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ERROR MODELING AND ANALYSIS FOR TRAVEL TIME DATA OBTAINED FROM BLUETOOTH MAC ADDRESS MATCHING

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16. ABSTRACT
Travel time data had been very difficult to collect until recently. Current attempts at exploiting short-range communication protocols that rely on unique identifiers, primarily Bluetooth, have significantly simplified the travel time collection task. Many transportation agencies are now considering using Bluetooth travel time estimates to feed a variety of applications, such as user information systems. As Bluetooth-based travel time data collection increases in popularity, investigating the errors that are characteristic of this detection type becomes more important.

A Bluetooth sensor is developed for travel time data collection in this study to facilitate testing system configurations and allow for future deployments. Three types of antennae and three different sensor arrangements are tested to determine the effects of these variables on travel time error. The collected travel time data is compared to license plate reader data, which, due to its relatively small detection zone for vehicle license plate recognition, are taken as the ground truth travel time. A regression model was used to investigate if travel time error can be predicted with observable explanatory variables. Descriptive statistical analysis was also employed to evaluate impacts of individual variables on the travel time error. The results suggest that a combination of sensors is desirable, despite the potential loss of accuracy, as the higher matching rates obtained by the system will improve sample size and reduce random error rates. Findings of this study are helpful to transportation professionals attempting to understand the errors associated with the Bluetooth-based travel time data collection technology and configure the sensors to mitigate the errors.

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Bluetooth, travel time, error, linear model

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EXECUTIVE SUMMARY

The growing popularity of mobile devices, combined with the wireless communications used to connect these devices to each other and the internet has allowed a Media Access Control (MAC) address-based tracking method to be developed for the purposes of collecting corridor travel times. This approach relies on recording the MAC addresses of bypassing devices at one location and noting the time difference between matching MAC addresses at a different location. Due to its significantly lower overall cost, ease of deployment and relatively fewer privacy concerns when compared to traditional methods, interest in this means of collecting travel time data is growing.

Although MAC address-based collection techniques have significant advantages in most aspects, there are some drawbacks to their use. Relatively small sample size is an issue for some purposes – most studies using MAC address matching have found that they are able to capture somewhere between five to ten percent of the total vehicle volume. An additional, and perhaps most serious, issue is the ambiguity of accuracy due to the inherent properties of the MAC address broadcast protocols. Because the Bluetooth readers are capable of detecting MACs within a specific range, the travel times obtained can be thought of as zone to zone. Since these zones can be large, a certain level of uncertainty exists when using MAC-addressed based travel times.

The purpose of this study is to investigate the Bluetooth travel time errors that are inherent to the data collection technique and the development of a robust MAC address sensor device (recorder).

A Bluetooth protocol based device was developed and tested. The current device design consists of three main components; (1) a Bluetooth chipset that constantly scans the available channels, (2) a 60 GHz ARM processor that records MACs and (3) a communications module that synchronizes to the UTC time and transmits data in near real-time (GPS + GSM). This provides an excellent base for testing mounting locations and various antennae as it can be mounted to signposts and signal posts and will accept a wide range of antenna types. The current design allows the device to function for up to a week without external power using one 6-cell LiPo pack (15.6Ah capacity @ 3.7V). The device can use up to two battery packs at a time, resulting in a maximum runtime of two weeks without external or solar power. As data is collected, it is sent over the GSM network to a server in STAR Lab, where the data is uploaded to the Digital Roadway Interactive Visualization and Evaluation Network (DRIVE Net) developed by the Smart Transportation Applications and Research Laboratory (STAR Lab) as a data sharing, modeling, and online analysis platform. This approach to data collection allows for real-time information flow to the users while maintaining a level of privacy.

Multiple tests were conducted in a variety of locations, testing the device's ability to measure travel times in freeway, arterial, and highway conditions. An extensive test was conducted on SR-522 in Seattle, Washington, where the travel times obtained from Bluetooth devices were compared to those collected by Automatic License Plate Recognition (ALPR) devices mounted at intersections. Error analysis was performed on the resulting data, which produced a set of recommendations for future Bluetooth deployments:

(1) Bluetooth-based MAC address matching is an effective, low cost means for travel time data collection. Bluetooth-based travel times are sufficiently accurate for most transportation applications. However, because slower vehicles have a better chance to be detected by Bluetooth readers, Bluetooth-based travel time tends to slightly overestimate travel time.

(2) A site-specific evaluation may be necessary to ensure that the measured travel times reflect the desired delays – nearby signals may superimpose additional travel time. Extraneous sources of delay, such as bus stops, should also be considered.

(3) Combinations of sensors working in tandem help reduce error in most cases. Tandem setups greatly increase the detection and matching rates, which is important for time-critical applications such as real-time travel information.

(4) Sensor configuration can significantly affect the performance of the Bluetooth-based travel-time collection system, especially if the chosen corridor has a short travel time. The travel time data collected using Bluetooth sensors along the 0.98 mile long corridor tested in this study produced average errors between 2.4 and 11.4 seconds (4% to 13%) when compared to aligned ALPR sensors.

1 INTRODUCTION

1.1 BACKGROUND

Travel time is considered to be one of the most important transportation metrics, as it is easily understood by roadway users. Travel time is one often directly conveyed to users through the use of Dynamic Message Signs (DMS), 511 and online systems to allow individuals to make choices about their routes. The Federal Highways Administration (FHWA) has encouraged jurisdictions to provide travel time estimates using existing DMS infrastructure (Paniati, 2004). The Travel Time Handbook, published by the FHWA, provides an extensive overview of travel time data collection methodologies, listing three major means of obtaining travel time estimates for a corridor – "active" test vehicles, license plate matching and "passive" probe vehicles (Travel Time Data Collection Handbook, 1998). The handbook mentions platoon and video matching as some potential emerging methods, but the three primary technologies mentioned have been the most common means of obtaining travel time information for the past few decades.

In the past few years a new methodology for obtaining travel time measurements has been generating interest. The growing popularity of mobile devices, combined with the wireless communications used to connect these devices to each other and the internet has allowed a Media Access Control (MAC) address-based tracking method to be developed. This approach relies on recording the MAC addresses of bypassing devices at one location and noting the time difference between matching MAC addresses at a different location. This approach is becoming very popular due to its significantly lower overall costs, ease of deployment and relatively fewer privacy concerns when compared to the three traditional methods outlined in the Travel Time Data Collection Handbook (Turner et al., 1998). The lower costs are associated primarily with the lower cost of the Bluetooth reader as well as the fact that one device used to collect the MAC addresses spans multiple lanes, which is of significant advantage when compared to Automatic License Plate Recognition (ALPR) systems that require lane-based detection. Additionally, Bluetooth-based travel time data collection systems are easy to install and do not require high bandwidth for communications. When compared with Global Positioning Systems (GPS), the MAC address-based systems do not require willing volunteers with properly equipped vehicles whose GPS coordinates are constantly being recorded – the MAC address is broadcast freely to all surrounding devices. Users who do not wish to disclose their MAC's location can simply turn off the broadcast function of their device, although it is nearly impossible to tie a particular MAC to an individual.

Although the MAC address-based collection techniques have significant advantages in most aspects, there are some drawbacks to their use. Relatively small sample size is an issue for some purposes – most studies using MAC address matching have found that they are able to match somewhere between five to ten percent of the total vehicle volume. An additional, and perhaps most serious, issue is the ambiguity of accuracy due to the inherent properties of the MAC address broadcast protocols. One of the most common protocols is known as Bluetooth, published by Special Interests Group (SIG). This protocol is common in mobile telephones and has been the focus of MAC address-based travel time estimation. The ambiguity of accuracy of the use of the Bluetooth protocol for travel time measurement comes from the random frequency hopping characteristic of the protocol. As the protocol was designed to function in the same 2.4 GHz band as WiFi, a frequency hopping mechanism was implemented to prevent interference (Special Interests Group, 2010). The constantly changing frequency mandated by the Bluetooth protocol could delay the device connection time by up to 10.24 seconds. This “connection time” complication is further exacerbated by the variety of ranges that a receiving Bluetooth sensor device may have. However, devices mounted in tandem could provide better results by increasing the detection range and detection time. These complications that arise in using MAC address-based travel time measurements have not yet been described in detail within the transportation research community.

1.2 PROBLEM STATEMENT

Obtaining travel time measurements using Bluetooth devices involves matching an observed MAC address between at least two locations. The difference in time between the two observations is the travel time. Because the Bluetooth readers are capable of detecting MAC addresses within a specific range, the travel times obtained can be thought of as zone to zone. However, ALPR travel times can be thought of as point to point travel times, as the window of video-based detection is relatively small. This is illustrated in Figure 1-1, where the dashed lines represent the Bluetooth detection zone and the squares represent the ALPR detection points. The average travel times obtained from both types of sensors can be expressed as:

$$TT_{ALPR}(k) = \frac{\sum_{i=1}^{m_k} (t_{i,A}(k) - t_{i,B}(k))}{m_k} \qquad (1)$$

$$TT_{BT}(k) = \frac{\sum_{j=1}^{n_k} (t_{j,A}(k) - t_{j,B}(k))}{n_k} \tag{2}$$

where $TT_{ALPR}(k)$ and $TT_{BT}(k)$ are the ALPR-based and Bluetooth-based average travel times between nodes A and B during period k, respectively; *m* and *n* are the number of observations by ALPR and Bluetooth based systems, respectively; *t* is the time stamp when a license plate or a Bluetooth device is detected. A vehicle's MAC address may be detected multiple times by the Bluetooth sensor, so it is imperative that a consistent convention is taken, either matching first detection to first detection or last detection to last detection to mitigate detection errors.

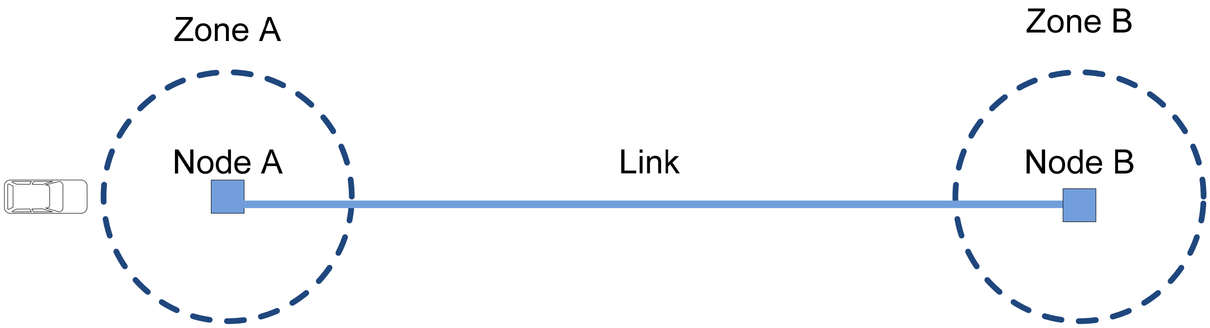


Figure 1-1: Segment composition

The purpose of this study is to investigate the Bluetooth travel time errors that are inherent to the collection technique. In particular, the authors realize that the travel time reported by the Bluetooth device will be subject to the following sources of error:

- Spatial error: A Bluetooth-equipped vehicle may be detectable anywhere in the circle of the detection zone. However, the detection zone radius varies with different Bluetooth detectors, in-traffic Bluetooth devices and environments. Furthermore, since Bluetooth signal is easily affected by home appliances, such as microwaves and wireless phones in residential areas (Bullock et al., 2010), the detection zone formed by an omni-directional antenna is usually an irregular shape rather than an ideally round circle area.

