Evaluation of Freeway Traffic Data Acquisition: Technology, Quality, and Cost

or

A Comparative Analysis of Alternative Travel Time Data Sources on I-80 Freeway

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Final Report

by

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16. Abstract

This study evaluates the accuracy of the travel time data that are estimated by Dual loop, Waze, HERE, and INRIX against Bluetooth data on multiple segments of the I-80 freeway between Davis and Sacramento, CA. We conduct a simulation-based critical sampling rate analysis, which suggests that the Bluetooth travel time data qualifies for approximating the ground truth. Further, we apply evaluation methods and derived indices, Travel Time Error Bias (TEB), Average Absolute Travel Time Error (ATE), and Standard Error of Mean (SEM), to compare the travel time data reported by Waze, HERE, and INRIX with the benchmark (Bluetooth) data on the selected testing segments on I-80. The results show that the INRIX and HERE data closely match the Bluetooth data, both in the trends and values of reported travel time. Moreover, all three vendors' data accuracy deteriorates when the traffic congestion intensifies.

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EXECUTIVE SUMMARY

Travel time is of great interest to both Caltrans and the traveling public, and is a fundamental input/output to any intelligent transportation system. Traditionally, travel times on freeways were primarily obtained from spot speeds measured by or estimated from loop detectors. The advancement of technology and the emergence of commercial data vendors, however, offer new options for acquiring travel time data. For example, Bluetooth based detectors can measure freeway travel times directly by matching the MAC addresses of vehicles that carry Bluetooh devices at different sensor locations. On the other hand, private companies, such as INRIX, Waze, and HERE, also collect and commercialize integrated travel time data from various data sources including but not limited to vehicles, smartphones, and other GPS devices.

In this project, we investiage the quality of travel time data from various source: Loop detectors (Caltrans), Bluetooth (Caltrans) and private vendors (INRIX, HERE, and Waze). Apart from loops. We set the Bluetooth travel time data as the benckmark to compare the travel time data reported by Waze, HERE, and INRIX on the selected testing segments on I-80.

Different from other data sources, the Bluetooth detector measures the passing vehicles travel time by matching the same MAC address from two locations on the road, which makes the Bluetooth data sources more reliable. We therefore used the travel times provided by the Bluetooth sensors as the ground truth, and compared them with the travel times from other sources to evaluate the quality of the travel time data from these other sources. A comparison between the Bluetooth travel times and the estimated travel times from dual loop speeds (the average speeds from two dual loops are used to derive the travel times between the two loops) show great discranpacy and as a result, the quality of the travel times estimated from the dual loop speeds were considered poor and not included in further analysis.

The following three indices, Travel Time Error Bias (TEB), Average Absolute Travel Time Error (ATE), and Standard Error of Mean (SEM) were used to compare the quality of the travel times data from different vendors. The TEB calculates the error between the objective data and the Bluetooth data ("ground truth") for each time point at a specific location, and it can have positive or negative values. ATE applies the same procedure as the TEB, except that ATE takes the absolute value of TEB. The SEM adds up the number of 5-min time intervals that stays within the SEM band for the given time period. This method will calculate a percentage of the time points that fall within the SEM band. The analyses are performed under four comparison scenarios including overall comparison, comparison by days of the week, comparison by weeks, and comparison by segments. Furthermore, three periods, all-day, morning peak, and afternoon peak, were analyzed to investigate the performance differences among different data sources.

The comparison results show that among all the data sources analyzed, INRIX and HERE data closely match the Bluetooth data, both in travel time trend and values. Waze produced similar travel time trends but tends to systematically underestimate travel times compared with other vendors. The comparison of segment travel times show that they vary signigicantly from segment to segment. It is also noted that all the three vendors' comparison error measures increased under congested conditions.

1. Introduction

The direct measurement or estimation of travel time is an essential element of intelligent transportation systems. Traditionally, travel time on freeways was primarily derived from loop detectors, a fixed point sensor that can directly measure traffic flow and occupancy, and with dual loops can measure vehicle speed as well. Travel time (speed) derived from flow and occupancy of a single loop is known to be dependent on the vehicle length distribution. Even with dual loops, literature shows that it is not reliable to assume that the point speeds captured by dual loops are the same as the speeds of a segment (Soriguera and Robust´e, 2011). Despite this lack of reliability, loops are often used in practice to provide travel times because they are the most widely available sensors on freeways until recent days. With the application of some emergent technologies in travel time collection, more precise estimation methods, or direct collection of travel time become a reality.

Various Automatic Vehicle Identification (AVI) technologies enable the direct measurement of travel time. The travel time of a vehicle is simply the absolute difference of a pair of time instants when passing by the upstream and downstream AVI sensors. AVI traditionally relied on video-based plate recognition technology (Ozbay and Ercelebi, 2005). Recently, with the rapid growth of smartphones and hands-free devices, Bluetooth based AVI technology has become a viable tool for acquiring travel time measurements for freeway segments (Haghani et al., 2010).

Furthermore, some commercial data vendors, such as Waze, HERE, and INRIX, collect and commercialize integrate travel time data from multiple data sources, including GPS-enabled smartphones, or other GPS devices (Haghani et al., 2009). However, since data collection and integration methods differ among data sources, it is expected that the travel times obtained from different sources will show variability and in some cases inconsistency

Therefore, this report investigates the quality of travel time data on nine study segments alone I-80 corridor from various sources: Loop detectors (provided by Caltrans), Bluetooth (provided by Caltrans) and private data vendors (INRIX, HERE, and Waze). We take the Bluetooth travel time data as the benchmark and apply three indices, Travel Time Error Bias (TEB), Average Absolute Travel Time Error (ATE), and Standard Error of Mean (SEM) in a variety of proposed comparison scenarios. The comparison compares the travel time data reported by Waze, HERE, and INRIX with the benchmark (Bluetooth data) on the selected testing segments on I-80. Finally, we summarize the result of the travel time data comparison and provide insights based upon it.

2. Literature Review

Many studies have been carried out to compare the quality of the travel time or traffic speed data from a number of sources that include floating cars, Bluetooth sensors, loop detectors, TOMTOM, HERE, INRIX, and TRANSMIT readers. This section comprehensively reviewed the common practice of data evaluation and comparison methods, and the table (Table 1 in Appendix B) shows a summary of these literatures. The goal of these studies was to find the best data sources that can represent the population's traffic speed or travel time. Since it is hard to acquire the raw data from private data vendors, these studies generally trusted the estimated travel time from Bluetooth, loop detector, or floating car as ground truth.

