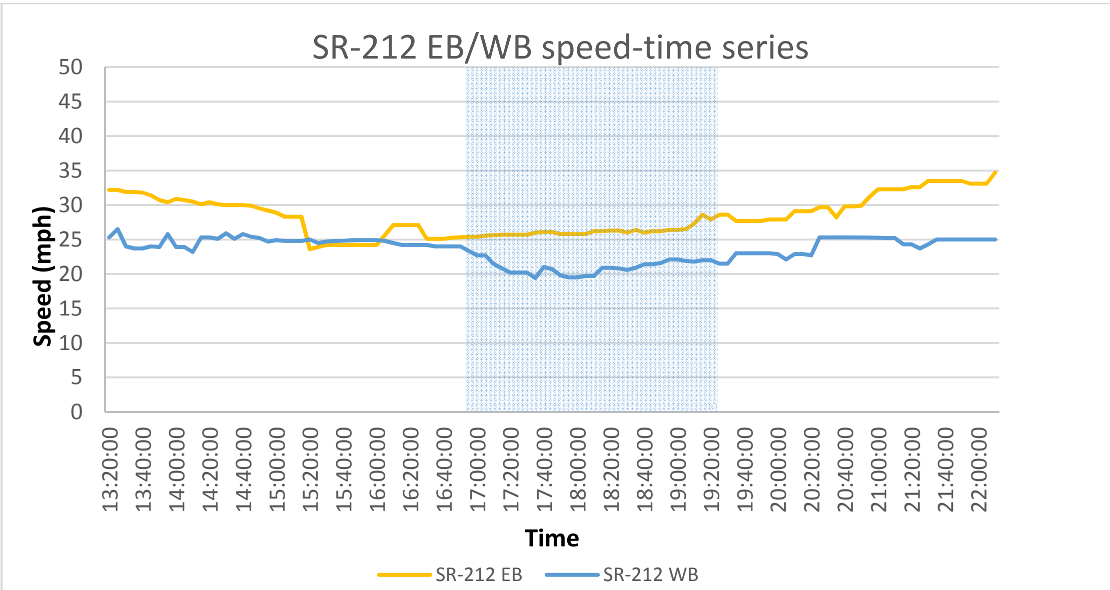
Table 3.8 presents the route travel times calculated through BlueTOAD and HERE traffic, as well as the field-measured travel times for each of the measurements for the SR-212 EB and WB approaches.

Table 3.8. Travel times along SR-212 EB/WB study site

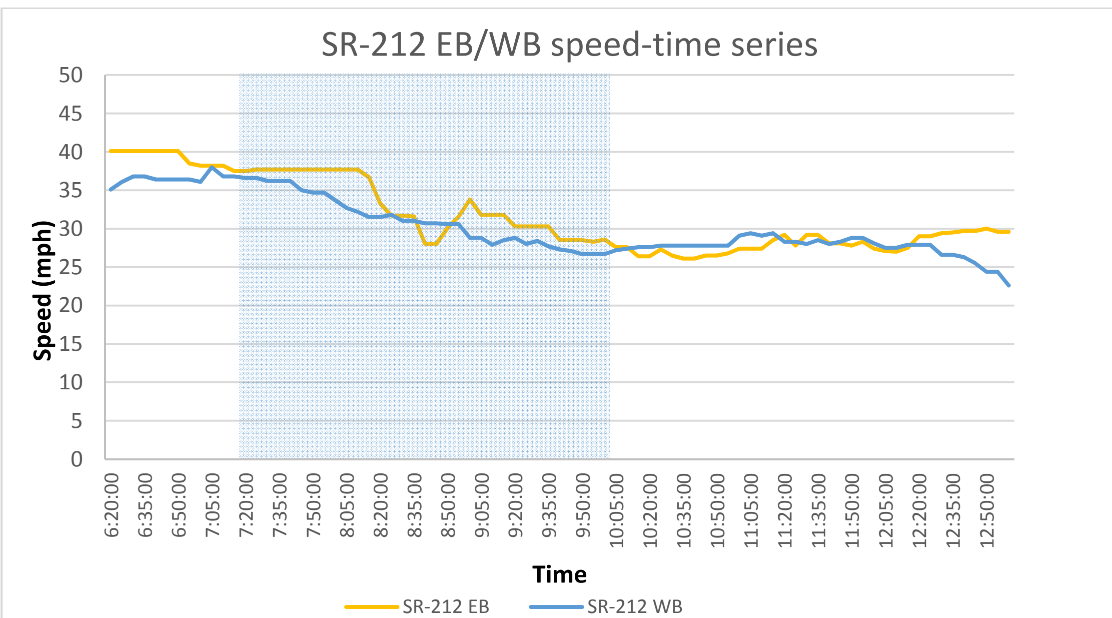
Run #	Field Start Time	TRAVEL TIME (min)		
		BlueTOAD	HERE	Field Data
SR-212 EB				
1	12/5/2013 5:02:00 PM	*	12.865	9.87
2	12/5/2013 5:33:00 PM	11.283	14.877	12.63
3	12/5/2013 6:04:00 PM	11.299	8.494	7.42
4	12/5/2013 6:30:00 PM	11.219	12.000	8.7
5	12/5/2013 6:50:00 PM	11.187	8.669	7.83
6	12/6/2013 7:38:00 AM	7.797	15.120	9.97
7	12/6/2013 8:05:00 AM	7.797	8.394	9.97
8	12/6/2013 8:31:00 AM	9.285	12.399	8.75
9	12/6/2013 8:56:00 AM	9.018	7.186	9.72
10	12/6/2013 9:18:00 AM	9.691	9.976	6.63
11	12/6/2013 9:39:00 AM	10.312	9.534	7.43
SR-212 WB				
1	12/5/2013 5:14:00 PM	*	10.980	13.92
2	12/5/2013 5:49:00 PM	15.027	9.909	13.00
3	12/5/2013 6:14:00 PM	14.159	9.479	11.33
4	12/5/2013 6:40:00 PM	13.572	6.895	7.95
5	12/5/2013 7:01:00 PM	13.419	10.871	10.8
6	12/6/2013 7:26:00 AM	8.008	10.244	9.82
7	12/6/2013 7:52:00 AM	8.224	10.611	8.8
8	12/6/2013 8:19:00 AM	9.215	8.974	9.02
9	12/6/2013 8:43:00 AM	9.517	10.968	9.8
10	12/6/2013 9:07:00 AM	9.895	7.216	8.37
11	12/6/2013 9:26:00 AM	10.267	18.653	8.32

Notes:
* Not enough matches through BlueTOAD

Figure 3.14(a) displays the average speeds along the study section for the EB and WB approaches during the pm peak. The average speeds shown were obtained from BlueTOAD. The figure shows that speeds are within the 20 to 25 mi/h range for that arterial street, which are slightly less than the prevailing speeds during the off-peak period. The shaded area represents the data collection duration which includes the peak period. Similarly, Figure 3.14(b) presents the average speeds along the study site for the am peak period. This figure shows some deterioration of speeds during the field data collection.



(a)



(b)

Figure 3.14. Time-series plot of speed at the study section along SR-212 EB and WB directions on (a) December 5th, 2013, and (b) December 6th, 2013

4. DATA ANALYSIS

This chapter presents the statistical analyses results comparing the various travel time measurement sources with the field-measured travel times. The first section presents the comparison conducted for each site separately, the second section conducts a comparison for all sites and conditions aggregated, the third section presents the analysis by facility type, and the last section by traffic condition.

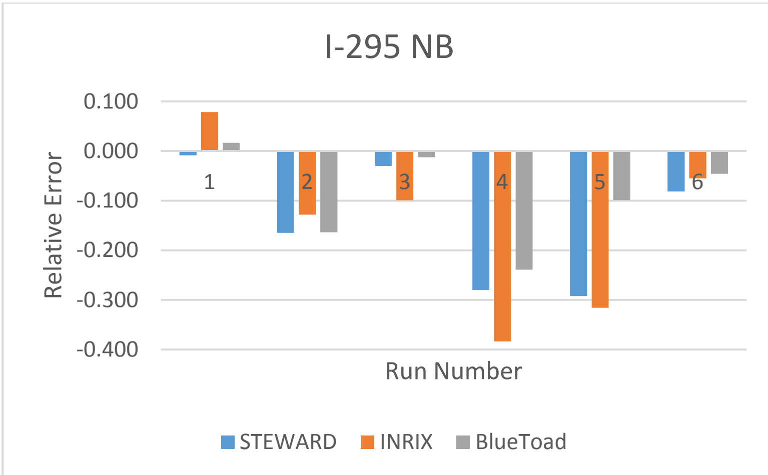
4.1. Statistical Comparison by Site

4.1.1. I-295 NB/SB, Jacksonville, FL

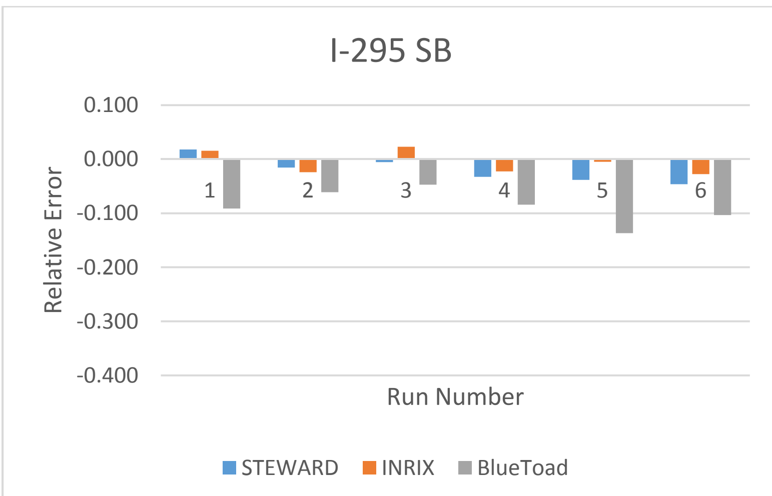
The common statistical measures for comparing travel times estimated by STEWARD, INRIX, and BlueTOAD are presented in Table 4.1. HERE traffic travel time data were not available during the data collection period. The percent error, shown graphically in Figure 4.1, is considerably higher during runs 4 and 5, which were the most congested. In lighter traffic, the percent error is lower. In the majority of the runs, the travel times measured from all three methods underpredicted the field-measured travel times (negative percent error). The results of the statistical analysis using the confidence interval method and the target accuracy method are presented below.

Table 4.1. Statistical measures for the comparison of travel time estimates with benchmark values obtained for the I-295 NB/SB site

Run #	Percent Error			Error Bias / Absolute Error					
	STEWARD	INRIX	BlueTOAD	STEWARD		INRIX		BlueTOAD	
I-295 NB									
1	-0.0087	0.0784	0.0167	-0.06	0.06	0.55	0.55	0.12	0.12
2	-0.1649	-0.1282	-0.1636	-1.45	1.45	-1.13	1.13	-1.44	1.44
3	-0.0302	-0.0992	-0.0125	-0.24	0.24	-0.79	0.79	-0.10	0.10
4	-0.2800	-0.3833	-0.2389	-3.21	3.21	-4.40	4.40	-2.74	2.74
5	-0.2923	-0.3158	-0.0989	-3.14	3.14	-3.39	3.39	-1.06	1.06
6	-0.0814	-0.0549	-0.0461	-0.62	0.62	-0.42	0.42	-0.35	0.35
I-295 SB									
1	0.0182	0.0157	-0.0911	0.12	0.12	0.11	0.11	-0.62	0.62
2	-0.0155	-0.0240	-0.0610	-0.11	0.11	-0.17	0.17	-0.43	0.43
3	-0.0055	0.0232	-0.0471	-0.04	0.04	0.16	0.16	-0.33	0.33
4	-0.0326	-0.0225	-0.0842	-0.23	0.23	-0.16	0.16	-0.60	0.60
5	-0.0384	-0.0047	-0.1367	-0.28	0.28	-0.03	0.03	-0.98	0.98
6	-0.0462	-0.0277	-0.1034	-0.34	0.34	-0.20	0.20	-0.76	0.76



(a)



(b)

Figure 4.1. Travel time percent error statistic along I-295, (a) NB, and (b) SB directions (Jacksonville, FL).