- Temporal error: A Bluetooth-equipped vehicle can be detected anytime in a time range of up to 10.24 seconds after it enters the detection zone. It can also be missed entirely or be detected multiple times depending on the time it stays in the detectable area. The time until its first detection is determined by several factors, such as the probabilistic characteristics of channel hopping behavior, the signal strength from the Bluetooth device, sensitivity of the Bluetooth detector, etc (Special Interests Group, 2009).

- Sampling error: This type of error results from the sampling process of the Bluetooth devices in the traffic. First, multiple Bluetooth devices in the same vehicle may be regarded as several vehicles and the same vehicle's travel time will be duplicated in calculations. Second, fast-moving cyclists could be counted as vehicles, since Bluetooth-based method collects travel time data from multiple transportation modes, such as pedestrians, cyclists, and bus passengers in addition to motor vehicles, unlike an ALPR reader that only collects motor vehicle travel time data.

To analyze Bluetooth travel time error, ALPR data is used. Relative to the large detection zone of a Bluetooth device, an ALPR has a very small detection window, resulting in a small travel time error, particularly at higher speeds (Mizuta, 2007). Therefore, the ALPR collected travel times are chosen to serve as the ground-truth data in this study. After travel times are calculated from Equations (1) and (2), the absolute travel time error $E(k)$ for each period *k* can be calculated as

$$E(k) = \left| TT_{BT}(k) - TT_{ALPR}(k) \right| \tag{3}$$

The absolute travel time error will be used to compare a variety of Bluetooth sensor configurations to determine which is most accurate when compared to ALPR sensors mounted at the same location. The short length of the corridor greatly exacerbates any detection errors, and while this ensures that the error will be of significance and its determination relevant.

2 REVIEW OF PREVIOUS WORK

Travel time information is regarded to be of primary importance in user information systems. As of 2005, over 300 million dollars have been invested into Dynamic Message Signs nationwide with the Federal Highway Administration (FHWA) recommending that the default message (when higher priority information is not available) should state estimated travel times to popular destinations. Such systems have gained much support from the public as well, with 85-90% of roadway users responding favorably in cities to implement such systems, such as Seattle and Salt Lake City (Meehan, 2005). However, the quality and usefulness of the DMS-based travel time information greatly relies on travel time accuracy. Inaccurate travel times can have a detrimental effect on the system, as users lose trust in the posted travel times and do not alter their decision based on the information provided. Thus, understanding the accuracy of the available means of collecting travel time information is critical. The FHWA guidelines suggest a maximum error of +/-20%, with an ideal goal of +/-10% error. An overview of current travel time data collection methods and their associated error sources follows.

2.1 PROBE VEHICLE-BASED TRAVEL TIME ANALYSIS

Probe vehicle based analysis relies on a willing volunteer vehicle, or set of vehicles to provide travel times that are encountered along the corridor in question. Probe vehicles may be simply hired vehicles that drive the corridor and report travel time or can be GPS-equipped vehicles that relay their exact coordinates from which corridor travel time information can be extracted. This type of data collection has been fairly expensive in past, involving the use of special vehicles and hiring drivers, but has recently become much more affordable due to increased use of GPS among fleet vehicles as well as the capability of purchasing GPS data from routing service providers such as TomTom or Google. While individual, representative, “pilot” vehicle results can be very accurate, results coming from fleet services such as taxis and delivery trucks may be significantly different, depending on the number of stops the driver makes. Additional concerns can be raised for GPS data coming from freight trucks, as their speeds tend to be different from passenger cars under identical conditions. Another potential drawback of using GPS probe vehicle data is the relatively small sample size that can be attained. Test vehicle runs often represent an insignificant fraction of the total volumes and fleet-based GPS penetration rates are also quite low if one considers the size of the whole traffic population.

2.2 LICENSE PLATE READER-BASED TRAVEL TIME ANALYSIS

ALPRs extract travel time data by reading license plate numbers at one location and matching them with those read at another using Optical Character Recognition (OCR) software. This approach provides a nearly complete record of the vehicle populations within the lane of analysis, with detection rates of up to 98% possible using properly mounted cameras (Mizuta, 2007). The accuracy of this approach is very high due to a very limited detection zone and nearly instant recognition, however false positives may occur due to an improper OCR match, resulting in erroneous data. Such error rates have been noted to be around 8%. (Pokrajac, 2009).

ALPR systems demonstrate some of the most accurate results; however their cost is often prohibitively high. In order to instrument a four-lane arterial, a minimum of 8 sensors is needed (4 at each corridor location, 2 in each direction). Sensor prices have been around $10,000 apiece, resulting in an $80,000 price tag that does not yet include mounting arms/booms and installation costs. The expenses involved with such systems have resulted in their limited deployment, despite their advantages in accuracy.

2.3 TRAVEL TIME ESTIMATION USING HISTORICAL DATA

Travel time estimation using historical data in conjunction with available sensor data, predominantly loop, has been a popular means of estimating travel time. Speeds obtained from individual loops using an average vehicle length are extrapolated over the corridor and the corresponding travel times are computed and compared against historical data (Monsere et al., 2006). This approach requires existing sensor infrastructure as well records, and thus may not be applicable in all corridors; however the greatest concern is one of accuracy. A study by Monsere et al. shows that on average the link travel time estimates obtained by such an approach are within the FHWA-suggested 20% error margin. However, the study found that incidents and special events create situations where this approach is no longer within the accepted accuracy range.

2.4 MAC ADDRESS-BASED TRAVEL TIME ANALYSIS

The increasing ubiquity of electronic devices in our daily lives, combined with the need for those devices to communicate among each other has created a steady stream of information that is generated and maintained around our immediate vicinity. This has since become a lucrative information source for all those wishing to determine travel patterns of individuals, with tracking happening in zoos, shopping malls and airports (Bullock, 2010). Of the several available data exchange protocols available, Bluetooth has become by far the most popular. The transportation community has become increasingly interested in Bluetooth tracking, particularly for the collection of travel time data (Ahmed et al., 2008; Wasson et al., 2008; Tarnoff et al., 2009; Haseman et al., 2010; Haghani et al., 2010 and Quayle et al., 2010). Tracking via Bluetooth provides an inexpensive and simple means of collecting data that could otherwise be obtained using probe vehicle or ALPR only. Thus, the number of jurisdictions that are interested in using Bluetooth sensors has increased drastically with applications ranging from work zone delay estimations (Haseman et al., 2010) to facility improvement “before and after” studies and traveler information systems.

The popularity of the approach can be attributed not only to the significantly lower costs of data collection, but also to the relative ease of the sensor construction and customization. In fact, there appears to be at least half a dozen groups in the U.S. that are now manufacturing their own Bluetooth sensors (Traffax, TraffiCast, CalTrans, WSDOT/UW, TTI, Kittleson). Although the basic hardware for these devices may be similar, the antenna choices (physical size, directional properties or gain) and mounting strategies vary. While this creates a good opportunity for innovation and experimentation, relatively little research has been done to systematically evaluate the effects of these variables on the detection accuracy of the devices. Haghani et al. compared Bluetooth travel time with floating car data, demonstrating that the travel times collected by Bluetooth sensors are not significantly different from actual travel times (Haghani et al., 2010).

Even though the Bluetooth-based method has been demonstrated on freeways and arterial corridors, several important issues have not been addressed by previous studies. The first one is the temporal error introduced by the channel scan process. Bluetooth splits the 2.4-GHz band into 79 channels with 32 of them used for detecting nearby devices during the discovery process. Typically, a Bluetooth detector sends a message to each channel repeatedly and waits for the reply from the nearby devices. Although the discovery process takes about 5 seconds on average, it may take up to 10.24 seconds in theory (Huang and Rudolph, 2007). In other words, a Bluetooth device may be detected at any time from 0 to 10.24 seconds after it enters the detection range, resulting in errors in travel time estimation.

The second issue lies in the spatial uncertainty regarding when a Bluetooth MAC address is registered. The Bluetooth-based method is subject to various spatial errors because of different device types, antenna types, and geometric configurations of Bluetooth detectors. Given the above spatial and temporal uncertainties, the accuracy of Bluetooth-based travel time measurements is unclear to the researchers and practitioners. The last issue relates to noisy sources of MAC addresses. Detected Bluetooth devices may be carried by passenger cars, buses, bicycles, or pedestrians. Proper filtering procedures must be applied to screen out the travel time measurements from transportation modes other than those of interest. Therefore, an in-depth analysis of errors in Bluetooth MAC address-based travel time data is important for understanding the limitations of this new technology.

Error modeling has been widely employed for sensor evaluation and calibration (Feng and Potkonjak, 2006). Recently, Bluetooth error models have been developed by Hao-Hsiang and Ling-Jyh (2008). However, the analytical models only considered the error resulting from the theoretical channel hopping process using Markov chains. Such models are difficult to use for real-life applications and are not directly helpful for understanding the errors associated with the travel time data collected by the Bluetooth-based method.

This investigation attempts to better characterize the error that is inherent to the Bluetooth detection technology by formulating an initial relationship between error and antennae type and strength and mounting configurations. License plate matching systems are used to provide ground-truth results regarding travel time data. The objectives of this study were as follows:

- Develop a Bluetooth MAC Address Detection (MACAD) system;
- Extract travel time data for a highway section using Bluetooth MAC address matching;
- Evaluate the travel time data error of the Bluetooth-based method by comparing travel time data between those extracted from Bluetooth MAC address matching and those resulted from ALPR;
- Conduct a thorough investigation on error sources of the Bluetooth-based method; and
- Propose error control guidelines for Bluetooth-based travel-time data collection.

3 SYSTEM DESIGN AND DEVELOPMENT

3.1 SYSTEM DESIGN

As of early 2009, there were very few commercially available Bluetooth readers on the market, with their accuracy levels largely untested and unknown. Furthermore, in order to understand Bluetooth-based travel time measurement errors, a number of different configurations involving different antennae had to be tested, requiring a custom solution. Therefore, a significant amount of effort was invested into designing and testing a device that would be not only able to perform well but was also very modular. Additional considerations were made for the devices' eventual professional use, allowing not only a variety of antenna choices but also power and communications options.

3.1.1 Design Evolution

Throughout the project, the designed MACAD device has gone through two version changes and a number of upgrades. Figure 3-1 outlines the evolution of the device throughout the year-long project. The first version of the device was designed based on a Gumstix platform. The Gumstix platform provides a full Linux-based operating system running on a 600 MHz processor, all on a footprint about the size of a stick of gum (Gumstix, 2010). The device was powered by eight "D" cell batteries which allowed it to function continuously for 40 hrs. At the time an 8 dBi "rubber duck" external antenna and a 12 dBi in-lid antenna was used with a DCE-ANT NEMA 6 rated enclosure. Although this setup provided ample processing power and functioned well, there were concerns about the relatively short running time as well as the use of "D" cell batteries in wet environments, which was not recommended by WSDOT field engineers.

To reduce power consumption, a 60 MHz processor was chosen for the second version of the device (V2.0). This greatly increased run time, allowing the device to operate for 5 days on just six "D" cell batteries. However, concerns about oxidation of the batteries, as well as the general wastefulness of single-use batteries prompted a rechargeable battery-based system. Version 2.1 of the system included a Lithium-Iron (LiFE) rechargeable battery and an N-Male interface that allowed for a variety of waterproof, external omni-directional Laird antennae to be mounted on the device.