The evaluation methods mainly include analyzing the biases and absolute errors between the studied measurements to that of the ground truth (or the approximating ground truth). These two methods help the researcher understand the distribution of the overall measurements and the true error magnitude of the study data source. Some studies included an SEM band test to investigate the satisfied time intervals within the study period to further describe the good of fitting between the study data source to the ground truth (or the approximating ground truth). The comparison scenarios include a whole day comparison, or either morning peak hours or afternoon peak hours comparison. However, the experiment setting is mostly depending on the availability of the data sources. Therefore, the next chapter starts with the introduction of study site selection and data sources.

3. Study Sites and Data Sources

3.1 Study Area

Two highway sites were selected in this study: a section of the eastbound of I-80 and a section of the westbound of I-80. The primary reasons for choosing these two sites are two-fold: both sites have Bluetooth and dual loops installed, and both sites have variable levels of traffic conditions with typical geometric configurations. The eastbound I-80 study section is 9.17 miles long. It starts from Richards Boulevard in Davis to Enterprise Boulevard in West Sacramento with three Bluetooth measuring segments (The associated information and locations are listed in the table (Table 2 in Appendix B) and mapped on the figure (Figure 1 in Appendix A) respectively. The westbound I-80 study section is 10.4 miles long. It starts from Pinell Street in Sacramento to Enterprise Boulevard in West Sacramento with six Bluetooth measuring segments(The associated information and locations are listed in the table (Table 3 in Appendix B) and mapped on the figure (Figure 2 in Appendix A) respectively. Accordingly, there are nine Bluetooth measuring segments in total, and the rest data sources also collect the travel time according to these segments for comparability.

3.2 Data Sources

Bluetooth

It is noted that the wireless Media Access Control (MAC) address is unique for each Bluetooth data collection device (Ozbay and Ercelebi, 2005), so that the travel time are estimated by matching the MAC addresses from an upstream and a downstream Bluetooth readers. Our Bluetooth data were collected and provided by Caltrans. The following variables are provided in the raw Bluetooth data file:

- Detection date
- Detection time
- IP address of the detector

- Location name of the detector
- Processed device ID

For the same Bluetooth device, the ID will always be the same, so it is used to distinguish different trips. One single data file contains all the detections within one day on the basis of detection time.

Bcause the majority of vehicles are not stopping between readers and there's a fairly consistent flow of traffic, we applied moving average filtering technique for each 25-min interval recursively to reduce the number of outliers.

Dual Loop Data

Caltrans also provided the dual loop data. The data contains dual loop readings (speed, occupancy and count) for each controller. The update time is every 30 seconds. One controller usually controls all dual loop detectors within one intersection.

The travel time was estimated by using the segment average speed from fixed-point dual loop speed, where the segment average speed was calculated by averaging all the dual loop speed readings on the segment.

Waze

All Waze travel time data are achieved through their API. The update time is random, but always within 1-3 minutes, and we recorded them every 1 min to avoid any updates missing.

The Waze data is aggregated into a 5-min interval average by calculating the average travel time for each segment.

HERE

HERE provided the aggregated speed and travel time data for each study segments in 1-min interval, and confidence information for the quality of the data. The confidence factor in the data is a numerical indication of whether the data feed is based on real-time data or historical data. When real-time data is unavailable, historical data is provided. 98.48% of the HERE data in our study period are real-time reords.

For the HERE data, we aggregated them into 5-min interval travel time data by calculating the average for each segment.

INRIX

INRIX provided the aggregated speed and travel time data according to the study segments in 5-min interval. Hence, we just directly use the data for analysis without any processing.

3.3 Aggregated dataset

This study collects five different data sources as listed above for direct measurement or estimation of freeway segment travel times. The data collection period is from 10/14/2018 to 11/16/2018, and only the data collected by Bluetooth has raw data (the individual vehicle travel time from two detection places). Due to our hardware issues, no data was collected for 11/14/2018. Therefore, to make sure the fairness of comparison, the other data sources(Bluetooth, dual loop, HERE, and INRIX) on this day were discarded. Finally, all data from these sources are aggregated to obtain a 5-min interval mean travel times for comparability. The main reason for choosing 5 minutes as the time interval is to have enough Bluetooth samples in each time interval for analysis.

The final dataset consists of time, date, week, day, location, Bluetooth travel time, Bluetooth count, Waze travel time, HERE travel time, INRIX travel time. This dataset only contains travel time data from 4a.m. to 11p.m. For the week and day column, since the beginning date of the data collection process is 10/14, which is a Sunday, a Sunday whose indices for week and day are respectively 1 and 7. Similarly, the week is 2 and the day is 1 for 10/15. The purpose of these two columns is for day-by-day travel time comparison. The location column matches the study segments. It consists of the start Bluetooth detector name and the end Bluetooth detector name. For example, location for Richards Blvd-Chiles Rd segment is Richards Blvd to Chiles Rd. All the travel time data are in seconds, which is the result of an average of 5 minutes of data.

3.4 Data Quality Evaluation Methods

Due to the subtle differences in data collection and processing methods, and the sources of data, it is expected that the travel times obtained from the four sources will show variability and, in some cases inconsistency. Because Bluetooth measures the passing vehicles travel time by matching the same MAC address from two locations on the road, which has a different collection method than other data sources, we use the Bluetooth data in our data sets as the benchmark (resembling the ground truth). The problem is therefore defined as finding the goodness of fit between an objective data source and the Bluetooth data. To quantify the goodness of fit, this study applies three evaluation methods and derived indices to find out the better-performed data sources through three comparison groups of HERE vs. Bluetooth, Waze vs. Bluetooth, and INRIX vs. Bluetooth.

Standard Error of Mean (SEM) Band Satisfaction

The SEM is commonly used to represent the uncertainty associated with a given measurement because it is a straightforward calculation, which is sensitive to both the variability and volume of data. The SEM is defined as the standard deviation of raw Bluetooth data over the square root of the number of data points *n* in the 5-minute time interval:

$$\sigma_{sem} = \frac{\sigma_t}{\sqrt{n}} = \sqrt{\frac{\sum_{t=1}^{n}(b_{i,t} - \bar{b_t})^2}{n}} / \sqrt{n} \tag{1}$$

where, σ_t, $b_{i,t}$ and $_t$ is the standard deviation, the ith and the mean of the raw Bluetooth travel times in the time interval t respectively.