CONFIDENCE INTERVAL METHOD – MAXIMUM RELATIVE ERROR

The confidence intervals considering a 20% desired value for the MRE are shown in Table 4.2. As shown, using this method, all three measurement methods fail to provide accurate travel time estimates during the congested runs at the NB direction. With the exception of BlueTOAD, the travel time data collection methods provide satisfactory estimates for the non-congested SB direction.

Table 4.2. Confidence interval method results for I-295 NB/SB site

Run #	Start Time	Benchmark value (min)	$\bar{X} - \frac{e_{max}\bar{X}}{2+e_{max}}$	$\bar{X} + \frac{e_{max}\bar{X}}{2+e_{max}}$	STEWARD	INRIX	BlueTOAD
I-295 NB							
1	3:51 PM	7.05	6.41	7.69	√	√	√
2	4:19 PM	8.82	8.02	9.62	X	X	X
3	4:51 PM	7.95	7.23	8.67	√	X	√
4	5:22 PM	11.48	10.44	12.52	X	X	X
5	5:59 PM	10.73	9.75	11.71	X	X	X
6	6:32 PM	7.62	6.93	8.31	√	√	√
I-295 SB							
1	3:37 PM	6.83	6.21	7.45	√	√	X
2	4:05 PM	7.05	6.41	7.69	√	√	√
3	4:37 PM	6.95	6.32	7.58	√	√	√
4	5:06 PM	7.15	6.50	7.80	√	√	√
5	5:44 PM	7.17	6.52	7.82	√	√	X
6	6:18 PM	7.33	6.66	8.00	√	√	X

Note:
√: accurate
X: inaccurate

ACCURACY TARGET METHOD – ABSOLUTE PERCENT ERROR

The accuracy target method assumes an acceptable travel time error less than 20% and evaluates whether the absolute percent error falls within the acceptable range. The results of this analysis are presented in Table 4.3. Using this method, all three travel time measurement methods fail to provide acceptable travel times during the most congested runs; however, the BlueTOAD results appear to be accurate during one of the congested intervals.

Table 4.3. Accuracy target method results for I-295 NB/SB site

Run #	Benchmark value (min)	Absolute Percent Error			Acceptable travel time relative error less than 20%		
		STEWARD	INRIX	BlueTOAD	STEWARD	INRIX	BlueTOAD
I-295 NB							
1	7.05	0.009	0.078	0.017	√	√	√
2	8.82	0.165	0.128	0.164	√	√	√
3	7.95	0.030	0.099	0.012	√	√	√
4	11.48	0.280	0.383	0.239	X	X	X
5	10.73	0.292	0.316	0.099	X	X	√
6	7.62	0.081	0.055	0.046	√	√	√
I-295 SB							
1	6.83	0.018	0.016	0.091	√	√	√
2	7.05	0.015	0.024	0.061	√	√	√
3	6.95	0.005	0.023	0.047	√	√	√
4	7.15	0.033	0.023	0.084	√	√	√
5	7.17	0.038	0.005	0.137	√	√	√
6	7.33	0.046	0.028	0.103	√	√	√

Note:
√: accurate
X: inaccurate

4.1.2. I-95 NB/SB, Jacksonville, FL

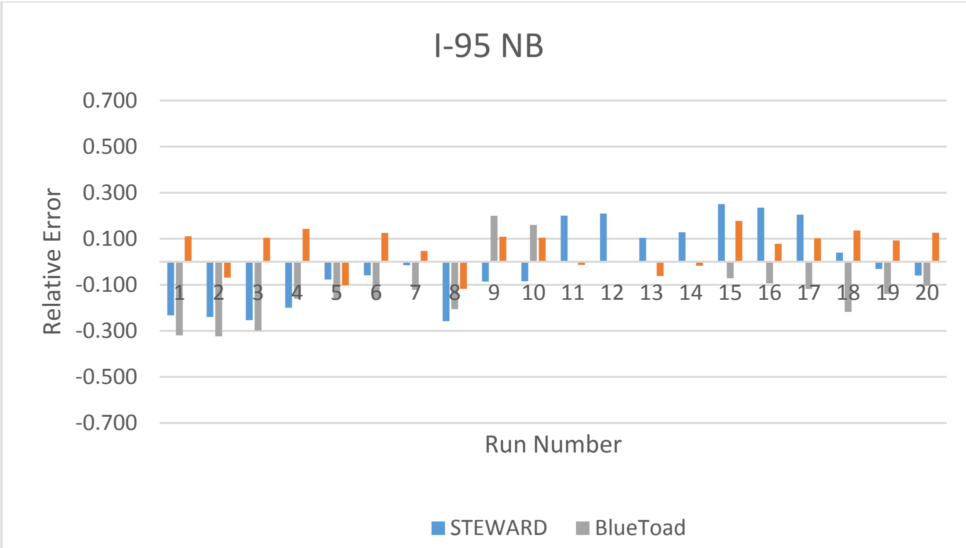
Travel time data at this site were available through STEWARD, BlueTOAD and HERE traffic. INRIX travel time data were not available for this site during the field data collection period. The statistical values for comparing the different travel time measurement methods with the benchmark values are presented in Table 4.4. The percent error, graphically shown in Figure 4.2, is considerably higher in the southbound direction, which is also the most congested. The error is higher for the STEWARD and BlueTOAD methods. These graphs also show that HERE traffic tends to overestimate travel times (positive relative error), whereas the other two methods underestimate travel times (negative relative error).

The results of the statistical analysis using the confidence interval method and the target accuracy method are presented below.

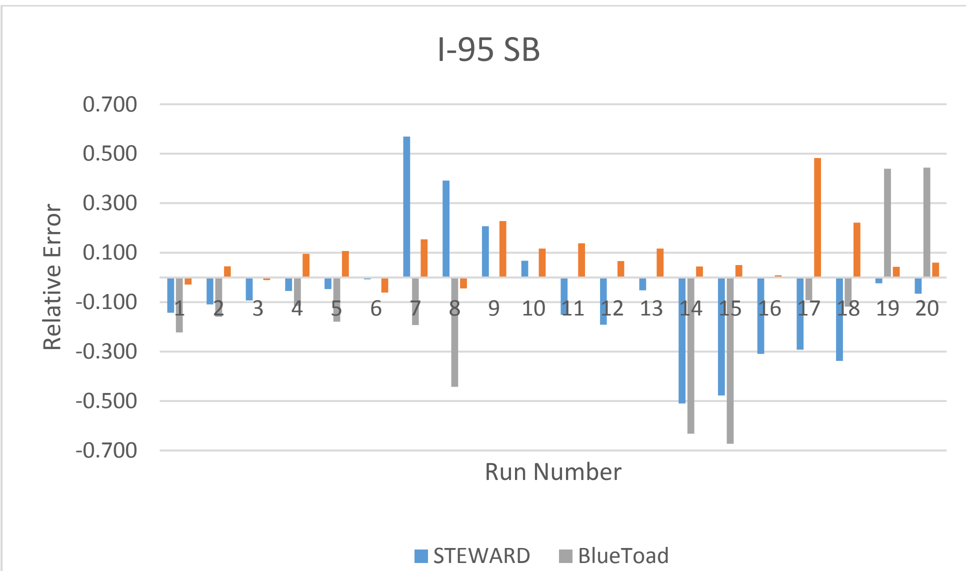
Table 4.4. Statistical measures for the comparison of travel time estimates with benchmark values obtained for the I-95 NB/SB study section

Run #	Percent Error			Error Bias / Absolute Error					
	STEWARD	BlueTOAD	HERE	STEWARD		BlueTOAD		HERE	
I-95 NB									
1	-0.2329	-0.3195	0.1106	-0.88	0.88	-1.20	1.20	0.42	0.42
2	-0.2397	-0.3242	-0.0685	-0.92	0.92	-1.24	1.24	-0.26	0.26
3	-0.2540	-0.2985	0.1044	-1.02	1.02	-1.19	1.19	0.42	0.42
4	-0.1997	-0.1603	0.1425	-0.76	0.76	-0.61	0.61	0.54	0.54
5	-0.0774	-0.1603	-0.1023	-0.29	0.29	-0.61	0.61	-0.39	0.39
6	-0.0587	-0.1589	0.1250	-0.23	0.23	-0.62	0.62	0.48	0.48
7	-0.0153	-0.1216	0.0465	-0.06	0.06	-0.47	0.47	0.18	0.18
8	-0.2579	-0.2059	-0.1177	-1.08	1.08	-0.86	0.86	-0.49	0.49
9	-0.0862	0.1998	0.1082	-0.25	0.25	0.58	0.58	0.31	0.31
10	-0.0848	0.1598	0.1046	-0.25	0.25	0.48	0.48	0.31	0.31
11	0.2000	*	-0.0140	0.63	0.63	*	*	-0.04	0.04
12	0.2095	*	0.0011	0.66	0.66	*	*	0.00	0.00
13	0.1037	*	-0.0620	0.35	0.35	*	*	-0.21	0.21
14	0.1280	*	-0.0173	0.39	0.39	*	*	-0.05	0.05
15	0.2500	-0.0717	0.1771	0.71	0.71	-0.20	0.20	0.50	0.50
16	0.2350	-0.0939	0.0778	0.69	0.69	-0.27	0.27	0.23	0.23
17	0.2046	-0.1181	0.1018	0.61	0.61	-0.35	0.35	0.31	0.31
18	0.0395	-0.2173	0.1355	0.13	0.13	-0.73	0.73	0.46	0.46
19	-0.0309	-0.1397	0.0923	-0.10	0.10	-0.44	0.44	0.29	0.29
20	-0.0597	-0.1052	0.1260	-0.19	0.19	-0.33	0.33	0.39	0.39
I-95 SB									
1	-0.1432	-0.2227	-0.0290	-0.47	0.47	-0.73	0.73	-0.10	0.10
2	-0.1095	-0.1588	0.0449	-0.33	0.33	-0.48	0.48	0.14	0.14
3	-0.0930	*	-0.0110	-0.28	0.28	*	*	-0.03	0.03
4	-0.0550	-0.1153	0.0949	-0.16	0.16	-0.33	0.33	0.28	0.28
5	-0.0469	-0.1794	0.1069	-0.14	0.14	-0.53	0.53	0.32	0.32
6	-0.0078	*	-0.0615	-0.02	0.02	*	*	-0.19	0.19
7	0.5693	-0.1930	0.1541	1.72	1.72	-0.58	0.58	0.47	0.47
8	0.3915	-0.4423	-0.0444	1.71	1.71	-1.93	1.93	-0.19	0.19
9	0.2073	*	0.2279	0.75	0.75	*	*	0.83	0.83
10	0.0676	*	0.1165	0.19	0.19	*	*	0.33	0.33
11	-0.1513	*	0.1378	-0.73	0.73	*	*	0.67	0.67
12	-0.1913	*	0.0660	-0.95	0.95	*	*	0.33	0.33
13	-0.0524	*	0.1164	-0.21	0.21	*	*	0.47	0.47
14	-0.5100	-0.6323	0.0443	-3.83	3.83	-4.74	4.74	0.33	0.33
15	-0.4773	-0.6731	0.0497	-4.47	4.47	-6.31	6.31	0.47	0.47
16	-0.3094	*	0.0088	-1.53	1.53	*	*	0.04	0.04
17	-0.2924	-0.0925	0.4824	-1.53	1.53	-0.48	0.48	2.52	2.52
18	-0.3375	-0.1181	0.2210	-1.82	1.82	-0.64	0.64	1.19	1.19
19	-0.0236	0.4396	0.0427	-0.08	0.08	1.42	1.42	0.14	0.14
20	-0.0659	0.4441	0.0597	-0.21	0.21	1.43	1.43	0.19	0.19

* Not enough matches through BlueTOAD



(a)



(b)

Figure 4.2. Travel time percent error statistic along I-95, (a) NB, and (b) SB directions (Jacksonville, FL).