After completing V2.1, questions arose about data communication – previous versions have been saving the data onto MicroSD cards which had to be extracted prior to data analysis. Although this was convenient for short tests, additional information during longer tests was seen as an advantage. Eventual practical deployment of the device also would require a means to transfer data in real time, allowing for use in conjunction with user information systems. A GPS/GSM module was added to the device to resolve communications as well as clock synchronicity issues. Finally, a custom board was designed to hold all of the components and yet another battery was chosen. The reasoning behind switching from LiFE to Lithium Polymer (LiPo) batteries was mainly practical – LiPo batteries could be charged significantly faster, on the order of hours, compared to days when using LiFE batteries. With the design finalized, four units were produced for field testing. The exact end product is described in greater detail in the following section.

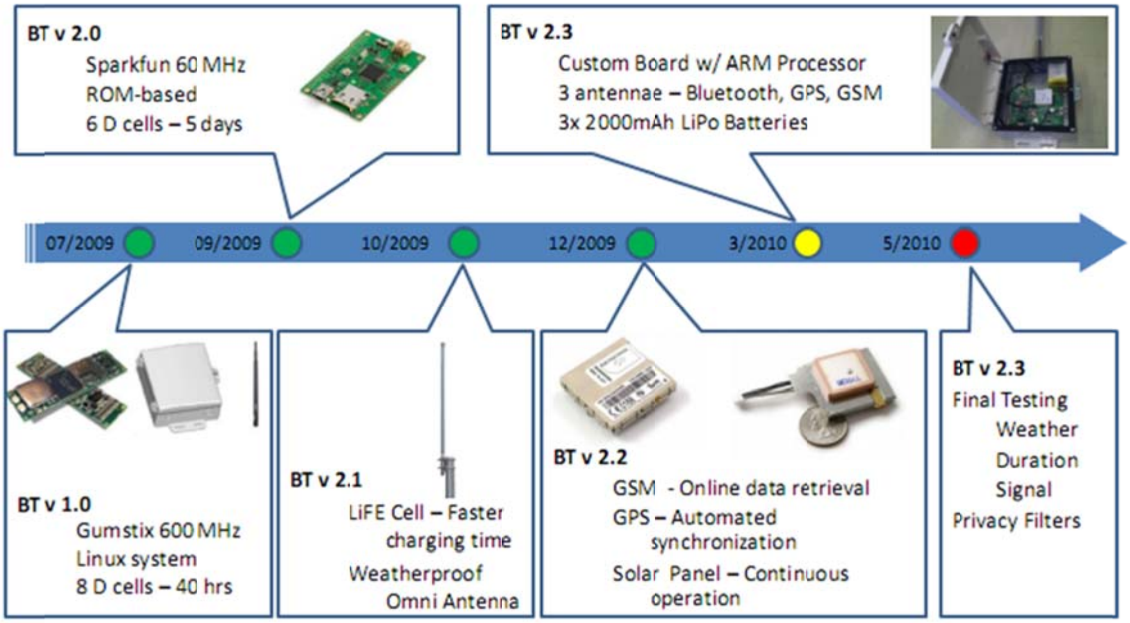


Figure 3-1: MACAD device evolution

3.1.2 Current Design Overview

As alluded to in the previous section, the current device design consists of three main components; (1) a Bluetooth chipset that constantly scans the available 79 channels, (2) a 60 GHz ARM processor that records MACs and (3) a communications module that synchronizes to the UTC time and transmits data in near real-time (GPS + GSM). The device is enclosed in a weatherproof NEMA-rated box (254x180x57mm or 10”x7.1”x2.25”) which provides a port for an external antenna as well as a space for a 12 dBi directional antenna in the lid, as shown in Figure 3-2. This provides an excellent base for testing mounting locations and various antennae as it can be mounted to signposts and signal posts and will accept a wide range of antenna types. The current design allows the device to function for up to a week without external power using one 6-cell LiPo pack (15.6Ah capacity @ 3.7V). The device allows for up to two battery packs at a time, resulting in a maximum runtime of two weeks without external or solar power.

a) Mounted device b) Device interior

Figure 3-2: STAR Lab Bluetooth detector (MACAD device) used in this study

Solar power compatibility was also considered in the design and a solar power module has been designed and tested. The device operates using the power provided by the battery which is, in turn, charged by the solar panel. Preliminary testing indicates that the discharge rate is lower than the received solar power input rate, indicating that continuous operation is possible. However, a longer testing phase is necessary to ensure that the chosen solar panel is sufficiently large to power the unit for a full season, as winter solar power tends to be lower, particularly within Western Washington.

3.1.3 **Communications Design**

Once mounted, the device synchronizes to UTC time using the communications module. In addition to synchronizing over the GPS network, the system also sends its exact coordinates via GSM. These coordinates are then used for automatic geospatial organization of deployed sensor units. This initialization routine is repeated at regular intervals to prevent clock drift (Quayle et al., 2010) and ensure that the device is functioning properly and has not been tampered with. Once the synchronization and location recording is complete, the device begins data collection, recording the bypassing

MAC addresses and their respective timestamps. As data is collected, it is sent over the GSM network to a server in STAR Lab, where the MACs are kept for a specified time period (currently 60 minutes). If a matching MAC is received during this time period, a travel time is calculated, the MAC address is deleted and the data is uploaded to the Digital Roadway Interactive Visualization and Evaluation Network (DRIVE Net) developed by the Smart Transportation Applications and Research Laboratory (STAR Lab) at the University of Washington (UW) for data sharing, modeling, and online analysis (Ma et al., 2011). This approach to data collection allows for real-time information flow to the users while maintaining a level of privacy. Figure 3-3 illustrates the overarching structure of the data collection effort.

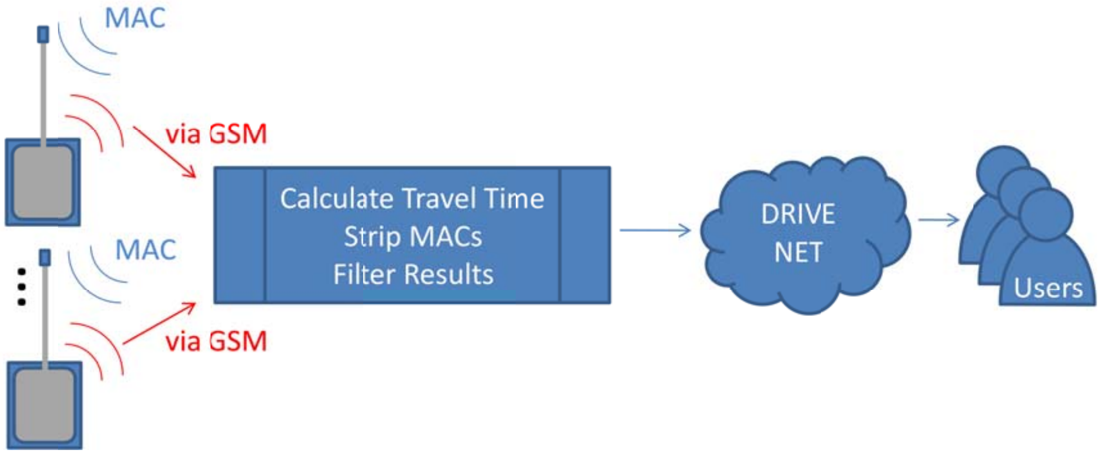
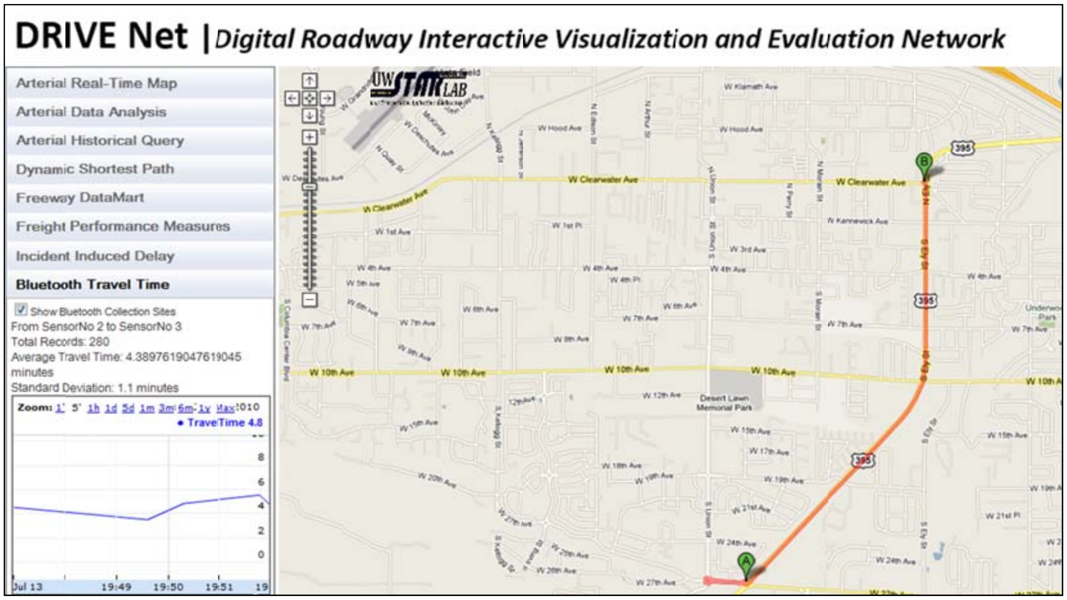


Figure 3-3: Bluetooth data collection and distribution diagram

DRIVE Net facilitates data sharing, visualization, aggregation and allows users to view instrumented routes' travel time in real-time. A screenshot of the user interface for accessing Bluetooth data can be seen in Figure 3-4. A user can click a specific corridor to find relevant information such as average travel time as well as more advanced statistics such as standard deviation. This platform allows for quick and seamless data integration and comparisons, making it an ideal candidate for a data quality study such as this one. Figure 3-4 below demonstrates the system in action – the user has selected a particular corridor that was instrumented with the sensors and is able to view the travel time trend as well as the mean and standard deviation. More details regarding DRIVE NET and the Bluetooth data collection and visualization module can be found in (Ma et al., 2011). Data collected by the sensors can also be retrieved for further processing, which is covered in the next section.