We chose 1.96 times SEM band to test if the aggregated 5-minute objective data in the time interval t stays in the band or not. This satisfaction is defined as the condition that the objective data is within the 1.96 SEM band. The figure (The Figure 3 in Appendix A) shows an example of 1.96 times SEM band for Richards Blvd to Chiles Rd segment on 10/20/2018. Finally, a 0 to 100% score will be given to tell the percentage of satisfied time intervals in the given scenario, and readers are able to find out how close between the objective data source and the Bluetooth data.

The Travel Time Error Bias (TEB)

For each time point at a specific location, calculate the error between the objective data and the Bluetooth data. The corresponding travel time error e_t for each 5-minute time interval can be defined as $e_t = o_t - b_t$, where o_t is the objective data in the time interval t, and b_t is the Bluetooth data in the same time interval t. Therefore, the TEB can be defined as the summation of travel time errors over the number of data points N, where N is the number of data collected during the evaluation time period T. Since we aggregated the data into 5 minutes intervals,

$$e_{TEB} = \frac{1}{N}\sum_{t=1}^{N} e_t \tag{2}$$

This method tells the bias between objective data and Bluetooth data, when there is consistent positive or negative errors, but when the positives and negatives balance each other out, the error can be zero even though there could be large positive and negtative errors in different time periods.

The Average Absolute Travel Time Error (ATE)

ATE's algorithm is the same as TEB, except that that ATE uses the absolute value of the corresponding travel time. Take the average of these absolute differences. In this way, positive errors and negative errors do not cancel out each other.

$$e_{ATE} = \frac{1}{N}\sum_{t=1}^{N} |e_t| \tag{3}$$

ATE focuses on the magnitude of errors instead of biases.

4. Data Quality Comparison

This section presents the comparison scenarios and results by applying SEM band satisfaction, TEB, and ATE goodness of fit measures. In order to conduct a comprehensive comparison, there are four comparison scenarios and three analyzing time periods proposed:

Comparison scenarios:

1. Overall

The average of valid 31 days and 9 study segments is calculated according to the different time interval of a day.

2. Compare by day of the week

   The day of the week information was derived by the date information. Based on the overall data set, we aggregate the data by Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, and Sunday.

3. Compare by week

   The week information was also derived by the date information. Based on the overall data set, we aggregate the data by first week, second week, third week, fourth week, and fifth week of the whole study period.

4. Compare by segment

   The segment property was embedded in the original data set, so based on the overall data set, aggregate the data by different segments.

Time periods:

1. All-day performances

   According to the comparison scenario, the evaluation methods will apply to the whole day data set.

2. Morning peak-hour performances

   From the observation of average bluetoth travel time by days, we choose the morning peak hours as the period from 7 a.m. to 10 a.m. for the peak hour. Moreover, the morning peak-hour performance analysis will only consider weekdays.

3. Afternoon peak-hour performances

   From the observation of average bluetoth travel time by days, we propose the afternoon peak hours as the period from 3:30 p.m. to 6:30 p.m. The afternoon peak-hour performance analysis will also only consider weekdays.

The following comparison scenarios are composed of combined scenarios and analysis time periods. The result are lists in table format.

4.1 Comparison results and discussion

- Overall all-day performances. (Table 4 in Appendix B)

- Overall peak-hour performances. (Table 5 in Appendix B and (Table 6 in Appendix B)

- All-day performances by day of the week. (Table 7 in Appendix B)

- Peak-hour performances by day of the week. (Table 8 in Appendix B and Table 9 in Appendix B)

- All-day performances by week. (Table 10 in Appendix B)

- Peak-hour performances by week.
  The data collection starts from 10/14/2018 to 11/16/2018, which includes 6 weeks. However, the first week only contain a Sunday (10/14/2018) data, so there is no available first week result for peak-hour performances by week. (Table 11 in Appendix B and Table 12 in Appendix B)

- All-day performances by study segments.

  The error was calculated by subtract Bluetooth data from the objective data source according to the same study segment, date, and the time of a day, and then aggregate the data by different study segments and apply the equation (2) and (3). (Table 13 in Appendix B, Table 14 in Appendix B, and Table 15 in Appendix B)

  Morning peak-hour comparison

  (Table 16 in Appendix B, Table 17 in Appendix B, and Table 18 in Appendix B)

  Afternoon peak-hour comparison

  (Table 19 in Appendix B, Table 20 in Appendix B, and Table 21 in Appendix B)

A striking difference between the Waze data plots and plots from other data is that they are shifted downward, although their shapes are similar (see Figure 4 and Figure 5 in Appendix A). This means that Waze consistently produced lower travel times than other data sources. Later, we conduct an adjustment study to shift the Waze data and see the comparison result.

We also note that the peaks (congested periods) of HERE and INRIX travel times are shifted rightward (to a later time) from those of the Bluetooth data. This could be the result of different data smoothing methods applied to the raw travel time data by different vendors than that used to filter and smooth the Bluetooth data.

4.2 Adjusted Waze data quality comparison and discussion

Comparing travel time readings with other data sources on study segments, each segment has a reading difference ranging from 0-50 seconds. Therefore, we set an integer that ranging of from -30 to 50 seconds as the control variable to add to or subtract from the recorded value of Waze and choose ATE as the measurement of goodness to be minimized. The table (Table 22 in Appendix B) shows the optimal shifted values .

Except Reed Ave to Enterprise Blvd segment, it is more likely to suspect the rest segments have a calculation error, especially for Chiles Rd to Webster, San Juan Rd to Bryte Bend Bridge, and Rio Linda Blvd to Truxel Rd.

5. Conclusions

This paper compared travel time data quality among various data sources: Bluetooth travel time data collection system, Dual loop detector, Waze, HERE, and INRIX.

We applied three measures to evaluate the performance of vendor data compared with those of the Bluetooth system (benchmark). They are Standard Error of Mean (SEM) Band Satisfaction, Travel Time Error Bias (TEB), and Average Absolute Travel Time Error (ATE). In order to observe the performances of the comparisons in different situations, we proposed several comparison scenarios: overall, by day of the week, by week, and by segment, and in three time periods: all-day, morning peak, and afternoon peak. The comparison results indicate that travel times from INRIX and HERE are as good as those from the Bluetooth system, but measurements from Waze systematically underestimate travel times, although the travel time patterns over the studied periods are similar to those from other vendors. It is challenged to proceed a more in-depth study on the causes of this systematic shift without the availability of Waze raw data, but we suspect that it is caused by a small problem (otherwise the travel time patterns would be quite different from others) and can be fixed by Waze relatively straightforwardly. After correcting for this shift, Waze and the two other vendors, INRIX and HERE, all provide as reliable travel time data as those obtained from Caltrans' Bluetooth system.