CONFIDENCE INTERVAL METHOD – MAXIMUM RELATIVE ERROR

The confidence intervals considering a 20% desired value for the MRE are shown in Table 4.5. This method indicates that the travel time measurement methods fail to provide acceptable travel times during the majority of the runs along this segment. BlueTOAD performs poorly in estimating travel time in both directions. STEWARD and HERE traffic provide comparable travel time estimates for both directions. HERE traffic appears to perform overall better than the other methods for the congested direction of traffic (SB direction).

Table 4.5. Confidence interval method results for I-95 NB/SB site

Run #	Start Time	Benchmark value (min)	$\bar{X} - \frac{e_{max}\bar{X}}{2+e_{max}}$	$\bar{X} + \frac{e_{max}\bar{X}}{2+e_{max}}$	STEWARD	BlueTOAD	HERE
I-95 NB							
1	10/14/2013 15:46	3.77	3.43	4.11	X	X	X
2	10/14/2013 16:02	3.82	3.47	4.17	X	X	√
3	10/14/2013 16:18	4.00	3.64	4.36	X	X	X
4	10/14/2013 16:35	3.80	3.45	4.15	X	X	X
5	10/14/2013 16:50	3.80	3.45	4.15	√	X	X
6	10/14/2013 17:07	3.87	3.52	4.22	√	X	X
7	10/14/2013 17:26	3.87	3.52	4.22	√	X	√
8	10/14/2013 17:44	4.20	3.82	4.58	X	X	X
9	10/14/2013 18:00	2.90	2.64	3.16	√	X	X
10	10/14/2013 18:12	3.00	2.73	3.27	√	X	X
11	10/15/2013 7:44	3.13	2.85	3.41	X	*	√
12	10/15/2013 8:03	3.13	2.85	3.41	X	*	√
13	10/15/2013 8:20	3.38	3.07	3.69	X	*	√
14	10/15/2013 8:38	3.05	2.77	3.33	X	*	√
15	10/15/2013 8:55	2.85	2.59	3.11	X	√	X
16	10/15/2013 9:14	2.92	2.65	3.19	X	X	√
17	10/15/2013 9:31	3.00	2.73	3.27	X	X	X
18	10/15/2013 9:47	3.38	3.07	3.69	√	X	X
19	10/15/2013 10:02	3.15	2.86	3.44	√	X	X
20	10/15/2013 10:17	3.10	2.82	3.38	√	X	X
I-95 SB							
1	10/14/13 15:39	3.28	2.98	3.58	X	X	√
2	10/14/2013 15:54	3.05	2.77	3.33	X	X	√
3	10/14/2013 16:09	3.02	2.75	3.29	X	*	√
4	10/14/2013 16:26	2.9	2.64	3.16	√	X	X
5	10/14/2013 16:43	2.97	2.70	3.24	√	X	X
6	10/14/2013 16:57	3.08	2.80	3.36	√	*	√
7	10/14/2013 17:14	3.02	2.75	3.29	X	X	X
8	10/14/2013 17:32	4.37	3.97	4.77	X	X	√
9	10/14/2013 17:50	3.62	3.29	3.95	X	*	X
10	10/14/2013 18:06	2.83	2.57	3.09	√	*	X
11	10/15/2013 7:51	4.85	4.41	5.29	X	*	X
12	10/15/2013 8:10	4.95	4.50	5.40	X	*	√
13	10/15/2013 8:27	4.05	3.68	4.42	√	*	X
14	10/15/2013 8:44	7.5	6.82	8.18	X	X	√
15	10/15/2013 9:00	9.37	8.52	10.22	X	X	√
16	10/15/2013 9:20	4.95	4.50	5.40	X	*	√
17	10/15/2013 9:38	5.23	4.75	5.71	X	X	X
18	10/15/2013 9:53	5.4	4.91	5.89	X	X	X
19	10/15/2013 10:08	3.23	2.94	3.52	√	X	√
20	10/15/2013 10:23	3.22	2.93	3.51	√	X	√

Note:
√: accurate
X: inaccurate
* Not enough matches through BlueTOAD

<u>ACCURACY TARGET METHOD – ABSOLUTE PERCENT ERROR</u>

The accuracy target method assumes an acceptable travel time error less than 20% and evaluates whether the absolute percent error falls within the acceptable range. The results of this analysis (Table 4.6) show that the HERE traffic travel times have acceptable travel time error of less than 20% for most of the runs in both directions. The HERE traffic data provide acceptable travel times for the two most congested runs (runs 14 and 15 at the SB direction) whereas the other two methods fail to do so. The STEWARD travel times also provide accurate travel times for the majority of the runs. The BlueTOAD travel time data also provided accurate measurements for the majority of the cases; however, the available travel times were considerably fewer due to insufficient matches obtained through Bluetooth.

4.1.3. I-275 NB/SB, Tampa, FL

Travel time data at this site were available through STEWARD and HERE traffic. INRIX travel time data are not available along this study site. The statistical values for comparing the travel time measurement methods with the benchmark values are presented in Table 4.7.

Table 4.6. Accuracy target method results for I-95 NB/SB site

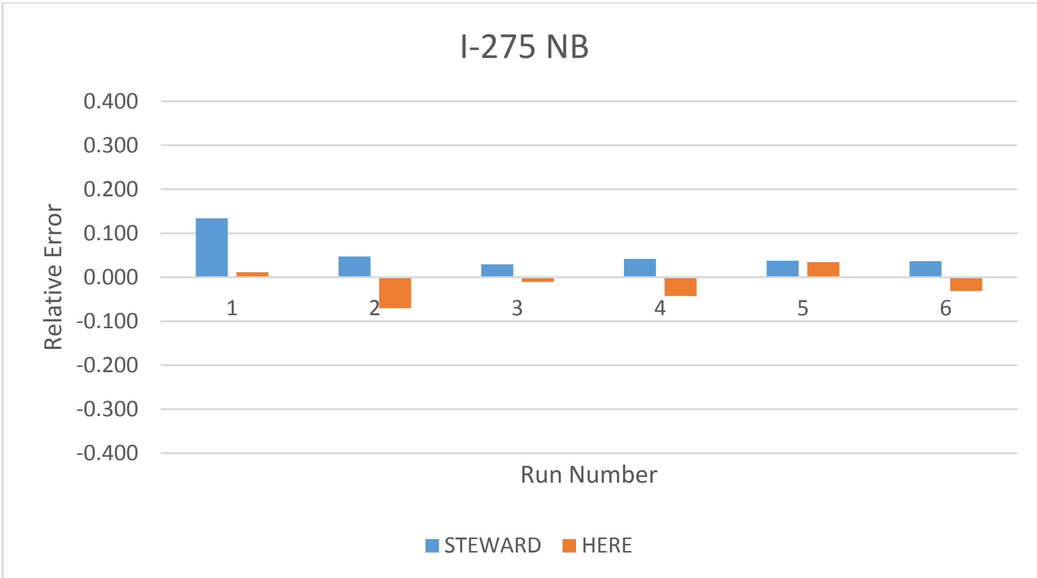
Run #	Benchmark value (min)	Absolute Percent Error			Acceptable travel time relative error less than 20%		
		STEWARD	BlueTOAD	HERE	STEWARD	BlueTOAD	HERE
I-95 NB							
1	3.77	0.233	0.319	0.111	X	X	√
2	3.82	0.240	0.324	0.069	X	X	√
3	4.00	0.254	0.298	0.104	X	X	√
4	3.80	0.200	0.160	0.143	√	√	√
5	3.80	0.077	0.160	0.102	√	√	√
6	3.87	0.059	0.159	0.125	√	√	√
7	3.87	0.015	0.122	0.047	√	√	√
8	4.20	0.258	0.206	0.118	X	X	√
9	2.90	0.086	0.200	0.108	√	√	√
10	3.00	0.085	0.160	0.105	√	√	√
11	3.13	0.200	*	0.014	X	*	√
12	3.13	0.209	*	0.001	X	*	√
13	3.38	0.104	*	0.062	√	*	√
14	3.05	0.128	*	0.017	√	*	√
15	2.85	0.250	0.072	0.177	X	√	√
16	2.92	0.235	0.094	0.078	X	√	√
17	3.00	0.205	0.118	0.102	X	√	√
18	3.38	0.040	0.217	0.135	√	X	√
19	3.15	0.031	0.140	0.092	√	√	√
20	3.10	0.060	0.105	0.126	√	√	√
I-95 SB							
1	3.28	0.143	0.223	0.029	√	X	√
2	3.05	0.109	0.159	0.045	√	√	√
3	3.02	0.093	*	0.011	√	*	√
4	2.9	0.055	0.115	0.095	√	√	√
5	2.97	0.047	0.179	0.107	√	√	√
6	3.08	0.008	*	0.062	√	*	√
7	3.02	0.569	0.193	0.154	X	√	√
8	4.37	0.392	0.442	0.044	X	X	√
9	3.62	0.207	*	0.228	X	*	X
10	2.83	0.068	*	0.116	√	*	√
11	4.85	0.151	*	0.138	√	*	√
12	4.95	0.191	*	0.066	√	*	√
13	4.05	0.052	*	0.116	√	*	√
14	7.5	0.510	0.632	0.044	X	X	√
15	9.37	0.477	0.673	0.050	X	X	√
16	4.95	0.309	*	0.009	X	*	√
17	5.23	0.292	0.093	0.482	X	√	X
18	5.4	0.338	0.118	0.221	X	√	X
19	3.23	0.024	0.440	0.043	√	X	√
20	3.22	0.066	0.444	0.060	√	X	√

Note:
√: accurate
X: inaccurate
* Not enough matches through BlueTOAD

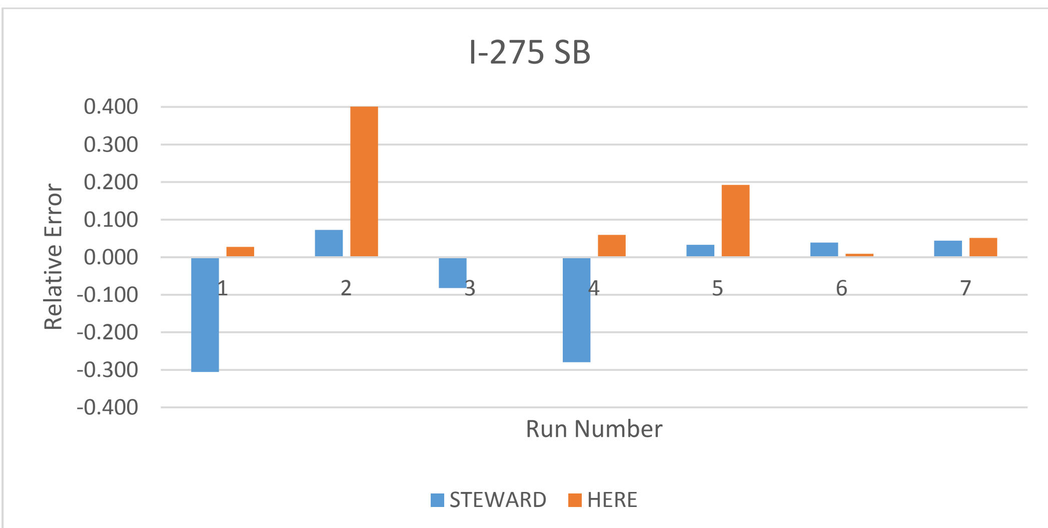
Table 4.7. Statistical measures for the comparison of travel time estimates with benchmark values obtained for the I-275 NB/SB study section

Run #	Percent Error		Error Bias / Absolute Error			
	STEWARD	HERE	STEWARD		HERE	
I-275 NB						
1	0.1339	0.0114	0.62	0.05	0.62	0.05
2	0.0472	-0.0703	0.23	-0.34	0.23	0.34
3	0.0295	-0.0106	0.15	-0.05	0.15	0.05
4	0.0418	-0.0425	0.21	-0.21	0.21	0.21
5	0.0377	0.0344	0.19	0.17	0.19	0.17
6	0.0368	-0.0313	0.18	-0.15	0.18	0.15
I-275 SB						
1	-0.3054	0.0272	-3.56	3.56	0.32	0.32
2	0.0727	0.4083	0.84	0.84	4.72	4.72
3	-0.0823	-0.0013	-1.39	1.39	-0.02	0.02
4	-0.2794	0.0595	-5.94	5.94	1.26	1.26
5	0.0328	0.1924	0.46	0.46	2.67	2.67
6	0.0390	0.0091	0.30	0.30	0.07	0.07
7	0.0443	0.0513	0.34	0.34	0.39	0.39

The percent error is also depicted in Figure 4.3. As shown, the percent error is considerably higher in the southbound direction for some of the runs. The results of the statistical analysis with the confidence interval method and the target accuracy method are presented below.