☑ Show Bluetooth Collection Sites
From SensorNo 2 to SensorNo 3
Total Records: 280
Average Travel Time: 4.3897619047619045 minutes
Standard Deviation: 1.1 minutes

Figure 3-4: DRIVE NET Bluetooth data collection interface

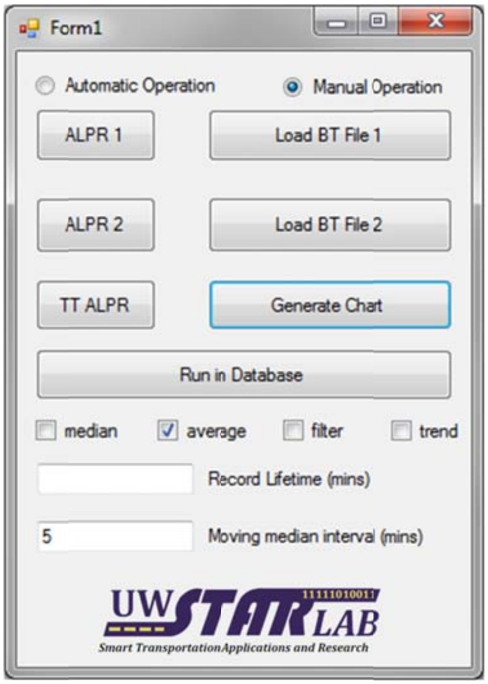
3.2 DATA OUTLIERS AND FILTERING

3.2.1 Outlier Sources

Once the MAC address data has been collected and matched within a 60-minute interval, the resulting travel times must be filtered for outliers. There are numerous potential sources for outliers within the travel time data. Perhaps the most apparent cause is drivers that stop on their way through the corridor, or choose a route that is significantly longer than most users. This creates a delay that is not experienced by other users, thus resulting in an outlier. Since the additional delay is unlikely a factor of the roadway design or any other transportation considerations, it is of little interest in the current scope. This type of outlier is often easy to recognize and is present in both ALPR and MAC address matched travel time data. An additional source of outliers is present only in ALPR data – as mentioned earlier errors in the OCR analysis of license plates can result in matches between plates that are similar in appearance, but are in fact unique (such as plates containing the number "1" and the letter "I".) Although the chances of such an error are quite low (8%, as mentioned before), the resulting errors can cause travel times that are not representative of the general pattern. Multiple modes present on the same corridor can also be a cause for outliers when one is looking at auto-only travel times. Since there is no way to discriminate between the modes using MAC addresses alone, the discrimination step occurs during the filtering of the travel time data. Procedures used to screen and filter travel time data obtained from MAC address readers are described in the following section.

3.2.2 **Data Filtering**

A customized program used to process both ALPR and Bluetooth MAC address data was written in C# to facilitate analysis. A screen shot of the software is given in Figure 3-5. The software system is capable of processing the data manually, using two or more ALPR and/or ALPR text files for matching (obtained from the MicroSD cards mounted in the MACAD devices), or doing it automatically using data that is sent to the server using GSM communications. Regardless of the source of the data, the filtering and aggregation techniques are identical.



○ Automatic Operation ● Manual Operation

☐ median ☑ average ☐ filter ☐ trend

Record Lifetime (mins):

Moving median interval (mins): 5

Figure 3-5: STAR Lab MAC address processing software screenshot

In addition to varying the record lifetime, which effectively filters any travel times above a certain length (60 minutes was used in this study), the software allows for a moving median analysis to be used on the data. A moving median filter, based on the one used by Quayle et al. is used. A standard deviation calculation based on a sliding time window is used to filter the results:

$$\sigma = \sqrt{\frac{1}{t}\sum_{i=x-\frac{t}{2}}^{t}(p_x - \mu)^2} \tag{4}$$

where t is time window, $p_x$is the travel time at timestamp x and μ is the mean calculated for the time window **t**. If a particular travel time measurement was within one standard deviation above the localized mean, it was accepted as a valid data point. A **t** of 15 minutes was used in all analysis scenarios, as it provided sufficient resolution to demonstrate any congestion delay peaks, but large enough to smooth over occasional outliers mentioned above.

Offline analysis for small data sets is performed with Excel – the software system automatically outputs aggregated data from all included sources as an ".xls" file. Online analysis is performed using Google Maps API tools, which an interactive timeline interface, allowing the users to view ongoing trends within a specified time window and provides basic statistics such as average trip time and standard deviation for the selected time window.

4 SYSTEM TESTING

4.1 SR-520 FREEWAY TEST IN SEATTLE, WA

One of the primary concerns with Bluetooth detection was the device's ability to capture fast moving vehicles. As mentioned before, since the Bluetooth protocol requires up to 10.24 seconds to detect a vehicle, it is imperative that the detection range of the MAC address collection device is sufficient to work at high speeds, for example is a vehicle is moving at 60 mph, the detection zone needs to be about 900 ft (275 m) in diameter to guarantee that the vehicle is in range for 10.24 seconds. A freeway test was done on February 22nd, 2009, early in the development cycle, to ensure that sufficient data could be collected when fast moving vehicles were present. The chosen corridor was a 3-mile long section along the SR-520 floating bridge in Seattle, WA at 24th Ave and 76th Ave overpasses. The speed limit on the bridge is 55 mph. Average speeds in free-flow conditions tend to be around 60 mph. A portable ALPR system was loaned from WSDOT to check the accuracy of the obtained data. Figure 4-1 shows: a) the locations chosen for testing (the west side locations is at 76th AVE and the east side location is at 24th AVE) and b) the testing setup the 24th Ave location. The MAC address readers were equipped with 7 dBi antennae.

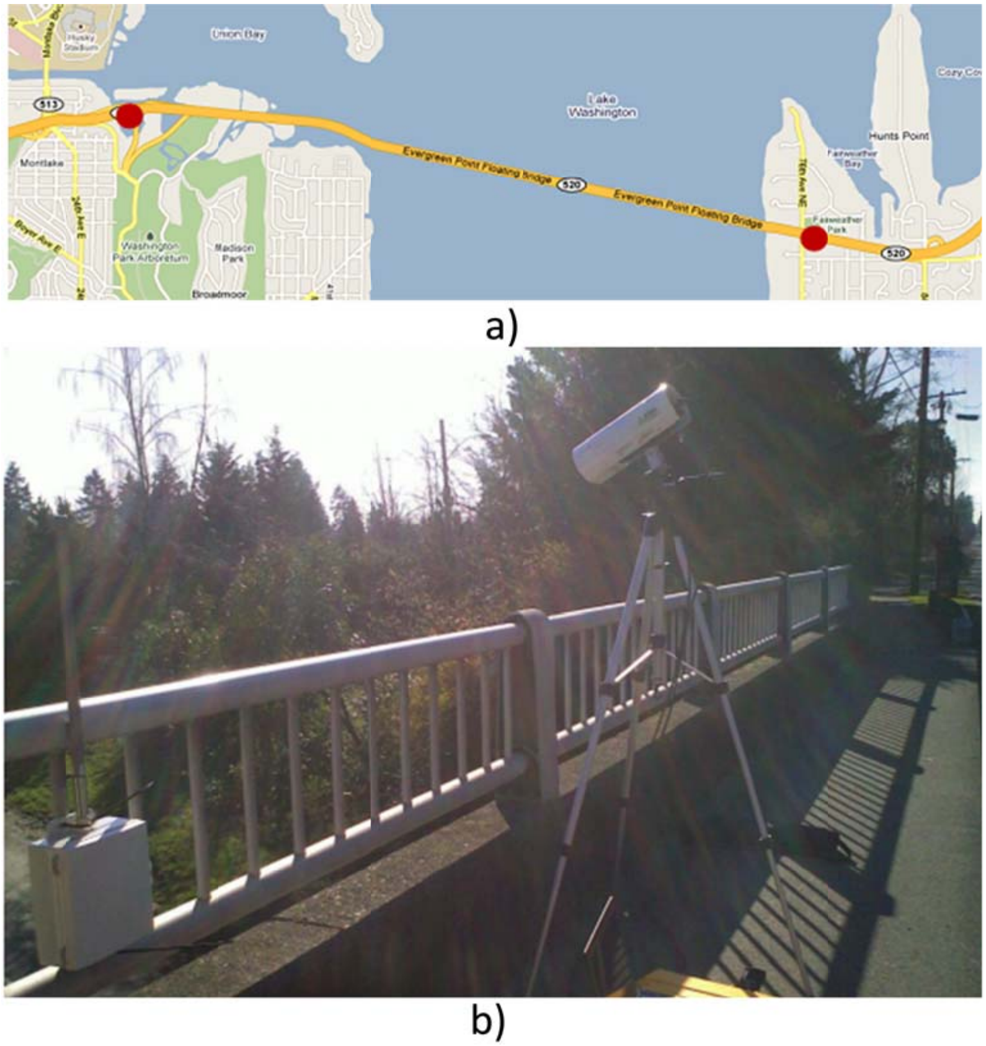


Figure 4-1: a) Selected freeway test corridor on SR-520. b) Bluetooth sensor (left) and portable ALPR (right) used to collect travel time data at the 24th Ave location.

The results confirmed the device’s ability to collect data on freeways, with the system collecting a sample that was consistent with what can be expected on arterials. During the hour long test, from 8:00 am to 9:00 am the ALPR devices captured 1957 vehicles at the 24th Ave location and 1368 vehicles at the 76th Ave location. It is important to note that the ALPR sensors were capturing just one of the two lanes, and only one direction – westbound. The number of unique MAC addresses obtained at the two locations were 432 and 190, respectively. A shielding effect of one of the concrete barriers on 76th Ave overpass is thought to be responsible for the lower detection rate. The matching rate was 61% for the corridor, 116 matches (of a maximum possible 190), compared to the ALPR system's 39% or 533 matches (of a maximum possible 1368). Although the ALPR system was able to obtain more samples from a given direction, the MAC address method was capable of covering all lanes and both direction while providing a higher matching rate.

The acquired travel times were aggregated and filtered as described above and the two means of collecting the data were compared. Figure 4-2a shows the comparison between ALPR and Bluetooth travel times on SR-520 in the westbound direction (the only direction measure with ALPRs). The average error for the hour-long test was 9.6%, ranging from 6% to nearly 20%. One of the most noticeable trends is the fact that all the error obtained was positive. In other words, Bluetooth based travel time estimates were consistently above the "ground truth" ALPR measurements. However, in this test the exact location of the centerlines and detection zones of the Bluetooth and ALPR sensors was not known, thus a compensating adjustment had to be made. The two data sources were also compared by adjusting the two datasets to a common mean. After a mean shift of .293 minutes, the error rates reduced to a maximum of 9.4% and a minimum of -3.95%, well within the FHWA recommended values. Figure 4-2b shows the resulting error and Bluetooth travel times after adjustment.

Although the SR-520 test site would have been ideal for longer testing using a number of configurations, as is done with SR-522, the use of a portable ALPR unit required in-person data collection at both ends of the corridor. Further restrictions were encountered due to WSDOT security concerns on freeway overpasses, therefore allowing only an hour of testing to be performed. SR-522 is equipped with permanently deployed ALPR units, making data collection there significantly easier.

It should be noted that the Bluetooth readers were mounted at a height of about 30 feet above the roadway in this scenario. This results in a significantly larger detection zone compared to what is experienced when the sensors are mounted near ground level (about 5 to 7 feet). The antennae used in the experiment have downward tilt of about five degrees, so the range of the antenna increases with height above ground plane. With the sensors mounted at a height of 30 feet, the detection range theoretically grows to about 400 feet (radius), giving an 800 foot detection zone, or the capacity to detect about 80% of the “detectable” traffic, which is consistent with the 60% matching rate observed.