Acknowledgement

We would like to thank California Department of Transportation and data suppliers (INRIX, HERE, and Waze) for providing the research with the travel time and other related data. In particular, we are grateful to John Slonaker of Caltrans DRISI, Andre Chavez, Gurdeep Sidhu, and Andrew Chang of Caltans District 3 for their assistane on acquiring the dual loop and Bluetooth data, as well as access to Waze data. This research is funded by the California Department of Transportation.

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Appendix A

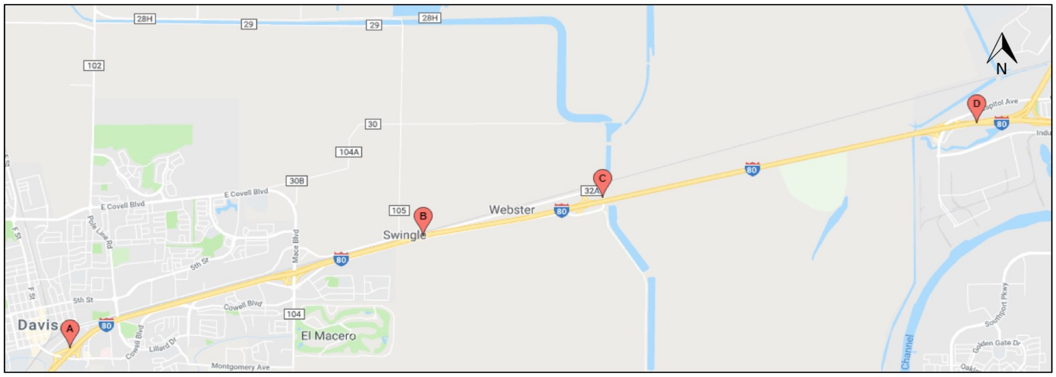

Figure 1: Map of Eastbound Bluetooth Detector locations

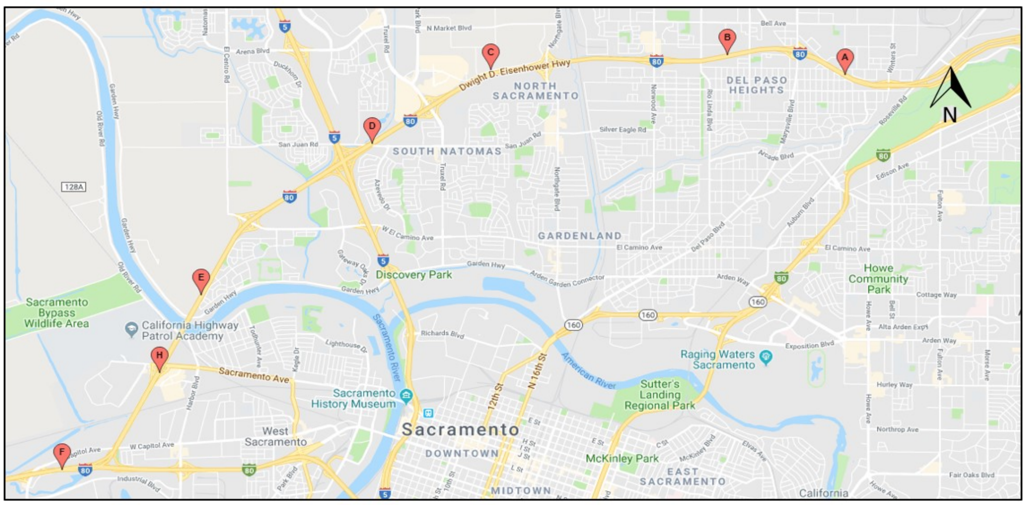

Figure 2: Map of Westbound Detector locations

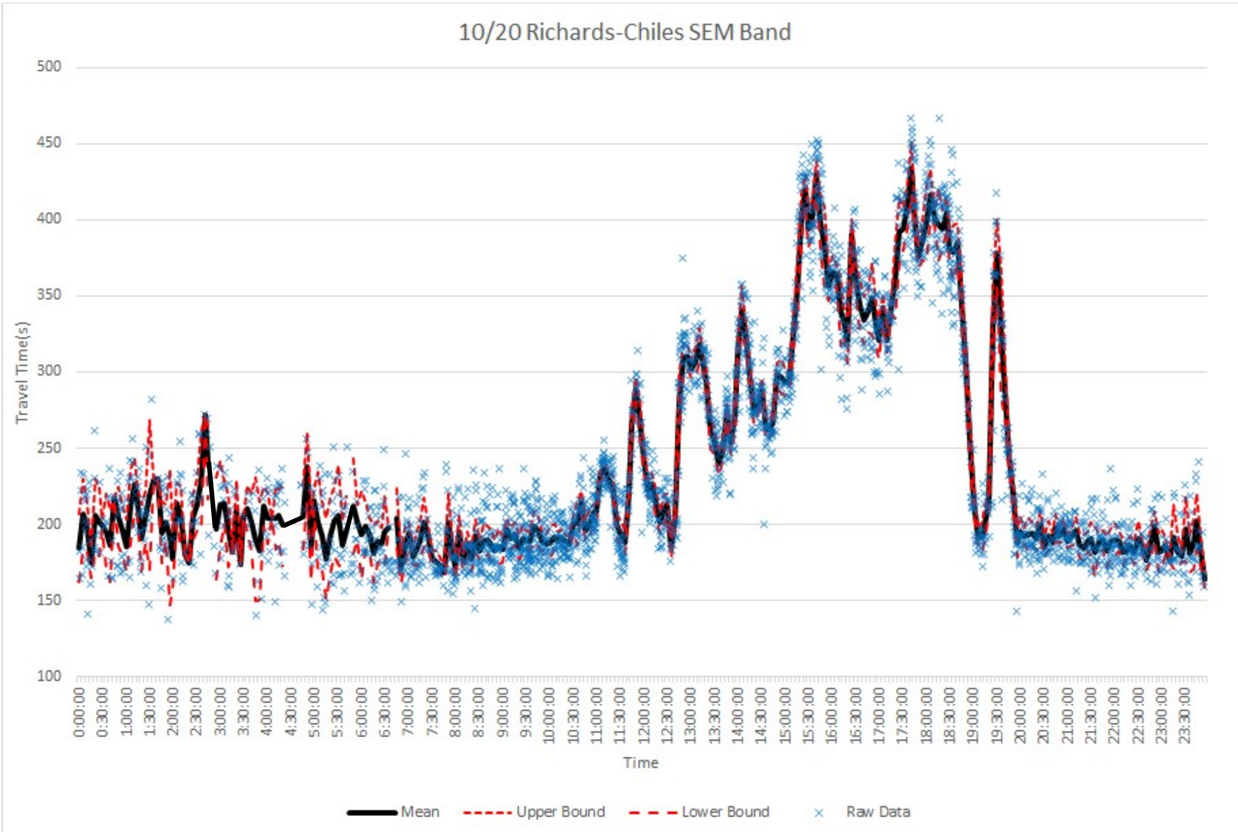

Figure 3: An example of Standard Error of Mean (SEM) band

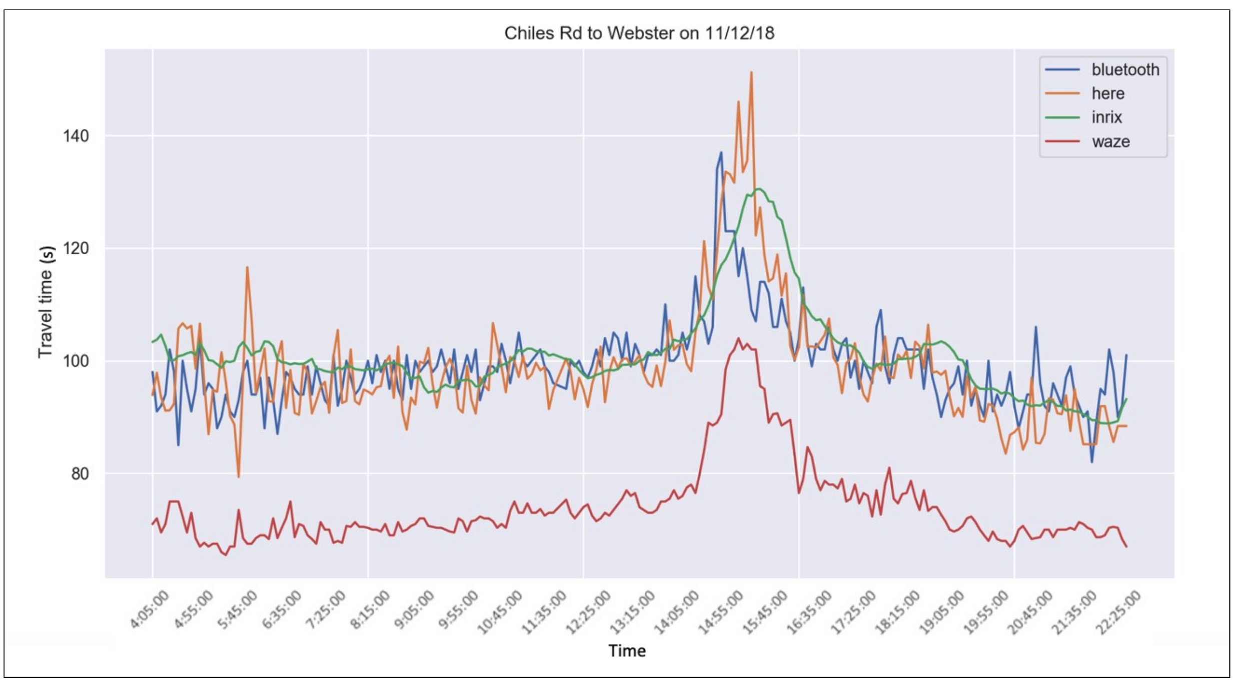

Figure 4: 11/12 Chiles Rd to Webster Travel time for all data sources

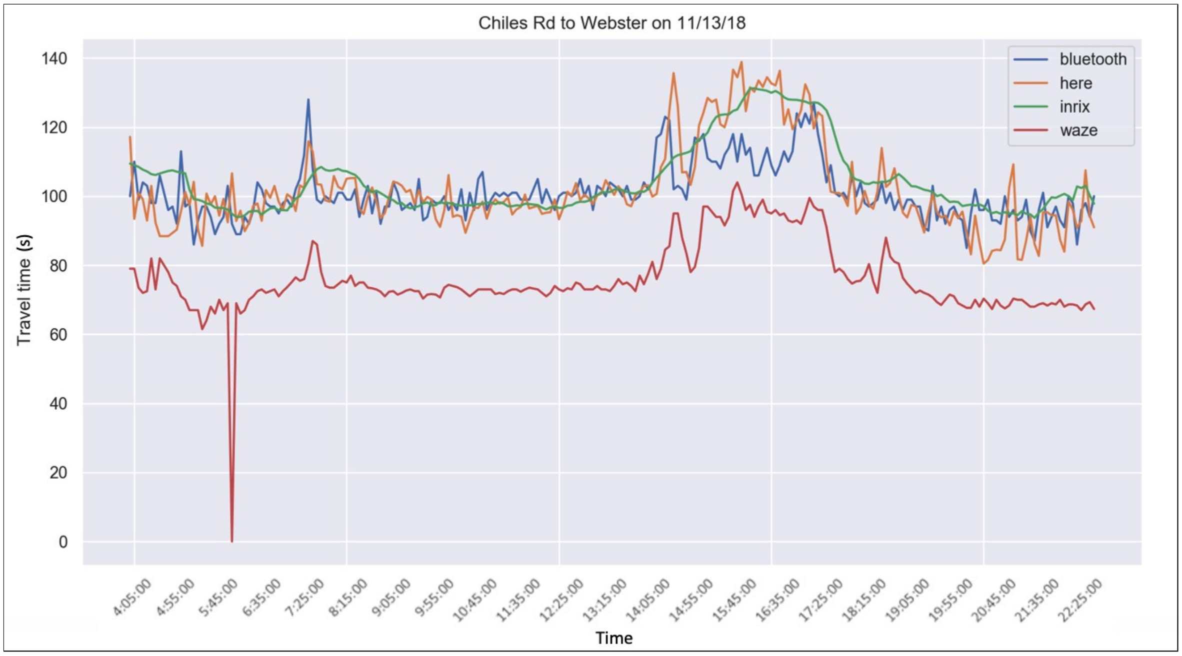

Figure 5: 11/12 Chiles Rd to Webster Travel time for all data sources

Appendix B

Table 1: Review Summary

Paper (authors)	Data sources	Ground truth data	Findings
Tarnoff, Philip John, et al, 2009	Floating car, INRIX, Bluetooth data	Bluetooth travel time	Both Bluetooth and INRIX travel time data had a good match with Floating car travel time data for the selected aterials
Haghani et al., 2010	Floating car, Bluetooth data	Floating car travel time	The bluetooth data is not significantly different from the actual travel times collected by the floating cars.
Kim et al., 2011	Floating car, TRANSMIT reader, INRIX, Bluetooth data	Floating car speed	1. The data of Bluetooth sensors are closer to the speeds of probe vehicles compared to the INRIX data. 2. For the same travel time record, INRIX would record in a latency time compared with other data sources. 3. Speed discrepancy and abrupt speed changes were found in the TRANSMIT data and it performed poorly in the comparison.