(a)



(b)

Figure 4.3. Travel time percent error statistic along I-275, (a) NB, and (b) SB directions (Tampa, FL).

CONFIDENCE INTERVAL METHOD – MAXIMUM RELATIVE ERROR

The confidence intervals considering a 20% desired value for the MRE are shown in Table 4.8.

Table 4.8. Confidence interval method results for I-275 NB/SB site

Run #	Start Time	Benchmark value (min)	$\bar{X} - \frac{e_{\max}\bar{X}}{2+e_{\max}}$	$\bar{X} + \frac{e_{\max}\bar{X}}{2+e_{\max}}$	STEWARD	HERE
I-275 NB						
1	7/31/2013 6:56	4.62	4.20	5.04	X	√
2	7/31/2013 7:21	4.88	4.44	5.32	√	√
3	7/31/2013 7:53	4.97	4.52	5.42	√	√
4	7/31/2013 8:29	4.95	4.50	5.40	√	√
5	7/31/2013 8:59	4.97	4.52	5.42	√	√
6	7/31/2013 9:23	4.88	4.44	5.32	√	√
I-275 SB						
1	7/31/2013 6:41	11.65	10.59	12.71	X	√
2	7/31/2013 7:06	11.57	10.52	12.62	√	X
3	7/31/2013 7:33	16.92	15.38	18.46	√	√
4	7/31/2013 8:05	21.25	19.32	23.18	X	√
5	7/31/2013 8:42	13.9	12.64	15.16	√	X
6	7/31/2013 9:11	7.78	7.07	8.49	√	√
7	7/31/2013 9:33	7.62	6.93	8.31	√	√

Note:
√: accurate
X: inaccurate

Using this method both HERE and STEWARD provide accurate travel time measurements for the majority of the runs performed.

<u>ACCURACY TARGET METHOD – ABSOLUTE PERCENT ERROR</u>

The accuracy target method assumes an acceptable travel time error less than 20% and evaluates whether the absolute percent error falls within the acceptable range. The results of this analysis are presented in Table 4.9.

Table 4.9. Accuracy target method results for I-275 NB/SB site

Run #	Benchmark value (min)	Absolute Percent Error		Acceptable travel time relative error less than 20%	
		STEWARD	HERE	STEWARD	HERE
I-275 NB					
1	4.62	0.134	0.011	√	√
2	4.88	0.047	0.070	√	√
3	4.97	0.029	0.011	√	√
4	4.95	0.042	0.042	√	√
5	4.97	0.038	0.034	√	√
6	4.88	0.037	0.031	√	√
I-275 SB					
1	11.65	0.305	0.027	X	√
2	11.57	0.073	0.408	√	X
3	16.92	0.082	0.001	√	√
4	21.25	0.279	0.059	X	√
5	13.9	0.033	0.192	√	√
6	7.78	0.039	0.009	√	√
7	7.62	0.044	0.051	√	√

Note:
√: accurate
X: inaccurate

The results from this analysis are consistent with the results from previous sites. Both HERE traffic and STEWARD travel times are accurate within the acceptable relative error of 20%. HERE traffic performs better than STEWARD for congested conditions (runs 3 to 5 in the SB direction).

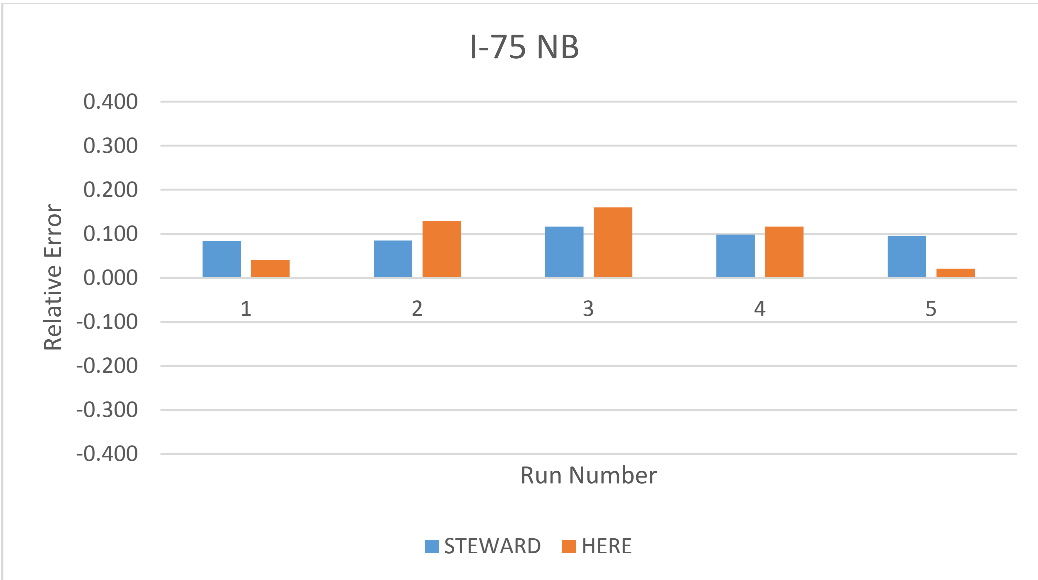
4.1.4. I-75 NB/SB, Tampa, FL

Travel time data at this site were available through STEWARD, and HERE traffic. INRIX travel time data are not available along this study site. The statistical values for comparing the available travel time measurement methods with the benchmark values are presented in Table 4.10.

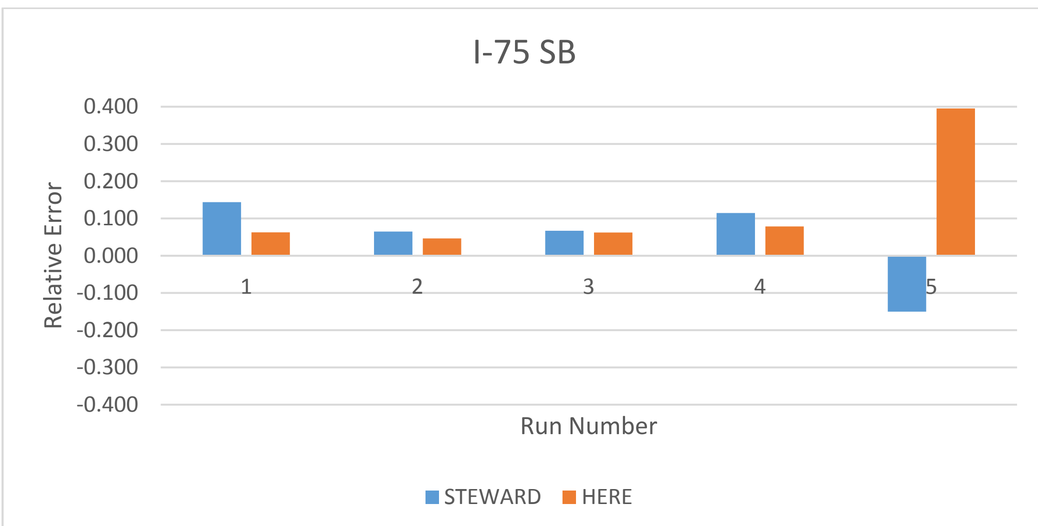
Table 4.10. Statistical measures for the comparison of travel time estimates with benchmark values obtained for the I-75 NB/SB study section

Run #	Percent Error		Error Bias / Absolute Error			
	STEWARD	HERE	STEWARD		HERE	
I-75 NB						
1	0.0835	0.0399	0.48	0.48	0.23	0.23
2	0.0848	0.1287	0.49	0.49	0.75	0.75
3	0.1162	0.1597	0.65	0.65	0.89	0.89
4	0.0980	0.1163	0.56	0.56	0.66	0.66
5	0.0955	0.0206	0.54	0.54	0.12	0.12
I-75 SB						
1	0.1440	0.0628	0.77	0.77	0.34	0.34
2	0.0650	0.0465	0.38	0.38	0.27	0.27
3	0.0671	0.0623	0.40	0.40	0.37	0.37
4	0.1145	0.0786	0.64	0.64	0.44	0.44
5	-0.1502	0.3951	-1.17	1.17	3.09	3.09

The percent error is also depicted in Figure 4.4. As shown, both measurement methods tend to slightly over predict travel times. The results of the statistical analysis of this site considering the confidence interval method and the target accuracy method are presented below.



(a)



(b)

Figure 4.4. Travel time percent error statistic along I-75, (a) NB, and (b) SB directions (Tampa, FL).

CONFIDENCE INTERVAL METHOD – MAXIMUM RELATIVE ERROR

The confidence intervals considering a 20% desired value for the MRE are shown in Table 4.11. Using this method, STEWARD fails to predict accurately several of the travel times at both directions while HERE is mostly valid in the SB direction.

Table 4.11. Confidence interval method results for I-75 NB/SB site

Run #	Start Time	Benchmark value (min)	$\overline{X} - \frac{e_{\max}\overline{X}}{2+e_{\max}}$	$\overline{X} + \frac{e_{\max}\overline{X}}{2+e_{\max}}$	STEWARD	HERE
I-75 NB						
1	7/30/2013 15:45	5.75	5.23	6.27	√	√
2	7/30/2013 16:16	5.82	5.29	6.35	√	X
3	7/30/2013 16:54	5.58	5.07	6.09	X	X
4	7/30/2013 17:33	5.70	5.18	6.22	X	X
5	7/30/2013 18:09	5.62	5.11	6.13	X	√
I-75 SB						
1	7/30/2013 15:29	5.38	4.89	5.87	X	√
2	7/30/2013 16:00	5.77	5.25	6.29	√	√
3	7/30/2013 16:38	6.02	5.47	6.57	√	√
4	7/30/2013 17:16	5.57	5.06	6.08	X	√
5	7/30/2013 17:50	7.82	7.11	8.53	X	X

Note:
√: accurate
X: inaccurate

ACCURACY TARGET METHOD – ABSOLUTE PERCENT ERROR

The accuracy target method assumes an acceptable travel time error less than 20% and evaluates whether the absolute percent error falls within the acceptable range. The results of this analysis are presented in Table 4.12.

Table 4.12. Accuracy target method results for I-75 NB/SB site

Run #	Benchmark value (min)	Absolute Percent Error		Acceptable travel time relative error less than 20%	
		STEWARD	HERE	STEWARD	HERE
I-275 NB					
1	5.75	0.084	0.040	√	√
2	5.82	0.085	0.129	√	√
3	5.58	0.116	0.160	√	√
4	5.70	0.098	0.116	√	√
5	5.62	0.096	0.021	√	√
I-275 SB					
1	5.38	0.144	0.046	√	√
2	5.77	0.065	0.062	√	√
3	6.02	0.067	0.079	√	√
4	5.57	0.115	0.395	√	**X**
5	7.82	0.150	0.000	√	√

Note:
√: accurate
X: inaccurate

The conclusions from this analysis are favorable for both methods. As shown in Table 4.12 both methods provide acceptable results considering an acceptable travel time error of less than 20%.