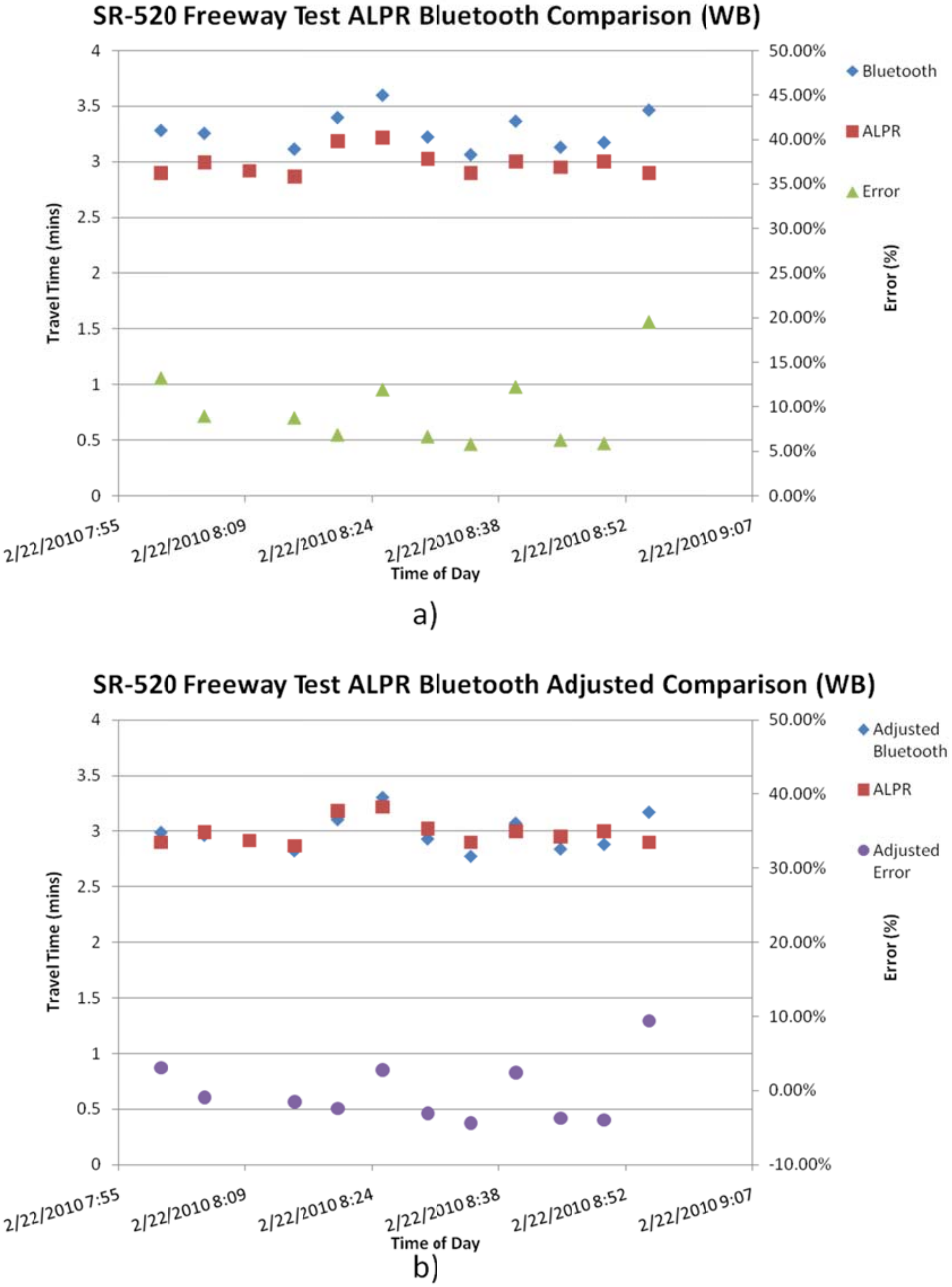


Figure 4-2: SR-520 freeway test

4.2 RURAL TESTS IN RICHLAND, WA AND YREKA, CA

An additional concern of using MAC-address based data collection was the overall penetration rate of MAC broadcasting devices. Rural communities feared that the population demographics and characteristics in metropolitan regions were sufficiently different and perhaps more “tech savvy” than those living in rural areas. It was therefore believed that MAC-based data collection would be less effective due to smaller sample sizes. A smaller city in rural Eastern Washington and a rural section of I-5 in California were tested to determine the validity of such concerns.

Richland, WA is a city of about 47,000 and, despite being located in a rural setting, is near a significant amount of hi-tech industry (Washington State Office of Financial Management, 2009; Weiss and Schmitt, 2009). SR-240 and the intersections of Van Giesen St and Swift Blvd were the primary focus sites in the study, as the mile-long corridor experiences significant peaks in traffic volume during morning and afternoon rush periods. Figure 4-3 shows MAC address based travel time data collected by the MACAD devices on July 12th through 14th in Richland. Southbound travel time values are positive, while northbound values are shown as negative. There appears to be a sufficient amount of data present within the city. The data clearly depicts the morning southbound peak (larger concentration of devices), yet it causes little delay. The afternoon peak however, is clearly visible in the opposite direction and increases travel times by up to three times. This type of information is useful for growing rural cities such as Richland and shows that there is sufficient MAC broadcasting devices in such areas to consider further studies or deployment.

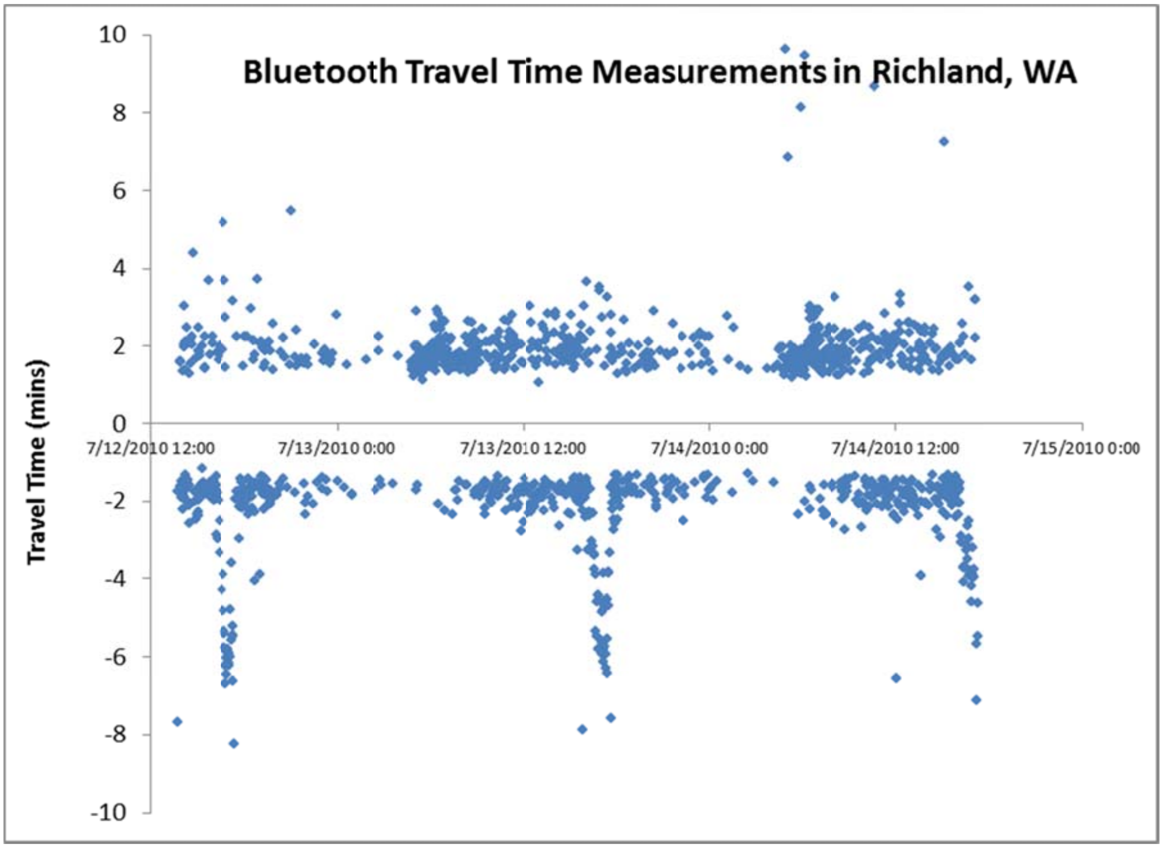


Figure 4-3: Bluetooth travel times collected by the MACAD devices in Richland, WA

Additional testing in Yreka, CA occurred on a 7.6 mile stretch of I-5, with average speeds often exceeding the 70 mph speed limit. This location provided an opportunity to further test the device in high-speed freeway conditions, as well as rural areas without a significant commuter volume. The test proved that the MACAD devices are capable of detecting vehicles even at these higher speeds. Furthermore, the number of bypassing MAC-broadcasting devices was noted to be much higher than anticipated, staying close to the 10% range recorded in urban areas. The prevalence of Bluetooth headsets among truck drivers is considered to be a potential factor in such a large number of devices broadcasting in rural areas.

5 EXPERIMENT DESIGN

5.1 SR-522 ALPR TEST CORRIDOR

5.1.1 Corridor Description

A 0.98 mile section of SR-522 (Bothell Way NE), shown in Figure 5-1, was selected for this study. The section is located on the northwest section of Lake Washington in Washington State. This corridor is ideal due to the availability of ALPR data along the corridor, minimal pedestrian and cyclist presence and a high volume of over 50,000 vehicles per day (Mizuta, 2007). The section starts at NE 170th Street in the City of Lake Forest Park and ends at 61st Ave NE in the City of Kenmore. The short length of the corridor emphasizes the need for error analysis and mitigation – the Bluetooth device range, especially for stronger antennae can contribute significantly to the travel time error encountered, as most travel times within the corridor are less than 2 minutes.

Figure 5-1: Study route on SR-522 [Image from maps.google.com]

5.1.2 **Corridor Spectrum Noise Testing**

Spectrum data was collected for this experiment to ensure that there was not a significant source of background noise that would severely impact detection quality. Since the Bluetooth protocol uses spread-spectrum frequency hopping, the device skips from frequency to frequency, thus largely not impacted by local sources that may be operating within a narrow band of the 2.399 MHz to 2.483 MHz spectrum. However, additional Wireless Local Area Networks (WLAN) located at the same location could significantly impact the detection performance by occupying large portions of the spectrum and rendering it unusable. Since WLAN networks have only 11 different channels, each of which occupies 22 of the 79 available Bluetooth channels (Hewlett Packard, 2002), the presence of multiple WLAN networks in the area could significantly reduce performance if the signal strengths of those networks is sufficient. It is important to ensure that the test sites chosen do not contain significant contamination of the 2.4 GHz spectrum.

Figure 5-2 below shows the spectrum characteristics at the 170th ST NE site. Each point on the graph represents a one-hour average along a 327 KHz strip of the spectrum, for a total of 256 strips. The location does appear to have several active networks that occupy some bands, but the signatures are narrow, thus creating little competition for Bluetooth devices. More importantly, the magnitude of the detected networks is very small, with the highest peaks reaching well under -100 dBm. Signals below -100 dBm are considered to be out of range for the directional and omni-directional antennae, thus having little impact on the detection speed.