Shollar, 2012	INRIX, Bluetooth data	Bluetooth travel time	The INRIX reference speed that uses for freeway (85th percentile of the weekly speeds) will produce high-speed values that were not representative of actual conditions on arterial roads.
Kim and Coifman, 2014	INRIX, loop detector data	loop detector speed	The INRIX data has latency and repeated speed records issues, and the confidence measures do not appear to reflect the latency or repeated speed records
Tahmasseby, 2015	TomTom, Bluetooth data	Bluetooth travel time	The TomTom travel time on the arterial road are comparable to the baseline Bluetooth results.
Wagner et al., 2016	INRIX, Bluetooth data	Bluetooth travel time	The comparison between Bluetooth and INRIX data showed encouraging results, but INRIX data have an issue about latency in recognizing the congestion event.
Gong, 2018	Floating car, HERE, Bluetooth data	Floating car	The accuracy and reliability of Bluetooth detectors data are better than private sector data

Table 2: The Bluetooth detectors on Eastbound

Indexes of From & to stations in figure 1	Segment name	From station latitude & longtitude	To station latitude & longtitude	Segment length (unit: miles)
A to B	Richards Blvd to Chiles Rd	38.54122, 121.7347596	38.55807, 121.671181	3.67
B to C	Chiles Rd to Webster UC	38.55807, 121.671181	38.56365, 121.638873	1.8
C to D	Webster UC to Enterprise Blvd	38.56365, 121.638873	38.57489, 121.571657	3.7

Table 3: The Bluetooth detectors on Westbound

Indexes of From & to stations in figure 2	**Segment name**	**From station latitude & longtitude**	**To station latitude & longtitude**	**Segment length (unit: miles)**
A to B	Pinell St to Rio Linda Blvd	38.63881, 121.419811	38.64198, 121.442691	1.3
B to C	Rio Linda Blvd to Truxel Rd	38.64198, 121.442691	38.63962, 121.488544	2.5