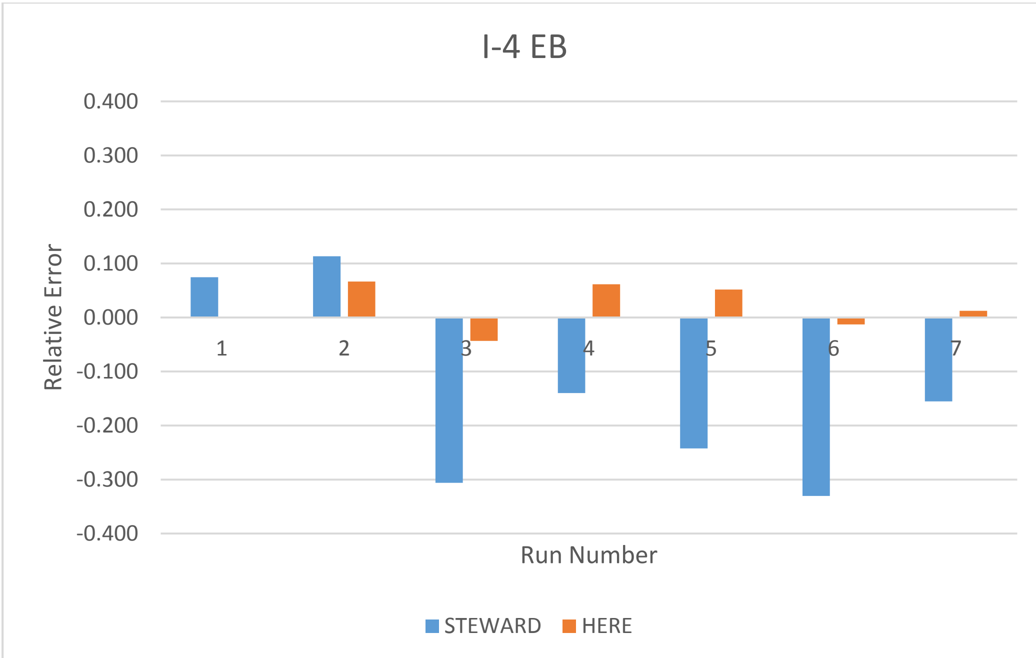
4.1.5. I-4 EB/WB, Tampa, FL

Travel time data at this site were available through STEWARD, and HERE traffic. INRIX travel time data are not available along this study site. The statistical values for comparing the different travel time measurement methods with the benchmark values are presented in Table 4.13.

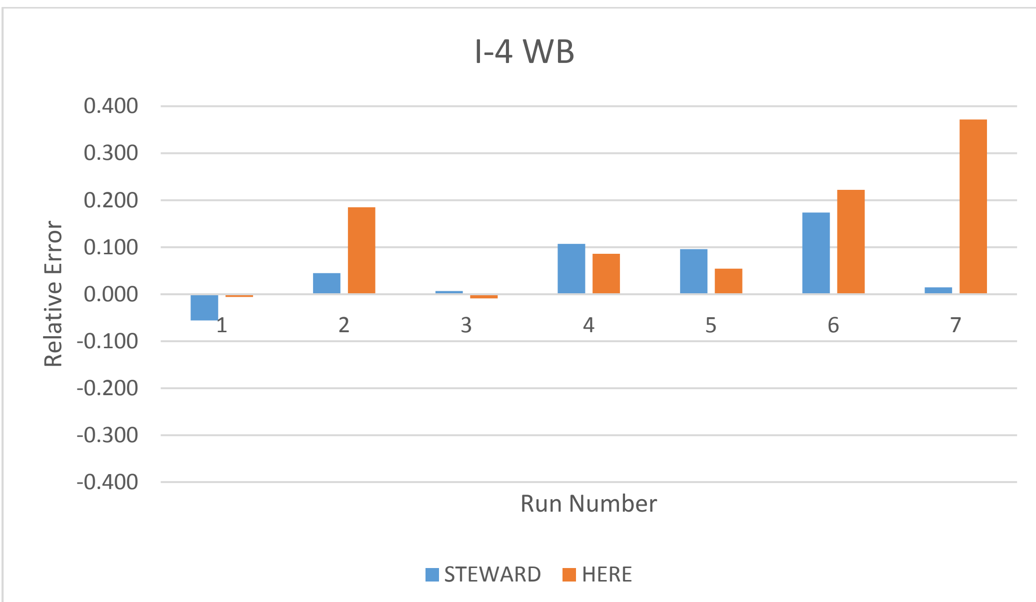
Table 4.13. Statistical measures for the comparison of travel time estimates with benchmark values obtained for the I-4 EB/WSB study section

Run #	Percent Error		Error Bias / Absolute Error			
	STEWARD	HERE	STEWARD		HERE	
I-4 EB						
1	0.0745	0.0004	0.50	0.50	0.00	0.00
2	0.1134	0.0666	0.75	0.75	0.44	0.44
3	-0.3058	-0.0432	-3.17	3.17	-0.45	0.45
4	-0.1400	0.0615	-1.17	1.17	0.52	0.52
5	-0.2422	0.0519	-2.29	2.29	0.49	0.49
6	-0.3302	-0.0127	-3.52	3.52	-0.14	0.14
7	-0.1552	0.0123	-1.30	1.30	0.10	0.10
I-4 WB						
1	-0.0560	-0.0059	-0.23	0.23	-0.02	0.02
2	0.0450	0.1850	0.19	0.19	0.77	0.77
3	0.0067	-0.0088	0.03	0.03	-0.04	0.04
4	0.1072	0.0861	0.46	0.46	0.37	0.37
5	0.0960	0.0543	0.40	0.40	0.23	0.23
6	0.1739	0.2222	0.74	0.74	0.94	0.94
7	0.0145	0.3720	0.06	0.06	1.61	1.61

The percent error is also depicted in Figure 4.5, which indicates that the percent error of STEWARD travel times is considerably higher in the eastbound direction. HERE slightly over predicts travel times whereas no consistent trend can be concluded based on the STEWARD travel times. The results of the statistical analysis for this site using the confidence interval method and the target accuracy method are presented below.



(a)



(b)

Figure 4.5. Travel time percent error statistic along I-4, (a) EB, and (b) WB directions (Tampa, FL).

CONFIDENCE INTERVAL METHOD – MAXIMUM RELATIVE ERROR

The confidence intervals considering a 20% desired value for the MRE is shown in Table 4.14.

Table 4.14. Confidence interval method results for I-4 EB/WB site

Run #	Start Time	Benchmark value (min)	$\bar{X}-\frac{e_{max}\bar{X}}{2+e_{max}}$	$\bar{X}+\frac{e_{max}\bar{X}}{2+e_{max}}$	STEWARD	HERE
I-4 EB						
1	7/31/2013 15:23	6.67	6.06	7.28	√	√
2	7/31/2013 15:47	6.57	5.97	7.17	X	√
3	7/31/2013 16:15	10.35	9.41	11.29	X	√
4	7/31/2013 16:55	8.38	7.62	9.14	X	√
5	7/31/2013 17:25	9.47	8.61	10.33	X	√
6	7/31/2013 17:57	10.65	9.68	11.62	X	√
7	7/31/2013 18:25	8.35	7.59	9.11	X	√
I-4 WB						
1	7/31/2013 15:14	4.17	3.79	4.55	√	√
2	7/31/2013 15:38	4.17	3.79	4.55	√	X
3	7/31/2013 16:03	4.48	4.07	4.89	√	√
4	7/31/2013 16:43	4.30	3.91	4.69	X	√
5	7/31/2013 17:11	4.18	3.80	4.56	X	√
6	7/31/2013 17:45	4.23	3.85	4.61	X	X
7	7/31/2013 18:16	4.32	3.93	4.71	√	X

Note:
√: accurate
X: inaccurate

From this analysis is it concluded that STEWARD does not provide accurate travel time measurements during the congested runs of the eastbound direction, whereas HERE performs very well. Although the WB direction does not have congestion, both methods fail to provide accurate travel times for three of the seven runs.

ACCURACY TARGET METHOD – ABSOLUTE PERCENT ERROR

The accuracy target method assumes an acceptable travel time error less than 20% and evaluates whether the absolute percent error falls within the acceptable range. The results of this analysis are presented in Table 4.15.

Table 4.15. Accuracy target method results for I-4 EB/WB site

Run #	Benchmark value (min)	Absolute Percent Error		Acceptable travel time relative error less than 20%	
		STEWARD	HERE	STEWARD	HERE
I-4 EB					
1	6.67	0.075	0.000	√	√
2	6.57	0.113	0.067	√	√
3	10.35	0.306	0.043	X	√
4	8.38	0.140	0.062	√	√
5	9.47	0.242	0.052	X	√
6	10.65	0.330	0.013	X	√
7	8.35	0.155	0.012	√	√
I-4 WB					
1	4.17	0.056	0.006	√	√
2	4.17	0.045	0.185	√	√
3	4.48	0.007	0.009	√	√
4	4.30	0.107	0.086	√	√
5	4.18	0.096	0.054	√	√
6	4.23	0.174	0.222	√	X
7	4.32	0.015	0.372	√	X

Note:
√: accurate
X: inaccurate

The results presented from this analysis show again that HERE performs better during the congested periods. In the uncongested direction (WB) the results are better than those based on the confidence interval method.

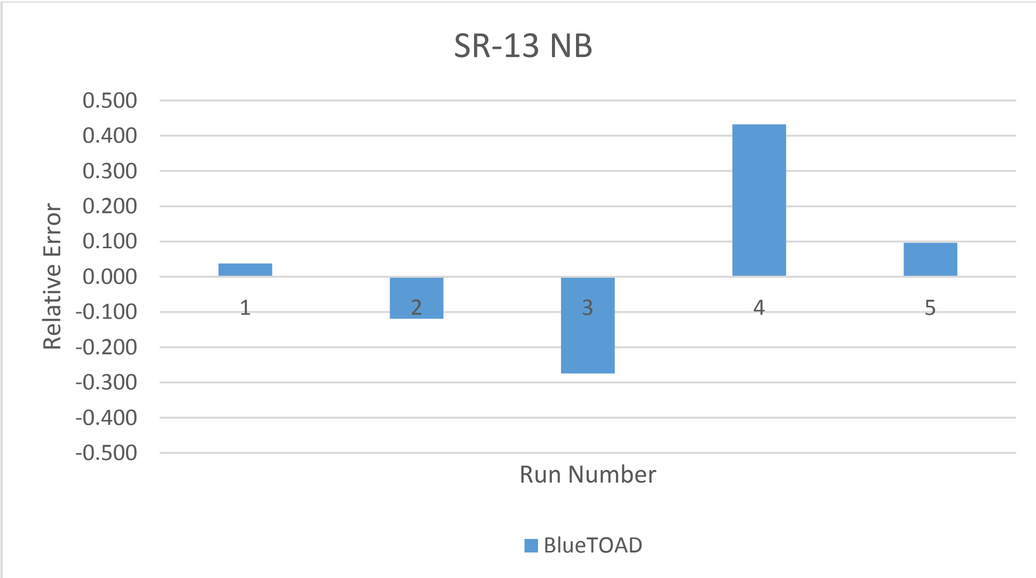
4.1.6. SR-13 NB/SB, Jacksonville, FL

Travel time data at this site were available only through BlueTOAD. The statistical values for comparing the BlueTOAD travel time measurements with the benchmark values are presented in Table 4.16.