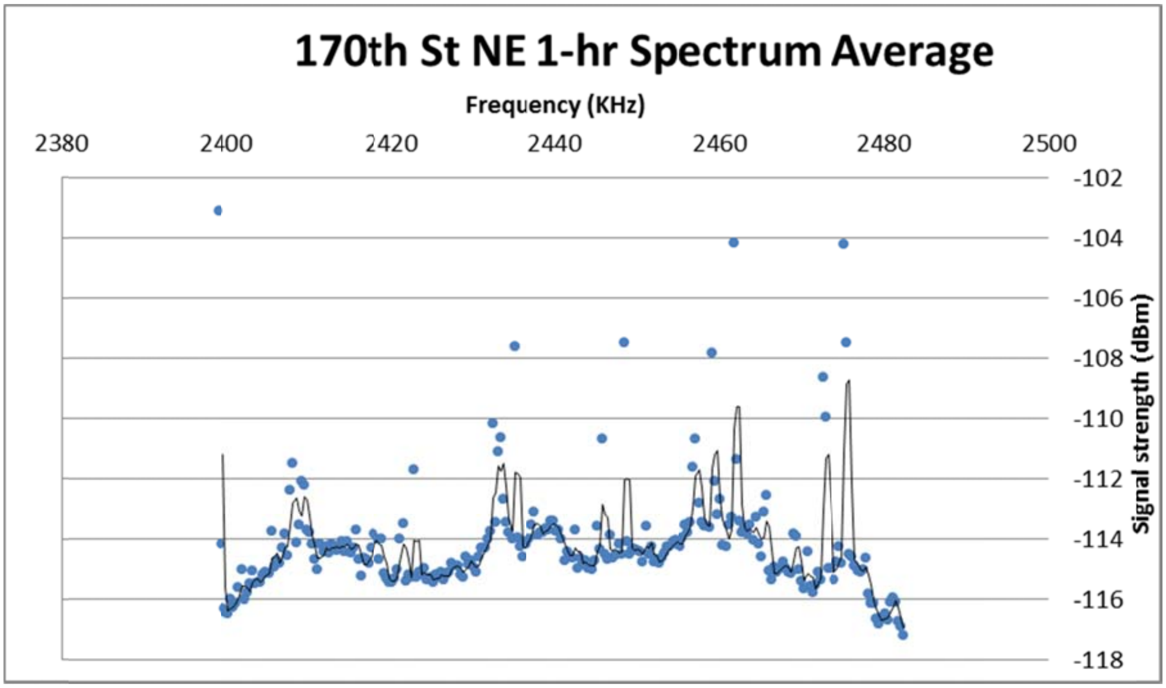


Figure 5-2: Spectrum average for 170th St NE.

Figure 5-3 shows a similar diagram for the NE 61st Ave site. The signature at this location is slightly different, as there appears to be two WLAN networks present, show on the right side as the wide peaks. However, the signal strengths are still too weak to cause any significant interference to the Bluetooth detectors.

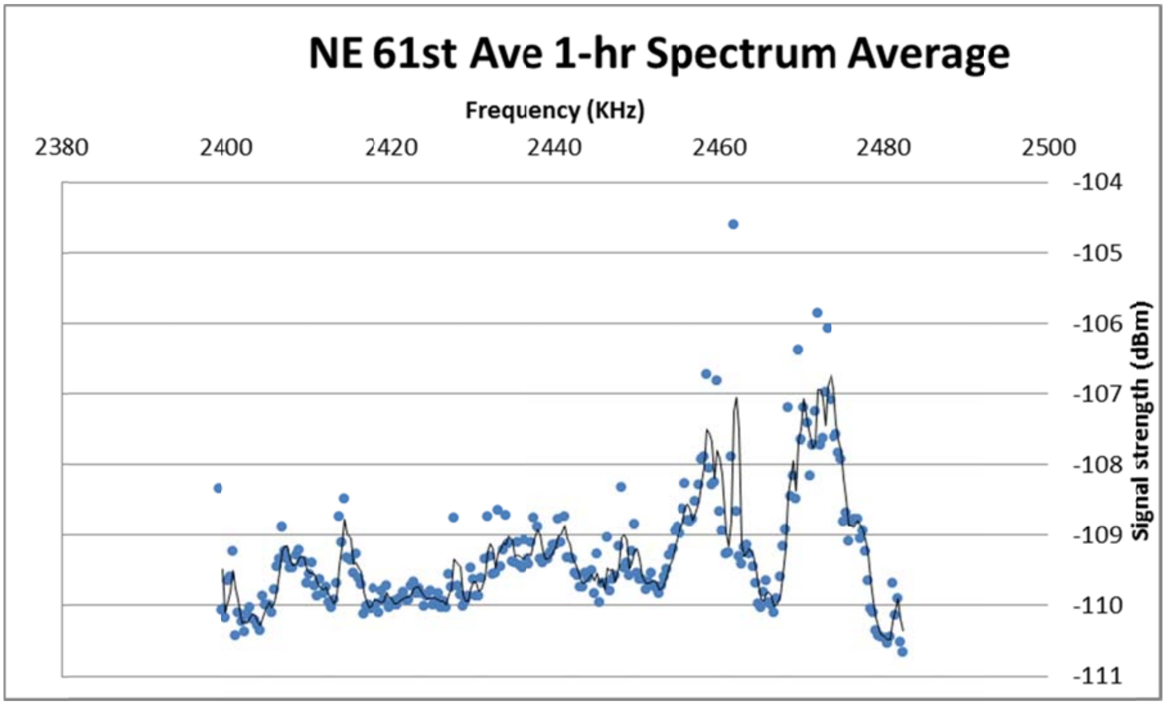


Figure 5-3: Spectrum average for NE 61st Ave.

To determine the effects of mounting two MACAD devices adjacently and operating them concurrently a short test was done to see the number of "collisions" that the devices would experience. Figure 5-4 below demonstrates the overall noise levels that are present when one device is scanning vs. when two devices are scanning. The graph shows the full 2.399 to 2.483 spectrum on the x-axis and time on the y-axis. Green areas represent "clear" sections of the spectrum where signal was strong. Yellow represent sections with some interference and the red sections represent moments when there is strong interference, indicating that another device was also using the spectrum. The testing was done at the 170th St site. Based on the resulting images, it is difficult to say that an additional Bluetooth device has a significant effect on the number of collision experienced by one device. The amount of red and yellow areas remained roughly the same, indicating that the additional device was unnoticeable among the noise. Both a) and b) of Figure 5-4 below contain about 68% red and yellow sections.

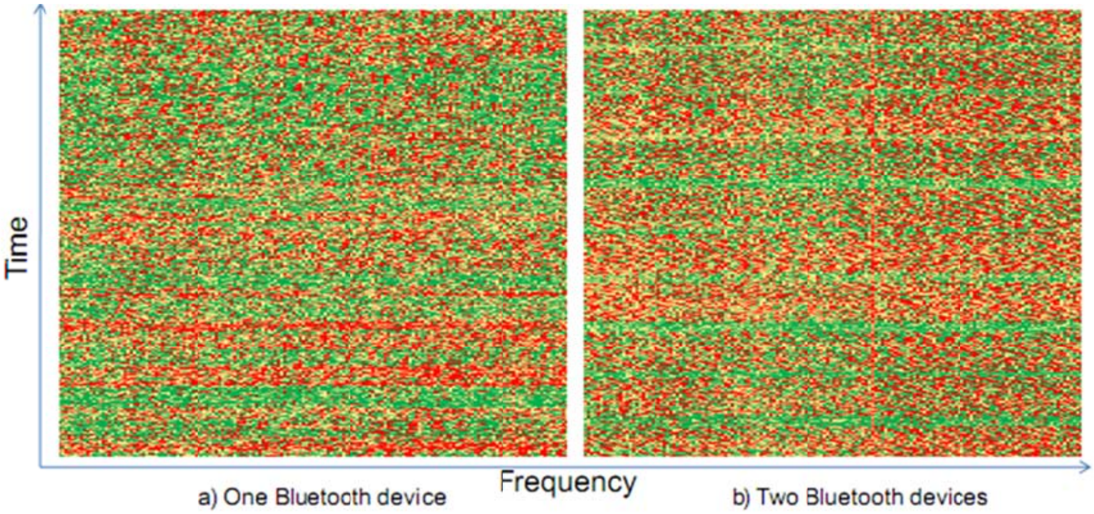


Figure 5-4: Spectrum noise image

5.2 MAC ADDRESS DATA AQUISITION

Up to four MACAD devices were used to collect travel time data, using a combination of antennae types and strengths and on-site placement positions. Table 5-1 shows the variables considered in this study. Three types of antennae were used in testing, a 7 dBi weatherproof omni-directional antenna, a 9 dBi weatherproof omni-directional antenna and a 12 dBi directional, 35 degree vertical and horizontal spread antenna mounted in the lid of an MACAD device. These are denoted as “O7”, “O9” and “D12” in Table 5-1.

The number of detectors at each location, up to two, is also considered as a variable. Finally, when two detectors were mounted at the same end of the corridor, they were either mounted one across from another (opposite), denoted as “O” or at the exact same location, as denoted by “S”. If only one sensor was mounted, “S” is used to indicate no overlap. Lane-ft covered represents the cumulative linear feet covered by the sensor configuration. These values are estimations based on manufacturer specifications and empty-field range testing. The values were computed by overlaying the approximate sensor ranges over the test site and measuring the lengths of the through lanes covered by the sensors. Figure 5-5 shows the lane-ft covered by the 12 dBi directional sensor at the NE 170th St location. The clover-like shape represents the 12 dBi directional antenna bloom as specified by the manufacturer. A total of 11 different configurations were tested and are summarized in Table 5-1 below.