C to D	Truxel Rd to San Juan Rd	38.63962, 121.488544	38.62773, 121.511553	1.5
D to E	San Juan Rd to Bryte Bend Bridge	38.62773, 121.511553	38.60313, 121.544713	2.5
E to H	Bryte Bend Bridge to Reed Ave	38.60313, 121.544713	38.59057, 121.552774	1
H to F	Reed Ave to Enterprise Blvd	38.59057, 121.552774	38.57489, 121.571657	1.6

Table 4: The Overall all-day performances of TEB, ATE, and SEM band satisfaction

Comparison Group	TEB	ATE	SEM Band Satisfaction
HERE-Bluetooth	-3.91	13.34	49.1%
Waze-Bluetooth	-11.32	20.21	27.1%
INRIX-Bluetooth	-0.47	14.15	50.3%

Table 5: : The morning-peak-hour performances of TEB, ATE, and SEM band satisfaction

Comparison Group	TEB	ATE	SEM Band Satisfaction
HERE-Bluetooth	-2.50	13.51	52.7%
Waze-Bluetooth	-9.54	21.86	25.4%
INRIX-Bluetooth	-1.35	16.47	51.1%

Table 6: The afternoon-peak-hour performances of TEB, ATE, and SEM band satisfaction

Comparison Group	TEB	ATE	SEM Band Satisfaction
HERE-Bluetooth	-2.34	18.04	42.4%
Waze-Bluetooth	-13.27	27.48	23.8%
INRIX-Bluetooth	-3.27	21.38	41.5%

Table 7: The All-day performances of TEB, ATE, and SEM band satisfaction varied by a day of a week

TEB Comparison							
Comparison Group	Mon.	Tue.	Wed.	Thur.	Fri.	Sat.	Sun.
HERE -Bluetooth	-3.52	-5.26	-3.88	-3.46	-2.95	-5.17	-3.72
Waze-Bluetooth	-11.22	-11.99	-12.63	-14.13	-10.99	-9.47	-8.76
INRIX-Bluetooth	0.19	-0.61	-0.74	-0.58	0.63	-0.85	-1.6
ATE Comparison							
Comparison Group	Mon.	Tue.	Wed.	Thur.	Fri.	Sat.	Sun.
HERE -Bluetooth	11.33	14.79	14.06	13.53	12.98	14.11	13.46
Waze-Bluetooth	18.11	21.71	22.18	23.43	20.58	18.15	17.77
INRIX-Bluetooth	12.57	15.5	16.36	15.48	14.13	13.58	12.38
SEM Band Satisfaction							
Comparison Group	Mon.	Tue.	Wed.	Thur.	Fri.	Sat.	Sun.
HERE	51.3%	50.4%	50.7%	49.9%	49.3%	45.5%	46.3%
Waze	26.1%	25.2%	26.9%	25.0%	25.1%	30.9%	31.5%
INRIX	51.3%	50.1%	50.1%	50.5%	48.5%	48.9%	52.3%

Table 8: The morning peak-hour performances of TEB, ATE, and SEM band satisfaction varied by weekday