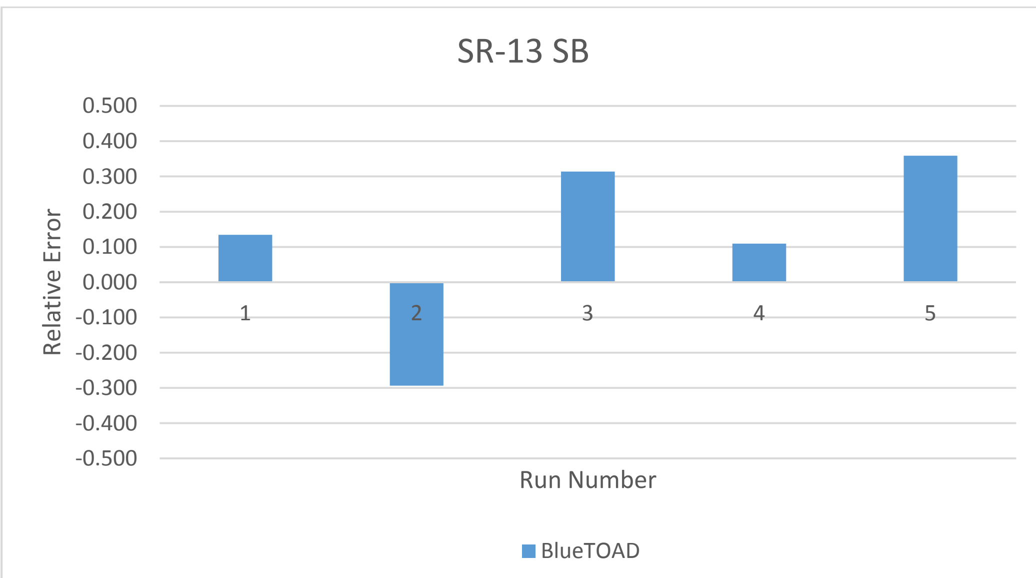
The relative error is also depicted in Figure 4.6. The figure shows that there is no apparent pattern in the relative error magnitude or direction. The results of the statistical analysis of this site with the confidence interval method and the target accuracy method are presented below.

Table 4.16. Statistical measures for the comparison of travel time estimates with benchmark values obtained for the SR-13 NB/SB study section

Run #	Percent Error	Error Bias / Absolute Error	
	BlueTOAD	BlueTOAD	
SR-13 NB			
1	0.0374	0.07	0.07
2	-0.1190	-0.33	0.33
3	-0.2745	-1.17	1.17
4	0.4326	0.78	0.78
5	0.0960	0.19	0.19
SR-13 SB			
1	0.1345	0.24	0.24
2	-0.2935	-0.88	0.88
3	0.3137	0.53	0.53
4	0.1093	0.24	0.24
5	0.3589	0.60	0.60



(a)



(b)

Figure 4.6. Travel time percent error statistic along SR-13, (a) NB, and (b) SB directions (Jacksonville, FL).

CONFIDENCE INTERVAL METHOD – MAXIMUM RELATIVE ERROR

The confidence intervals considering a 20% desired value for the MRE is shown in Table 4.17. Based on the analysis results, BlueTOAD fails to predict accurately travel times in both travel directions.

Table 4.17. Confidence interval method results for SR-13 NB/SB site

Run #	Start Time	Benchmark value (min)	$\overline{X} - \frac{e_{\max}\overline{X}}{2+e_{\max}}$	$\overline{X} + \frac{e_{\max}\overline{X}}{2+e_{\max}}$	BlueTOAD
SR-13 NB					
1	10/31/2013 6:54	1.98	1.80	2.16	√
2	10/31/2013 7:38	2.78	2.53	3.03	X
3	10/31/2013 8:29	4.27	3.88	4.66	X
4	10/31/2013 9:12	1.80	1.64	1.96	X
5	10/31/2013 9:49	2.03	1.85	2.21	X
SR-13 SB					
1	10/31/2013 7:03	1.78	1.62	1.94	X
2	10/31/2013 7:53	3.00	2.73	3.27	X
3	10/31/2013 8:39	1.70	1.55	1.85	X
4	10/31/2013 9:18	2.17	1.97	2.37	X
5	10/31/2013 9:56	1.68	1.53	1.83	X

Note:
√: accurate
X: inaccurate

ACCURACY TARGET METHOD – ABSOLUTE PERCENT ERROR

The accuracy target method assumes an acceptable travel time error less than 20% and evaluates whether the absolute percent error falls within the acceptable range. The results of this analysis are presented in Table 4.18. Although the results of this analysis are more favorable, it can be still concluded that BlueTOAD does not predict accurately travel times along this arterial segment.

Table 4.18. Accuracy target method results for I-75 NB/SB site

Run #	Benchmark value (min)	Absolute Percent Error	Acceptable travel time relative error less than 20%
		BlueTOAD	BlueTOAD
I-275 NB			
1	1.98	0.037	√
2	2.78	0.119	√
3	4.27	0.274	X
4	1.80	0.433	X
5	2.03	0.096	√
I-275 SB			
1	1.78	0.135	√
2	3.00	0.293	X
3	1.70	0.314	X
4	2.17	0.109	√
5	1.68	0.359	X

Note:
√: accurate
X: inaccurate

4.1.7. SR-212 EB/WB, Jacksonville, FL

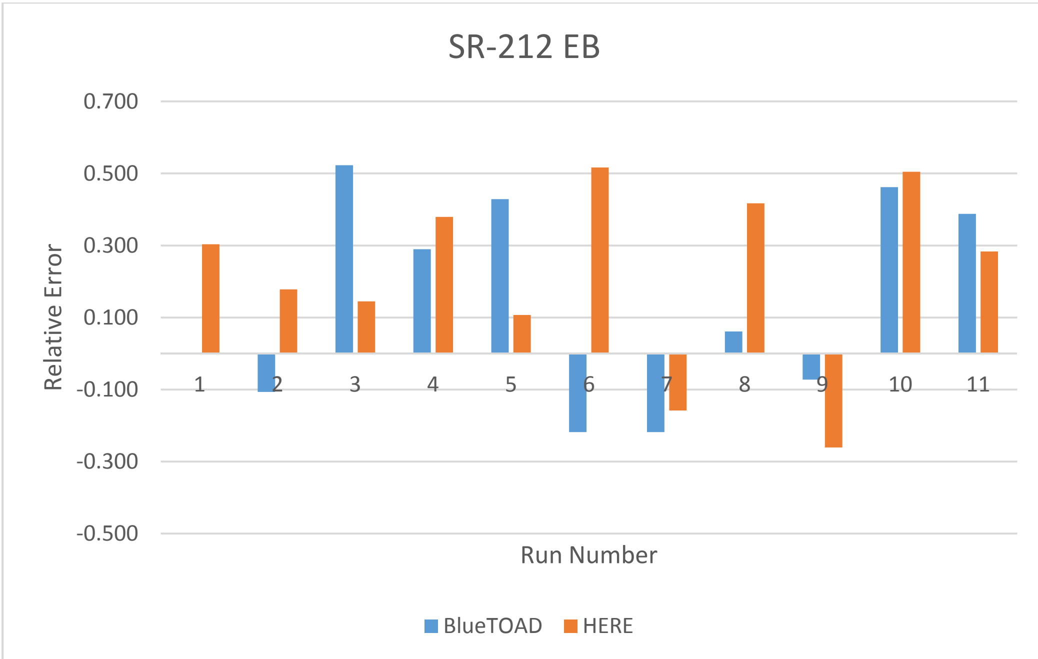
Travel time data at this site were available through BlueTOAD and HERE traffic. The statistical values for comparing the different travel time measurement methods with the benchmark values are presented in Table 4.19.

The percent error is also depicted in Figure 4.7. As shown, it varies significantly in both directions. Both BlueTOAD and HERE tend to over predict travel times. The EB direction travel times also have significant variability. The results of the statistical analysis of this site using the confidence interval method and the target accuracy method are presented below.

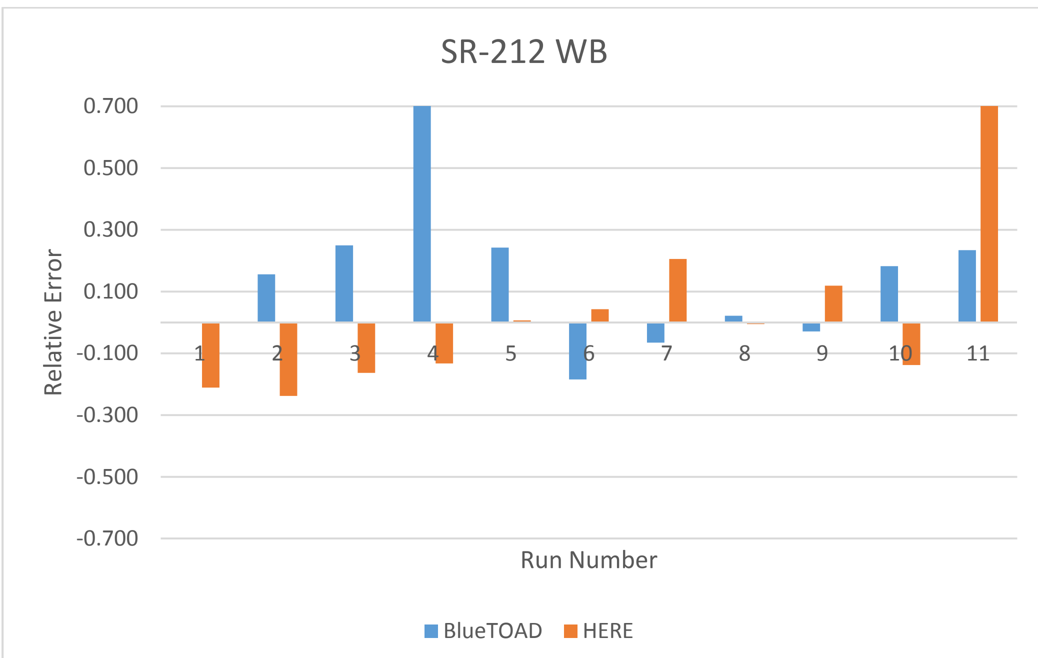
Table 4.19. Statistical measures for the comparison of travel time estimates with benchmark values obtained for the SR-212 EB/WB study section

Run #	Percent Error		Error Bias / Absolute Error			
	BlueTOAD	HERE	BlueTOAD		HERE	
SR-212 EB						
1	*	0.3035	*	*	3.00	3.00
2	-0.1067	0.1779	-1.35	1.35	2.25	2.25
3	0.5228	0.1448	3.88	3.88	1.07	1.07
4	0.2895	0.3794	2.52	2.52	3.30	3.30
5	0.4288	0.1072	3.36	3.36	0.84	0.84
6	-0.2180	0.5165	-2.17	2.17	5.15	5.15
7	-0.2180	-0.1581	-2.17	2.17	-1.58	1.58
8	0.0612	0.4170	0.54	0.54	3.65	3.65
9	-0.0723	-0.2607	-0.70	0.70	-2.53	2.53
10	0.4618	0.5047	3.06	3.06	3.35	3.35
11	0.3878	0.2832	2.88	2.88	2.10	2.10
SR-212 WB						
1	*	-0.2112	*	*	-2.94	2.94
2	0.1559	-0.2378	2.03	2.03	-3.09	3.09
3	0.2497	-0.1634	2.83	2.83	-1.85	1.85
4	0.7072	-0.1327	5.62	5.62	-1.06	1.06
5	0.2425	0.0066	2.62	2.62	0.07	0.07
6	-0.1846	0.0431	-1.81	1.81	0.42	0.42
7	-0.0654	0.2058	-0.58	0.58	1.81	1.81
8	0.0217	-0.0051	0.20	0.20	-0.05	0.05
9	-0.0289	0.1192	-0.28	0.28	1.17	1.17
10	0.1822	-0.1379	1.52	1.52	-1.15	1.15
11	0.2340	1.2420	1.95	1.95	10.33	10.33

* Not enough matches through BlueTOAD



(a)



(b)

Figure 4.7. Travel time percent error statistic along SR-212, (a) EB, and (b) WB directions (Jacksonville, FL).