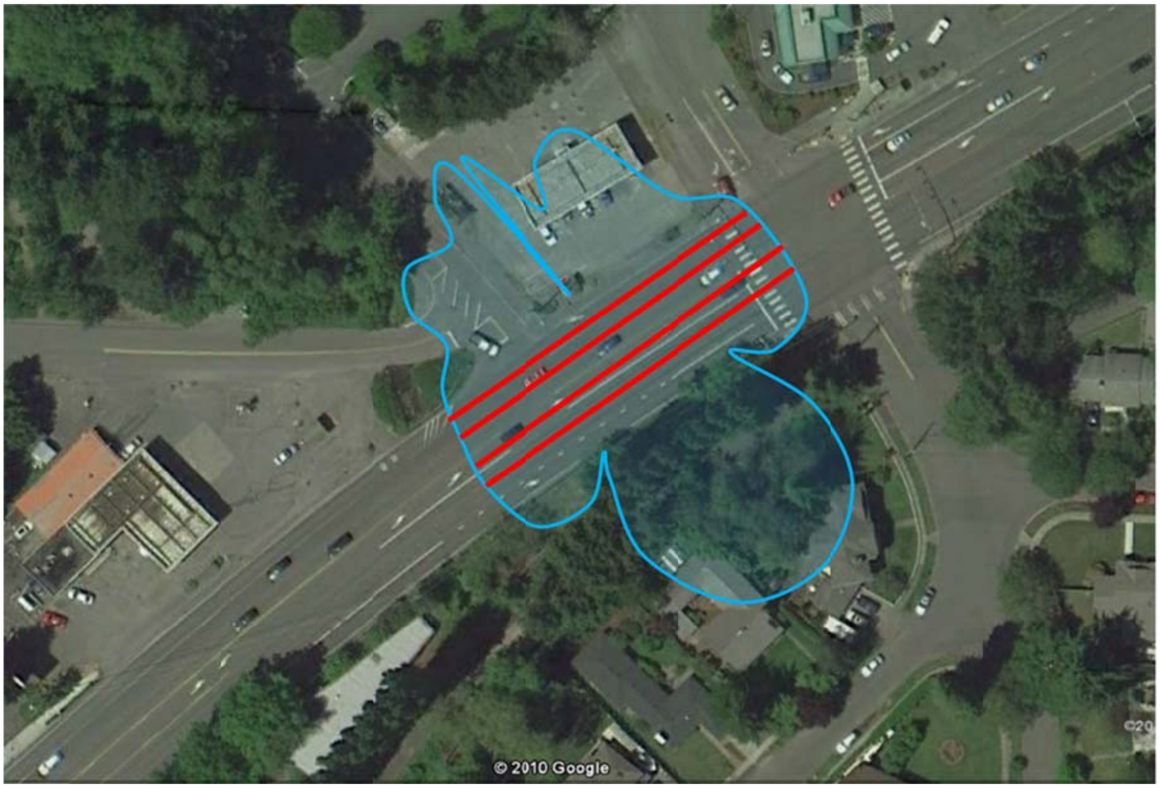
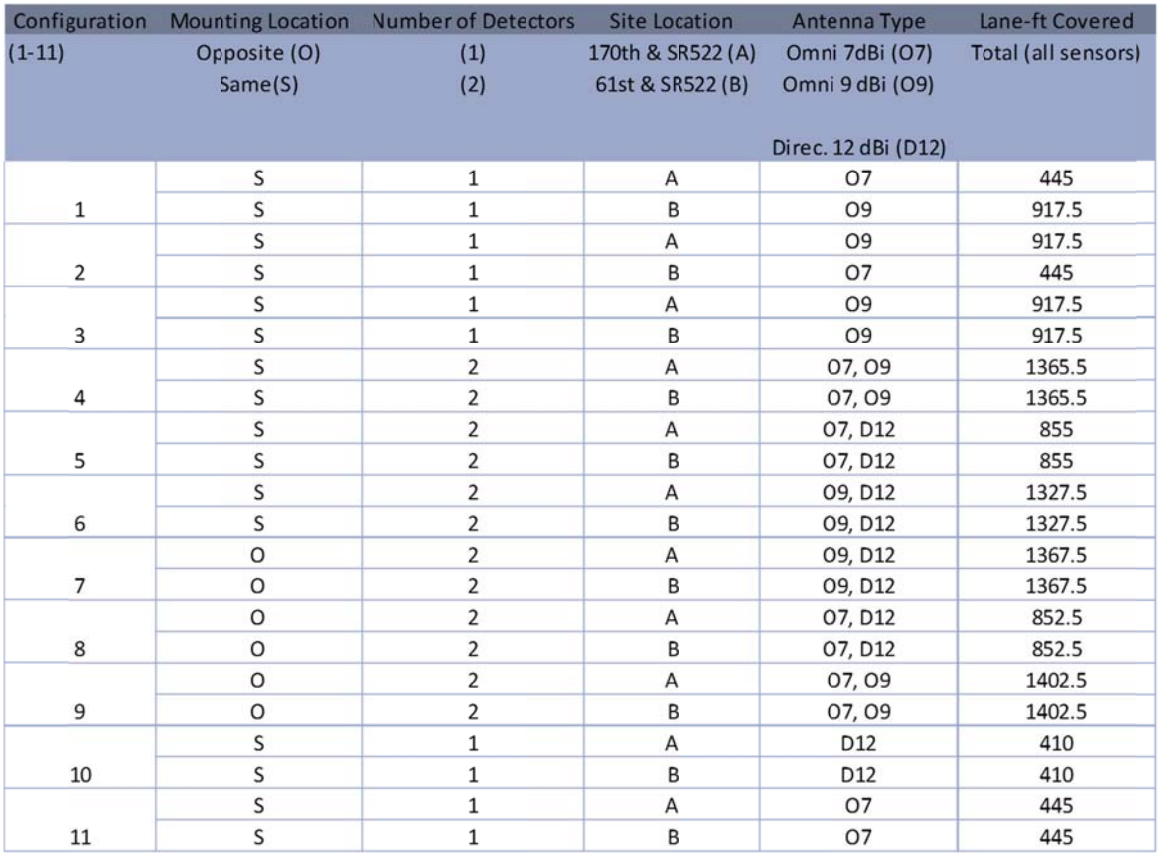


Figure 5-5: Lane-ft coverage of a 12 dBi directional sensor at NE 170th St

Table 5-1: Bluetooth device mounting and antenna configurations



Configuration (1-11)	Mounting Location Opposite (O) Same(S)	Number of Detectors (1) (2)	Site Location 170th & SR522 (A) 61st & SR522 (B)	Antenna Type Omni 7dBi (O7) Omni 9 dBi (O9) Direc. 12 dBi (D12)	Lane-ft Covered Total (all sensors)
1	S	1	A	O7	445
	S	1	B	O9	917.5
2	S	1	A	O9	917.5
	S	1	B	O7	445
3	S	1	A	O9	917.5
	S	1	B	O9	917.5
4	S	2	A	O7, O9	1365.5
	S	2	B	O7, O9	1365.5
5	S	2	A	O7, D12	855
	S	2	B	O7, D12	855
6	S	2	A	O9, D12	1327.5
	S	2	B	O9, D12	1327.5
7	O	2	A	O9, D12	1367.5
	O	2	B	O9, D12	1367.5
8	O	2	A	O7, D12	852.5
	O	2	B	O7, D12	852.5
9	O	2	A	O7, O9	1402.5
	O	2	B	O7, O9	1402.5
10	S	1	A	D12	410
	S	1	B	D12	410
11	S	1	A	O7	445
	S	1	B	O7	445

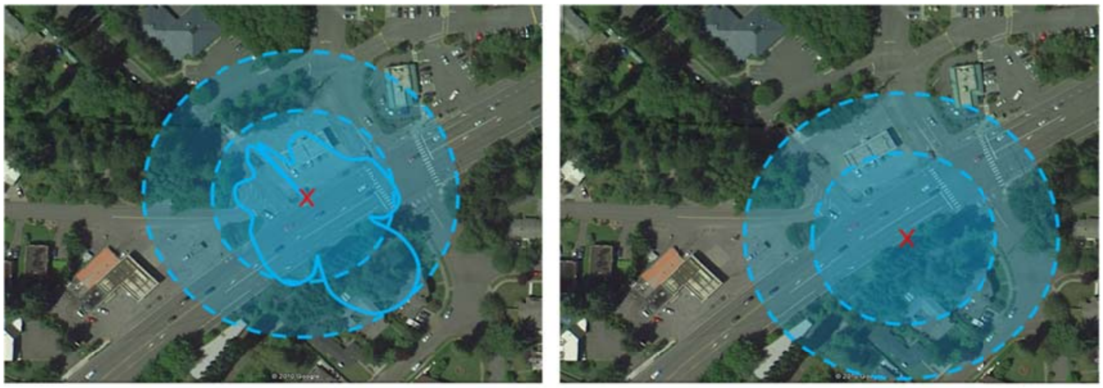
5.3 LICENSE PLATE DATA AQUISITION

The examined section of SR522 has a speed limit of 45 mph and is a six-lane arterial with four inside general purpose lanes and two transit-only outside lanes. ALPR readers are installed on the arms of the intersection signal heads to read license plates from the rear of passing vehicles. All the westbound ALPR readers were designed to read the vehicles traveling in the inside lane (closest to the median). All the eastbound readers were designed to read the vehicles traveling in outside general purpose lane (Mizuta, 2007). ALPR data is reported in aggregated 5-minute averages in the eastbound and westbound directions. ALPR capture rates are also reported upstream and downstream and are used as surrogates for volume data. Details of the installed systems can be found in (PIPS, 2009).

5.4 TEST CONFIGURATIONS

Detectors were conveniently mounted at a height of about 1.5 meters (5 ft) above the ground on roadside signage poles. Directional sensors were pointed across the roadway, near the westbound side of the route, as close as possible to the westbound ALPR detection zones. Figure 5-6 shows all of the possible sensor footprints that were tested in this study and their approximate detection zones. Bluetooth sensor locations are marked with an “x” and ALPR detection zones are shown as rectangles. These footprints were permutated through 11 different configurations that represent the potential variability of setups, bearing in mind the locations of the ALPR sensors. The directional antennae, for example, were only mounted near the ALPR detection zones as other placements were unlikely to produce better results. The westbound side provided convenient mounting locations for numerous sensors and was thus chosen as the primary focus of this study. The estimated ranges for the 7dBi, 9dBi omni-directional and 12dBi directional antennae are 40 meters (131 ft), 70 meters (230 ft) and 40 meters (131 ft), respectively. These sensors were configured to try and match the westbound ALPR detection zones as closely as possible. Eastbound travel times picked by these sensors are likely to be more different from their ALPR counterparts as they are separated by an intersection. This is clearly shown in the collected data and the results are presented separately.

Permutations with identical setups at each of the two locations (NE 170th St and 61st AVE NE) were primarily tested, but two configurations (1 and 2) with disparate antenna strengths were tested as well. Each antenna type was tested standalone as well as in tandem with another antenna type. During tandem tests for configurations 5-9, data for configurations 10 and 11 was extracted by looking at only one sensor set (while ignoring data from the other two). Since the interference between two devices was measured to be minimal, the impact of doing the two tests at once was considered negligible, while providing useful insights into the additional accuracy afforded by the extra devices.



a) NE 170th St

b) NE 170th St (Opposite)

c) 61st AVE NE

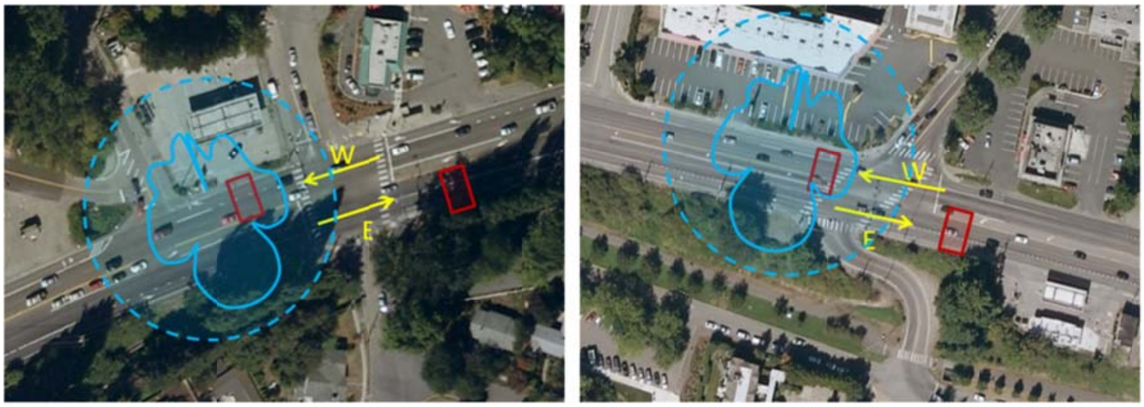
d) 61st AVE NE (Opposite)

Figure 5-6: Sensor configurations [Background images from maps.google.com]

6 FIELD EXPERIMENT AND DATA ANALYSIS

Due to the misalignment between the eastbound ALPR detection zones and the MACAD detection areas, the results for each direction are presented separately. As will be shown in sections 6.1 and 6.2, the westbound measurements were more accurate than the eastbound ones. This is due to the eastbound ALPR detection zones not correlating well with the antenna footprints. Figure 6-1 shows the approximate relative position of the detection zones and footprints. Last-to-last matching, or using the last available timestamp for each bypassing MAC for matching, was used to obtain the travel times on SR-522. This was done in order to minimize the effect of intersection delay on the results, as the timestamp is taken after the vehicles leave the intersection, regardless of direction of travel. Although this approach demonstrated better results than first-first or median matching, it was still insufficient to completely circumvent the problem, as the last timestamp may still occur within the intersection area due to noise and signal blockage issues.