TEB Comparison					
Comparison Group	Mon.	Tue.	Wed.	Thur.	Fri.
HERE -Bluetooth	-2.1	-2.93	-1.69	-2.66	-2.96
Waze-Bluetooth	-7.77	-7.89	-10.53	-10.49	-11.06
INRIX-Bluetooth	-0.9	-1.74	-4.18	-2.06	0.94
ATE Comparison					
Comparison Group	Mon.	Tue.	Wed.	Thur.	Fri.
HERE -Bluetooth	13.81	16.96	19.98	11.92	8.11
Waze-Bluetooth	22.03	27.32	29.25	19.99	14.78
INRIX-Bluetooth	18.33	20.27	26.17	13.95	8.06
SEM Band Satisfaction					
Comparison Group	Mon.	Tue.	Wed.	Thur.	Fri.
HERE	51.2%	50.7%	50.9%	53.8%	56.0%
Waze	25.4%	25.2%	27.6%	25.2%	24.2%
INRIX	47.9%	49.7%	48.0%	52.5%	56.1%

Table 9: The afternoon peak-hour performances of TEB, ATE, and SEM band satisfaction varied by weekday

TEB Comparison					
Comparison Group	Mon.	Tue.	Wed.	Thur.	Fri.
HERE -Bluetooth	-3.56	-0.98	-3.32	-2.18	-1.73
Waze-Bluetooth	-11.24	-9.00	-13.31	-20.65	-11.05
INRIX-Bluetooth	-0.42	0	-2.72	-8.38	-3.93
ATE Comparison					
Comparison Group	Mon.	Tue.	Wed.	Thur.	Fri.
HERE -Bluetooth	12.55	16.05	17.83	20.84	22.71
Waze-Bluetooth	19.16	22.65	27.69	34.98	32.25
INRIX-Bluetooth	15.9	18.43	22.7	24.73	25.32
SEM Band Satisfaction					
Comparison Group	Mon.	Tue.	Wed.	Thur.	Fri.
HERE	45.6%	42.8%	41.8%	39.6%	42.4%
Waze	22.7%	24.3%	24.6%	23.5%	24.5%
INRIX	45.2%	42.3%	39.9%	38.8%	41.1%

Table 10: The all-day performances of TEB, ATE, and SEM band satisfaction varied by week

TEB Comparison						
Comparison Group	1	2	3	4	5	6
HERE -Bluetooth	-7.23	-2.48	-3.43	-4.98	-3.92	-3.8
Waze-Bluetooth	-9.02	-10.71	-10.18	-11.12	-11.81	-14.01
INRIX-Bluetooth	-4.46	-0.85	-0.09	-0.8	-0.51	0.83
ATE Comparison						
Comparison Group	1	2	3	4	5	6
HERE -Bluetooth	16.42	14.73	13.12	14.11	13.56	9.77
Waze-Bluetooth	19.98	21.13	19.80	19.85	21.19	18.91
INRIX-Bluetooth	15.99	15.25	14.55	14.04	15.51	9.77
SEM Band Satisfaction						
Comparison Group	1	2	3	4	5	6
HERE	44.5%	46.7%	49.6%	49.0%	49.1%	52.5%
Waze	32.7%	26.3%	27.6%	27.7%	26.7%	25.9%
INRIX	49.8%	48.6%	50.4%	52.0%	49.4%	51.1%

Table 11: The morning peak-hour performances of TEB, ATE, and SEM band satisfaction varied by week

TEB Comparison					
Comparison Group	2	3	4	5	6
HERE -Bluetooth	-1.69	-1.6	-3.01	-2.9	-3.09
Waze-Bluetooth	-10.95	-7.42	-9.25	-9.65	-11.27
INRIX-Bluetooth	-0.55	-1.6	0.26	-4.77	0.31
ATE Comparison					
Comparison Group	2	3	4	5	6
HERE -Bluetooth	11.47	14.98	10.91	20.48	8.41
Waze-Bluetooth	19.67	25.44	17.07	30.14	15.47
INRIX-Bluetooth	13.01	19.54	11.73	27.58	8.33
SEM Band Satisfaction					
Comparison Group	2	3	4	5	6
HERE	52.3%	54.3%	52.4%	48.7%	56.2%
Waze	22.0%	24.4%	27.5%	24.5%	27.4%
INRIX	50.4%	50.5%	52.2%	47.3%	55.4%

Table 12: The afternoon peak-hour performances of TEB, ATE, and SEM band satisfaction varied by week

TEB Comparison					
Comparison Group	2	3	4	5	6
HERE -Bluetooth	-3.23	-2.6	-0.57	-2.42	-3.49
Waze-Bluetooth	-13.13	-10.21	-10.40	-15.75	-17.73
INRIX-Bluetooth	-6.42	-2.75	-5.05	-2.58	-0.11
ATE Comparison					
Comparison Group	2	3	4	5	6
HERE -Bluetooth	23.85	16.24	21.52	17.6	12
Waze-Bluetooth	31.34	22.54	29.18	29.84	25.62
INRIX-Bluetooth	27.75	19.32	24.87	22.71	13.14

Table 13: All-day TEB Comparison

Comparison Group	HERE-Bluetooth	Waze-Bluetooth	INRIX-Bluetooth
Richards Blvd to Chiles Rd	-1.07	14.93	-0.03
Bryte Bend Bridge to Reed Ave	-0.57	-6.09	4.49
Pinell St to Rio Linda Blvd	-2.80	-6.78	0.13
Truxel Rd to San Juan Rd	-2.56	-8.47	3.60
Chiles Rd to Webster	0.18	-28.63	1.53
San Juan Rd to Bryte Bend Bridge	-15.87	-30.74	-13.42
Reed Ave to Enterprise Blvd	7.80	6.89	8.38
Rio Linda Blvd to Truxel Rd	-14.94	-22.72	-5.69
Webster UC to Enterprise Blvd	-5.99	-21.33	-4.57

Table 14: All-day ATE Comparison

Comparison Group	HERE-Bluetooth	Waze-Bluetooth	INRIX-Bluetooth
Richards Blvd to Chiles Rd	20.34	29.19	26.85
Bryte Bend Bridge to Reed Ave	5.86	8.48	7.92
Pinell St to Rio Linda Blvd	5.59	7.48	4.40
Truxel Rd to San Juan Rd	6.90	9.49	7.95
Chiles Rd to Webster	10.64	29.41	10.60
San Juan Rd to Bryte Bend Bridge	21.86	32.60	19.72
Reed Ave to Enterprise Blvd	18.90	20.37	27.69
Rio Linda Blvd to Truxel Rd	16.80	23.06	9.83
Webster UC to Enterprise Blvd	15.88	24.32	15.62