CONFIDENCE INTERVAL METHOD – MAXIMUM RELATIVE ERROR

The confidence intervals considering a 20% desired value for the MRE are shown in Table 4.20.

Table 4.20. Confidence interval method results for SR-212 EB/WB site

Run #	Start Time	Benchmark value (min)	$\bar{X}-\frac{e_{max}\bar{X}}{2+e_{max}}$	$\bar{X}+\frac{e_{max}\bar{X}}{2+e_{max}}$	STEWARD	HERE
SR-212 EB						
1	12/5/2013 17:02	9.87	8.97	10.77	*	X
2	12/5/2013 17:33	12.63	11.48	13.78	X	X
3	12/5/2013 18:04	7.42	6.75	8.09	X	X
4	12/5/2013 18:30	8.7	7.91	9.49	X	X
5	12/5/2013 18:50	7.83	7.12	8.54	X	X
6	12/6/2013 7:38	9.97	9.06	10.88	X	X
7	12/6/2013 8:05	9.97	9.06	10.88	X	X
8	12/6/2013 8:31	8.75	7.95	9.55	√	X
9	12/6/2013 8:56	9.72	8.84	10.60	√	X
10	12/6/2013 9:18	6.63	6.03	7.23	X	X
11	12/6/2013 9:39	7.43	6.75	8.11	X	X
SR-212 WB						
1	12/5/2013 17:14	13.92	12.65	15.19	*	X
2	12/5/2013 17:49	13.00	11.82	14.18	X	X
3	12/5/2013 18:14	11.33	10.30	12.36	X	X
4	12/5/2013 18:40	7.95	7.23	8.67	X	X
5	12/5/2013 19:01	10.80	9.82	11.78	X	√
6	12/6/2013 7:26	9.82	8.93	10.71	X	√
7	12/6/2013 7:52	8.80	8.00	9.60	√	X
8	12/6/2013 8:19	9.02	8.20	9.84	√	√
9	12/6/2013 8:43	9.80	8.91	10.69	√	X
10	12/6/2013 9:07	8.37	7.61	9.13	X	X
11	12/6/2013 9:26	8.32	7.56	9.08	X	X

Note:
√: accurate
X: inaccurate
* Not enough matches through BlueTOAD

Based on this analysis it appears that neither BlueTOAD nor HERE predict accurately travel times along this arterial street for the majority of the cases.

ACCURACY TARGET METHOD – ABSOLUTE PERCENT ERROR

The accuracy target method assumes an acceptable travel time error less than 20% and evaluates whether the absolute percent error falls within the acceptable range. The results of this analysis are presented in Table 4.21.

Table 4.21. Accuracy target method results for SR-212 EB/WB site

Run #	Benchmark value (min)	Absolute Percent Error		Acceptable travel time relative error less than 20%	
		BlueTOAD	HERE	BlueTOAD	HERE
SR-212 EB					
1	9.87	*	0.303	*	X
2	12.63	0.107	0.178	√	√
3	7.42	0.523	0.145	X	√
4	8.70	0.290	0.379	X	X
5	7.83	0.429	0.107	X	√
6	9.97	0.218	0.517	X	X
7	9.97	0.218	0.158	X	√
8	8.75	0.061	0.417	√	X
9	9.72	0.072	0.261	√	X
10	6.63	0.462	0.505	X	X
11	7.43	0.388	0.283	X	X
SR-212 WB					
1	13.92	*	0.211	*	X
2	13.00	0.156	0.238	√	X
3	11.33	0.250	0.163	X	√
4	7.95	0.707	0.133	X	√
5	10.80	0.243	0.007	X	√
6	9.82	0.185	0.043	√	√
7	8.80	0.065	0.206	√	X
8	9.02	0.022	0.005	√	√
9	9.80	0.029	0.119	√	√
10	8.37	0.182	0.138	√	√
11	8.32	0.234	1.242	X	X

Note:
√: accurate
X: inaccurate
* Not enough matches through BlueTOAD

This analysis method shows that neither BlueTOAD nor HERE is accurate for a significant portion of the runs, especially for the EB direction.

4.2. Analysis for All Sites and Traffic Conditions

The statistical analysis results for each site show that the accuracy of the method depends on the traffic conditions (congested vs. uncongested) and also on the type of the facility (freeway vs. arterial). The two statistical analysis methods provided consistent results; however, it can be concluded that the confidence interval method yields more conservative results than the accuracy target method.

Next, a hypothesis test based on the binomial distribution is applied to evaluate the accuracy of each measurement method. We assume an acceptable probability of correct classification to be 90% (p = 0.9). In this case, a hypothesis test can be constructed to test whether the probability of correct classification (p) exceeds some critical value that corresponds to the critical quality threshold desired (c) for each individual travel time measurement method. We assume that the critical quality threshold desired is 90% (c = 0.9). Then, the null and the alternative hypotheses are:

$H_o : p \leq c$

$H_a : p > c$

This is a one-tail test so the null hypothesis is rejected when the test statistic is less than the significance level (e.g., $\alpha = 0.05$ for a 95% confidence level). Table 4.22 summarizes the number of accurate runs performed, as a function of the measurement method using both statistical analysis methods. The table also includes the calculated value of the binomial distribution (P) for each case. For example, for the comparison with the INRIX travel times considering the target accuracy method, the number of trials is 99 whereas the number of successes is 81 (corresponds to approximately 82%). Assuming a 0.9 critical quality threshold, the one-tail test becomes:

$H_o : p \leq 0.9$

$H_a : p > 0.9$

$P(K \geq 81 | n = 99, p = 0.9) = 0.009$

Table 4.22. Summary of accurate runs for all sites

	STEWARD	INRIX	BlueTOAD	HERE
Confidence Interval Method				
Total Accurate Runs	46	8	13	46
Total Runs	89	12	72	99
P-value	**0.000**	**0.021**	**0.000**	**0.000**
Accuracy Target Method				
Total Accurate Runs	65	10	42	81
Total Runs	89	12	72	99
P-value	**0.000**	**0.341**	**0.000**	**0.009**

Therefore, the null hypothesis that p=0.9 would fail to be rejected, and it cannot be concluded that HERE travel times meet the desired percent correct classification (p). It can be concluded that in all cases the null hypothesis cannot be rejected and that all travel time measurement methods do not meet the desired percent correct classification.

4.3. Analysis By Facility Type

A similar analysis was performed by facility type (freeway and arterial). Table 4.23 summarizes the number of accurate runs performed as a function of the measurement method and the facility type, using both statistical analysis methods. The table also includes the calculated value of the binomial distribution (P) for each case. Based on this table it can be concluded that none of the four measurement methods provided statistically acceptable travel time accuracy However, the HERE traffic data provided better results for the freeway sites compared to the other three measurement methods.

Table 4.23. Summary of accurate runs by facility type

	STEWARD	INRIX	BlueTOAD	HERE
Confidence Interval Method				
Freeways				
Accurate Freeway Runs	46	8	7	43
Total Freeway Runs	89	12	40	77
P-value	**0.00**	**0.02**	**0.00**	**0.00**
Arterials				
Accurate Arterial Runs	0	0	6	3
Total Arterial Runs	0	0	32	22
P=value	**-**	**-**	**0.00**	**0.00**
Accuracy Target Method				
Freeways				
Accurate Freeway Runs	65	10	28	70
Total Freeway Runs	89	12	40	77
P-value	**0.00**	**0.34**	**0.00**	**0.66**
Arterials				
Accurate Arterial Runs	0	0	14	11
Total Arterial Runs	0	0	32	22
P=value	**-**	**-**	**0.00**	**0.00**

4.4. Analysis By Traffic Condition

A similar analysis was conducted to investigate the measurement methods accuracy depending on the congestion level for each facility type. Two traffic conditions were examined: undersaturated and oversaturated. Oversaturated conditions are defined as those existing when average speeds across the study sites dropped significantly (at least 10 mi/h) for at least 10 minutes. Each run performed was classified as either oversaturated or undersaturated based on the average speeds along the study site at that particular time. The results of the statistical analysis are summarized in Table 4.24 and Table 4.25.

Table 4.24. Summary of accurate runs by traffic condition for freeway sites

	STEWARD	INRIX	BlueTOAD	HERE
Confidence Interval Method				
Oversaturated conditions				
Accurate Oversaturated Runs	22	0	2	30
Total Oversaturated Runs	57	3	30	54
P-value	**0.000**	**0.001**	**0.000**	**0.000**
Undersaturated conditions				
Accurate Undersaturated Runs	21	8	5	16
Total Undersaturated Runs	32	9	10	23
P-value	**0.000**	**0.613**	**0.002**	**0.006**
Accuracy Target Method				
Oversaturated conditions				
Accurate Oversaturated Runs	34	2	18	50
Total Oversaturated Runs	57	3	30	54
P-value	**0.000**	**0.271**	**0.000**	**0.802**
Undersaturated conditions				
Accurate Undersaturated Runs	32	9	10	20
Total Undersaturated Runs	32	9	10	23
P-value	**1.000**	**1.000**	**1.000**	**0.408**

As shown in Table 4.24, the accuracy target method provides more favorable results. For oversaturated conditions, the HERE traffic data perform better than the remaining methods, although the null hypothesis that p=0.9 failed to be rejected. For undersaturated conditions it seems that all measurement methods are sufficient, except the HERE traffic travel times. It should be noted that the available sample size from INRIX is small, therefore, additional measurements are required to confirm this conclusion.

Table 4.25. Summary of accurate runs by traffic condition for arterial sites

	BlueTOAD	HERE
Confidence Interval Method		
Oversaturated conditions		
Accurate Oversaturated Runs	0	-
Total Oversaturated Runs	3	-
P-value	**0.001**	**-**
Undersaturated conditions		
Accurate Oversaturated Runs	6	3
Total Undersaturated Runs	29	22
P-value	**0.000**	**0.000**
Accuracy Target Method		
Oversaturated conditions		
Accurate Oversaturated Runs	1	-
Total Oversaturated Runs	3	-
P-value	**0.028**	**-**
Undersaturated conditions		
Accurate Undersaturated Runs	13	11
Total Undersaturated Runs	29	22
P-value	**0.000**	**0.000**

Based on the analysis results presented in Table 4.25 it can be concluded that neither one of the two methods available along the arterial segments (BlueTOAD and HERE traffic) provided accurate estimates of travel times at either congested or uncongested traffic conditions. This finding is consistent with the literature, which suggests that travel time estimates are less accurate along arterial segments. It should be noted though, that the sample size, especially during congested conditions, is small.

5. CONCLUSIONS AND RECOMMENDATIONS

This research collected field travel time data with the use of an instrumented vehicle at various freeway and arterial locations in Florida, and compared the field-measured travel times with those obtained from four different sources, namely STEWARD, INRIX, BlueTOAD, and HERE traffic. A statistical analysis was performed to evaluate and compare these measurement methods to the field-measured (benchmark) travel times.

The results of the statistical comparison suggest that the HERE traffic data provide better freeway travel time estimates compared to the remaining methods. HERE traffic is more accurate for oversaturated conditions. On the other hand, when analyzing uncongested freeway segments, STEWARD, INRIX and BlueTOAD perform better than HERE traffic. Lastly, analysis at the arterial sites suggests that neither method is accurate, although the sample size especially during the oversaturated runs is relatively small.

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APPENDIX A

This appendix summarizes the literature review findings related to past comparisons of travel time measurement methods as well as statistical analysis methods used for the travel time comparison.

A.1. Comparison of Travel Time Measurement Methods

Travel time data obtained through Bluetooth or INRIX have received considerable attention, and several researchers (and practitioners) have compared these with probe vehicle data or tag readers.