Table 15: All-day SEM band satisfaction

Segment	HERE-Bluetooth	Waze-Bluetooth	INRIX-Bluetooth
Richards Blvd to Chiles Rd	47.4%	28.3%	47.2%
Bryte Bend Bridge to Reed Ave	58.2%	26.8%	40.6%
Pinell St to Rio Linda Blvd	57.6%	38.2%	69.5%
Truxel Rd to San Juan Rd	57.9%	36.9%	47.2%
Chiles Rd to Webster	48.5%	2.0%	55.0%
San Juan Rd to Bryte Bend Bridge	39.5%	15.3%	48.1%
Reed Ave to Enterprise Blvd	39.8%	57.1%	14.3%
Rio Linda Blvd to Truxel Rd	36.0%	14.7%	66.3%

Webster UC to Enterprise Blvd	54.7%	28.1%	60.7%

Table 16: Morning peak-hour TEB Comparison

Comparison Group	HERE-Bluetooth	Waze-Bluetooth	INRIX-Bluetooth
Richards Blvd to Chiles Rd	2.36	11.05	3.41
Bryte Bend Bridge to Reed Ave	2.45	-4.56	6.23
Pinell St to Rio Linda Blvd	-1.77	-4.45	0.33
Truxel Rd to San Juan Rd	-5.78	-10.30	2.28
Chiles Rd to Webster	-1.03	-27.50	0.01
San Juan Rd to Bryte Bend Bridge	-11.99	-29.18	-16.00
Reed Ave to Enterprise Blvd	10.27	22.73	-2.03
Rio Linda Blvd to Truxel Rd	-10.68	-18.73	-3.91
Webster UC to Enterprise Blvd	-4.69	-21.13	-3.68

Table 17: Morning peak-hour ATE Comparison

Comparison Group	HERE-Bluetooth	Waze-Bluetooth	INRIX-Bluetooth
Richards Blvd to Chiles Rd	14.59	19.02	18.65
Bryte Bend Bridge to Reed Ave	8.19	10.63	11.77
Pinell St to Rio Linda Blvd	5.04	7.13	6.06
Truxel Rd to San Juan Rd	9.92	13.07	14.84
Chiles Rd to Webster	7.89	28.76	7.53
San Juan Rd to Bryte Bend Bridge	22.34	33.62	24.95
Reed Ave to Enterprise Blvd	31.04	45.27	48.92
Rio Linda Blvd to Truxel Rd	13.35	20.06	8.87
Webster UC to Enterprise Blvd	13.03	24.61	12.62

Table 18: Morning Peak-hour SEM band satisfaction

Segment	HERE-Bluetooth	Waze-Bluetooth	INRIX-Bluetooth
Richards Blvd to Chiles Rd	54.9%	38.4%	54.5%
Bryte Bend Bridge to Reed Ave	54.5%	23.6%	33.4%
Pinell St to Rio Linda Blvd	63.0%	43.5%	60.6%
Truxel Rd to San Juan Rd	62.8%	37.8%	36.7%
Chiles Rd to Webster	59.8%	0.8%	65.7%
San Juan Rd to Bryte Bend Bridge	47.1%	12.9%	54.5%
Reed Ave to Enterprise Blvd	31.8%	45.9%	14.9%

Rio Linda Blvd to Truxel Rd	37.9%	11.1%	66.2%
Webster UC to Enterprise Blvd	59.9%	16.5%	70.5%

Table 19: Afternoon peak-hour TEB Comparison

Comparison Group	HERE-Bluetooth	Waze-Bluetooth	INRIX-Bluetooth
Richards Blvd to Chiles Rd	-9.73	15.26	-28.66
Bryte Bend Bridge to Reed Ave	-0.91	-7.83	4.04
Pinell St to Rio Linda Blvd	-3.33	-8.01	-0.38
Truxel Rd to San Juan Rd	-2.31	-10.06	4.46
Chiles Rd to Webster	7.62	-37.77	3.05
San Juan Rd to Bryte Bend Bridge	-16.95	-36.07	-15.96
Reed Ave to Enterprise Blvd	13.88	6.38	7.62
Rio Linda Blvd to Truxel Rd	-13.11	-22.34	-3.24
Webster UC to Enterprise Blvd	2.39	-20.16	-2.48

Table 20: Afternoon peak-hour ATE Comparison

Comparison Group	HERE-Bluetooth	Waze-Bluetooth	INRIX-Bluetooth
Richards Blvd to Chiles Rd	47.44	70.37	73.88
Bryte Bend Bridge to Reed Ave	8.20	10.86	9.67
Pinell St to Rio Linda Blvd	4.72	8.23	3.10
Truxel Rd to San Juan Rd	5.92	10.70	7.70
Chiles Rd to Webster	22.91	40.21	24.99
San Juan Rd to Bryte Bend Bridge	23.32	38.20	21.30
Reed Ave to Enterprise Blvd	22.42	22.26	27.60
Rio Linda Blvd to Truxel Rd	14.57	22.48	7.57
Webster UC to Enterprise Blvd	14.83	26.73	18.83

Table 21: Afternoon peak-hour SEM band satisfaction

Segment	HERE-Bluetooth	Waze-Bluetooth	INRIX-Bluetooth
Richards Blvd to Chiles Rd	20.0%	12.4%	12.5%
Bryte Bend Bridge to Reed Ave	59.1%	24.5%	35.2%
Pinell St to Rio Linda Blvd	60.7%	33.0%	79.8%
Truxel Rd to San Juan Rd	60.5%	34.4%	46.7%
Chiles Rd to Webster	18.6%	6.2%	15.9%
San Juan Rd to Bryte Bend Bridge	40.0%	14.9%	51.5%

Reed Ave to Enterprise Blvd	38.6%	53.7%	15.6%
Rio Linda Blvd to Truxel Rd	35.7%	13.0%	71.2%
Webster UC to Enterprise Blvd	47.9%	22.5%	44.9%

Table 22: The optimized ATE and Shifted Value

Segments	Optimized ATE	Shifted value
Richards Blvd to Chiles Rd	23.5	-15
Bryte Bend Bridge to Reed Ave	5.18	6
Pinell St to Rio Linda Blvd	4.44	6
Truxel Rd to San Juan Rd	6.10	7
Chiles Rd to Webster	9.78	26
San Juan Rd to Bryte Bend Bridge	17.57	25
Reed Ave to Enterprise Blvd	20.36	1
Rio Linda Blvd to Truxel Rd	9.572	21
Webster UC to Enterprise Blvd	16.27	17