KMJ Consulting (KMJ, 2010) conducted an evaluation of BlueTOAD equipment and its ability to collect and report travel times. The field test was conducted in Pennsylvania along I-76 at locations equipped with EZPass tag readers. The evaluation was conducted by comparing data gathered by BlueTOAD to data gathered by EZPass. The data obtained from BlueTOAD were 15-minute travel time and speed data, as well as matched pairs, collected by its devices during the time period from July 23, 2009 to August 15, 2009. Traffic volume data were obtained from PennDOT's Remote Traffic Microwave Sensor (RTMS) stations. Data were collected during both congested and uncongested conditions. 15-minute travel times and speeds as well as number of matched pairs were provided by EZPass. The study found that the travel times produced by BlueTOAD are comparable to EZPass tag readers. The average difference in travel times was less than 21 seconds for the westbound and 60 seconds for the eastbound approach. The authors indicated that some of the difference in travel times can be attributed to differences in physical placements of the devices. The BlueTOAD data resulted in matches of about four percent of the daily traffic stream, while the matches of the EZPass tag readers range from 10 to 37 percent of the daily traffic. The authors indicate that the cost of the BlueTOAD equipment is approximately one third of the cost of EZPass, while its installation appears to be relatively straightforward. The study found greater variability between travel times reported during midnight to 6:00 AM possibly as a result of the few data points collected during the early morning hours. Although travel time data were obtained during the peak hour, accuracy during congested conditions is not discussed.

Schneider et al. (2010) conducted a comparison study between floating car and Bluetooth travel times along freeways and arterials in Ohio and concluded that Bluetooth can replicate floating car data, while providing a significantly higher number of data points than the floating car method. The majority of the data obtained in this study correspond to undersaturated conditions. The study does not discuss the travel time accuracy during oversaturated vs. undersaturated conditions. The authors also compared travel times obtained from Oregon DOT (ODOT) with floating car and Bluetooth travel time data under both free-flowing and congested conditions. This comparison showed that travel time differences across the measurement methods increases during congested conditions.

Quayle et al. (2010) conducted a pilot study on the use of Bluetooth devices to measure arterial travel time, average running speed, and origin-destination patterns in Portland, Oregon. The researchers studied a 2.5-mile signalized arterial and compared Bluetooth matching data with GPS floating car studies. They found that the larger data set from the Bluetooth data are more effective in capturing performance characteristics of the arterial. Floating car measurements showed higher travel times than Bluetooth measurements towards the end of the congestion period.

The University of Maryland (Young, 2010) evaluates monthly and annually the INRIX data for two miles of arterials in Virginia. The researchers identified the following challenges regarding probe data collection on arterials:

- A higher sampling is required for arterials to achieve the same level of data quality as freeways. This is primarily due to the variability because of signalized intersections, increased turning opportunities, and mid-block access points.
- Traffic signals tend to separate traffic into two flows – a faster flow for vehicles that progress, and a slower flow for vehicles stopped on red and forced to wait through the next cycle.

- Arterial volumes are generally half that of freeways for the same number of lanes. Due to the variance noted previously, larger sample sizes are required to achieve the same level of accuracy.
- Congested flow on arterials is difficult to distinguish from free-flow. Congested flow on freeways can be identified based on a speed threshold, however, varying arterial travel times may occur depending on the signal timing plan in effect.
- Arterial segments are more complex to define than freeway segments due to the varying number and spacing of signals and the impact they have on free-flow travel.

A white paper prepared by Cambridge Systematics (2012) summarized past research on the comparison of travel time estimates technology. The technologies evaluated were: toll tag, Bluetooth, cellular phone, crowd-sourcing, private data providers (INRIX, Navteq, TomTom, American Transportation Research Institute), video image detection, radar, in-pavement loops, and magnetic detectors. According to this study, the advantages of the Bluetooth technology are that (i) the technology is new but rapidly maturing and it is simple to install and maintain; (ii) the percentage of vehicles having Bluetooth devices (smartphones, in vehicle connections, iPads, etc.) will grow rapidly; and (iii) the cost per unit is relatively low. The disadvantages are that currently the estimate of vehicles having Bluetooth devices is in the range of 5% and that Bluetooth readers cannot directly provide volume data.

Regarding private data providers such as INRIX, the advantages according to Cambridge Systematics (2012) are that there is no installation or maintenance cost for transportation agencies, that the data providers have great incentive to provide accurate, quality data at a low cost. Some disadvantages are that data accuracy tests have found that speeds were fairly accurate on freeways but less so on arterials. The method of speed calculation, underlying data and mix of real time and historic data that is used to make the speed estimates is not known. The data providers however, cannot provide volume data. Regarding spot measure technologies, such as radar, the study reports some advantages such as that these have been found to provide accurate speed data but it is not accurate for volumes. Radar units are also easy to maintain. Disadvantages of radars are that they generally require preventative maintenance and occasional repair.

Jia et al. (2012) compared freeway travel time estimates obtained through INRIX, BlueTOAD technologies with "ground truth" travel times collected through the license plate method. The study was conducted in three segments along I-91 in Western Massachusetts. The authors do not specify the congestion levels during the data collection period. Based on their analysis the authors concluded that both INRIX and BlueTOAD provided accurate travel time estimates since their Mean Average Percent Error (MAPE) were consistently less than six percent. They further found that the INRIX travel times were a little closer to the "ground truth" values than the BlueTOAD measurements by approximately 1 to 1.5 percent.

Chase et al. (2012b) compared 5-min speeds collected from microwave radar and acoustic sensors with speeds obtained through INRIX at five freeway sections. Their data collection effort also included GPS data through floating cars. The authors calculated the mean speed difference as the sum of speed differences divided by the total number of data obtained during the study period. They also calculated the standard deviation of the speed differences and the absolute speed difference. The comparison results showed that the speeds obtained through the floating cars GPS were close to the INRIX speeds. Their analysis also revealed inconsistencies in the reported beginning of congestion and recovery periods between the INRIX data and the Traffic.com data, with a small time lag of congested speeds in the INRIX data.

In general, there is good agreement between the various travel time measurement methods such as INRIX and Bluetooth, vs. an alternative "ground truth" method such as the floating car or tag readers. This appears to be the case for both freeways and arterials. However, past research has demonstrated that the accuracy of the travel time predictions is not the same for undersaturated and oversaturated conditions. Also, greater variability in travel times has been observed during oversaturated conditions. In summary, although various travel time measurement methods have been evaluated in the past, limited research has been conducted to evaluate accuracy levels as well as travel time differences in terms of congestion level.

A.2. Statistical Analysis for Travel Time Comparison

This section presents typical statistical methods that have been proposed in the literature for comparing travel time measurements with benchmark values (i.e., "ground truth" values). Turner et al. (2011) developed a set of guidelines for evaluating the accuracy of travel time and speed data. In their report, the authors identify methods to establish benchmark values from various travel time and speed data sources, and determine their accuracy level. They also recommend establishing acceptable accuracy targets, which can be accomplished in several ways. For instance, the analyst may decide to consider an absolute acceptable average speed error of, for example, 10 mph from the benchmark speed (this error can vary by speed level, such that it reduces when average speed reduces). Another possibility would be to use a relative measure, for instance the average absolute percent error of the benchmark travel time. For example, the analyst may establish an acceptable travel time error level of less than 15%. Concerning route travel time accuracy measures, Turner et al. (2011) recommend the use of the following:

- Average absolute percent error (%)
- Average absolute error per unit length (units of seconds per mile)
- Average absolute error (minutes)

These measures are briefly described below.

Mean Absolute Percent Error (MAPE):

The average absolute percent error (also called mean absolute percent error or MAPE) is a measure of the magnitude of the error and not of its direction (consistently positive of negative). This measure has also been suggested by Jia et al. (2013) for comparing Bluetooth and INRIX travel times. This measure is defined as:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|x_i - \mu_i|}{\mu_i} \qquad \text{(Eq. A. 1)}$$

Where:

μ_i = benchmark value for the ith comparison (minutes or seconds)

x_i = the ith travel time measurement method estimate (minutes or seconds)

n = number of estimate-to-benchmark comparisons (i.e., number of runs)

Average Absolute Error per Unit Length

The average absolute error per unit length is a measure to normalize the error by route length, which allows for comparisons across different routes. This measure is estimated as follows:

$$Average\ Absolute\ Error\ per\ Unit\ Length = \frac{1}{n}\sum_{i=1}^{n}\frac{|x_i - \mu_i|}{l_i} \qquad \text{(Eq. A. 2)}$$

Where:

l_i = route length for i^{th} travel time estimate,

all other variables as previously defined.

Average Absolute Error

The average absolute error is identical to the previous one measure except that it is not normalized by route length and thus it should not be used to aggregate results from different routes. It is estimated as follows:

$$Average\ Absolute\ Error = \frac{1}{n}\sum_{i=1}^{n}|x_i - \mu_i| \qquad \text{(Eq. A. 3)}$$

Where:

n = number of estimate-to-benchmark comparisons for the same route (i.e., number of runs)

all variables are defined previously.

Building on the guidelines developed by Turner et al. (2011), Richardson and Smith (2012) proposed an approach to quantify the distribution of errors associated with travel times and construct statistical hypothesis tests. Irrespective of whether the benchmark is treated as a fixed value or a random variable, two commonly used distance-based statistics can be used: the error bias and the absolute error. The authors also suggest the relative error in travel time as a measure of comparing different travel time measurements towards a benchmark, when link lengths vary. Finally, the authors recommend the use of the maximum relative error (MRE) for comparing benchmark values to travel time measurements. These four measures are described below.

Error Bias and Absolute Error:

The error bias reflects the magnitude and the direction of the error: The absolute error only accounts for the magnitude of the error. Both measures are provided in Eq. A. 4 and Eq. A. 5.

$$E_i = x_i - \mu_i \qquad \text{(Eq. A. 4)}$$

$$|E_i| = |x_i - \mu_i| \qquad \text{(Eq. A. 5)}$$

Where:

E_i = error bias,

$|E_i|$ = absolute error bias,

all other variables as previously defined.

Relative error:

The benefits in using the relative error are that this measure is not sensitive to the speed and that it corresponds to the quantity that appeals to most users, i.e., travel time accuracy. It is estimated as follows:

$$E_i = \frac{x_i - \mu_i}{\mu_i} \qquad \text{(Eq. A. 6)}$$

Where all variables as previously defined.

Maximum relative error (MRE)

The MRE occurs when the travel time estimate falls at the upper end of the confidence interval range, and the population mean (which is unknown) falls at the lower end of the confidence interval range. The MRE is estimated as follows:

$$e_{\max} = \frac{CI_{\max} - CI_{\min}}{CI_{\min}} \qquad \text{(Eq. A. 7)}$$

where CI_{max} and CI_{min} are the maximum and minimum of the confidence interval respectively.

According to Richardson and Smith (2012), a reasonable expectation for the maximum relative error – MRE based on field data is approximately 20%. This suggests that the travel time measurement estimate should be no more than 20% from the population mean, in order to be classified as accurate. This is described in Eq. A. 8.

$$\overline{X} - \frac{e_{\max}\overline{X}}{2+e_{\max}} \leq T \leq \overline{X} + \frac{e_{\max}\overline{X}}{2+e_{\max}} \qquad \text{(Eq. A. 8)}$$

The authors propose to consider a known MRE (e_{max}) value, approximately 20% which suggests that the travel time estimate is classified as accurate if it is no more than 20% in error from the population mean in 95% of the cases.

In summary, a number of statistics have been used in the literature for evaluating the differences between travel time measurements and benchmark values, such as the mean absolute percent error (MAPE), the average absolute error per unit length, the average absolute error, the error bias and absolute error, the relative error and the maximum relative error. Literature also suggests treating the benchmark values as random, and to consider a confidence interval, instead of its average value.