The combinations of mountings, antennae strengths and sensor quantities were tested during the week of July 19th-27th, 2010. The tests were stopped for a break on the afternoon of July 20th to the evening of the 21st, when the ALPR units were switched off for maintenance.



a) NE 170th St

b) 61st AVE NE

Figure 6-1: Sensor detection zones

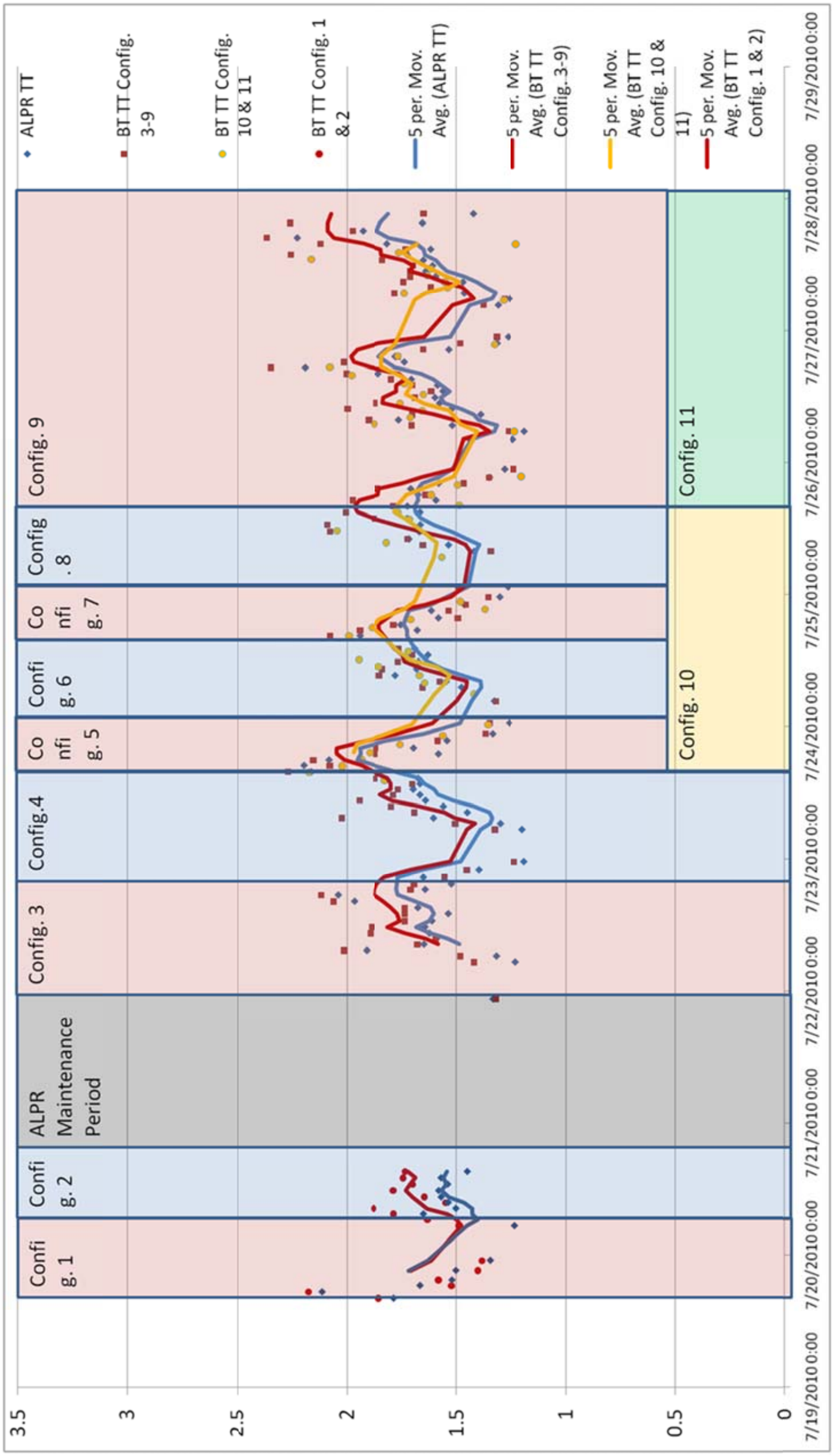
6.1 ERROR ANALYSIS WESTBOUND

6.1.1 **Descriptive Analysis Westbound Direction**

Figure 6-1 shows the 1-hr average travel time results in the westbound direction. Red points and lines are Bluetooth (BT) travel times while blue ones are ALPR travel times. The testing intervals for each configuration are labeled – configurations 10 and 11 run in parallel with 5-9. To differentiate them from other configurations their results are shown in orange. Trend lines are generates using a 5-point moving average window. Overall, the sensors follow the travel time trends recorded by the ALPRs. It can be seen that tandem sensor configurations do a better job of following the trends.

Figure 6-2 demonstrates the 1-hr averages of error rates and volumes encountered during testing in the westbound direction. Total volume in both directions is shown in blue and error in red. The graph is once again segmented into the testing configurations and error rates for configurations 10 and 11 are shows separately in orange. Trend lines were generated using a 5-point rolling average. Since the westbound approach had only one mounting location that was centered at the intersection approach (NE 61st AVE (Opposite), see Fig. 6-1), the results show that although there is some correlation with volume, there are configurations that are not as affected.

ALPR Travel Time (ALPR TT) vs. Bluetooth Travel Time (BT TT) Westbound SR-522



red

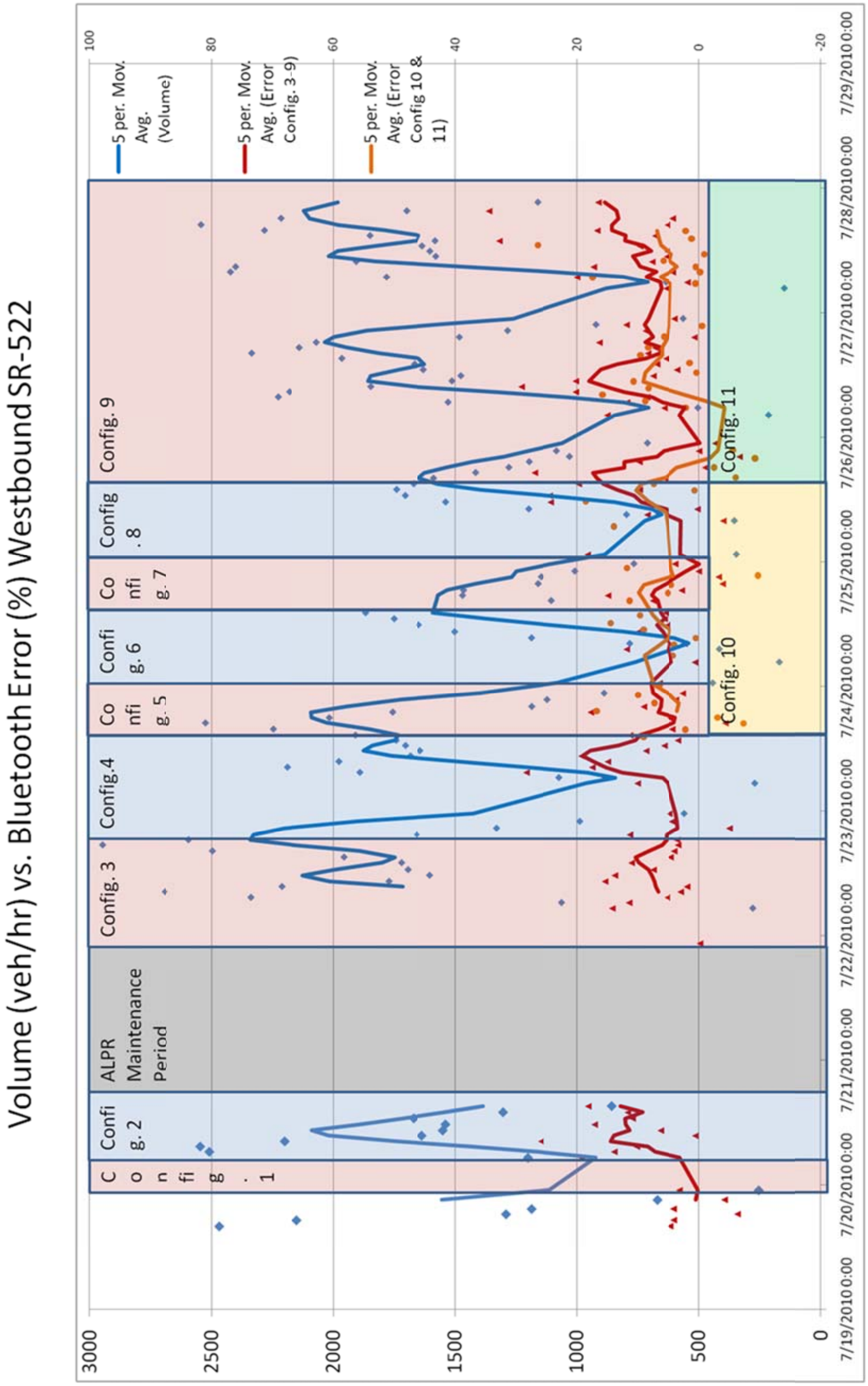


Figure 6-3: Westbound SR-522 error and volume (1hr averages)

Taking a closer look at the westbound data, it can be seen that configuration 5, 6, 7 and 8 appear to be almost unaffected by the additional intersection delay. These configurations contain a directional antenna that successfully discriminates the vehicles waiting at the intersection approach, outside its narrower range. Single sensor layouts also appear to have a lower error. This is expected, as the smaller overall footprint reduces error, which is especially true in the westbound direction, since the MACAD directional detection beam is focused right over the ALPR detection point. This smaller footprint however reduces the total available matches, thus reducing the accuracy of more precise 15-min intervals examined in the next section.

6.1.2 **Error Modeling Westbound**

Initial efforts in interpreting the data focused on modeling the detection rate and relating that to the accuracy of the acquired travel times. However, upon looking at the data collected at the sites chosen in this study, there was no immediate correlation between the detection rate and accuracy. This is likely due to the effect of the delay superimposed by the signal lights. To circumvent this issue, a more generic approach to error modeling was taken, considering all possible variables and their relationship with accuracy. A multivariate regression model was developed for each direction to determine which variables are significant. A 15 minute time window was chosen as an analysis element to show variation in traffic patterns while minimizing the effect of contamination by signal delay. All variables were aggregated to 15 minute intervals. Ten variables were considered in all:

(1) Volume (Categorical: <500[LOW], <1000[MED], >1000[HIGH])

(2) Detection Rate (Percentage of Volume)

(3) Matching Rate (Percentage of Volume)

(4) Lane-ft Covered by All Sensors in Configuration

(5) Directional Antenna (Categorical: 0 [no],1 [yes])

(6) Opposite Side Tandem Sensors (Categorical: 0,1)

(7) Sensor 1 Antenna Strength (Categorical [dBi]: 7,9,12)

(8) Sensor 2 Antenna Strength (Categorical [dBi]: 7,9)

(9) Sensor 3 Antenna Strength (Categorical[dBi]: 7,9)

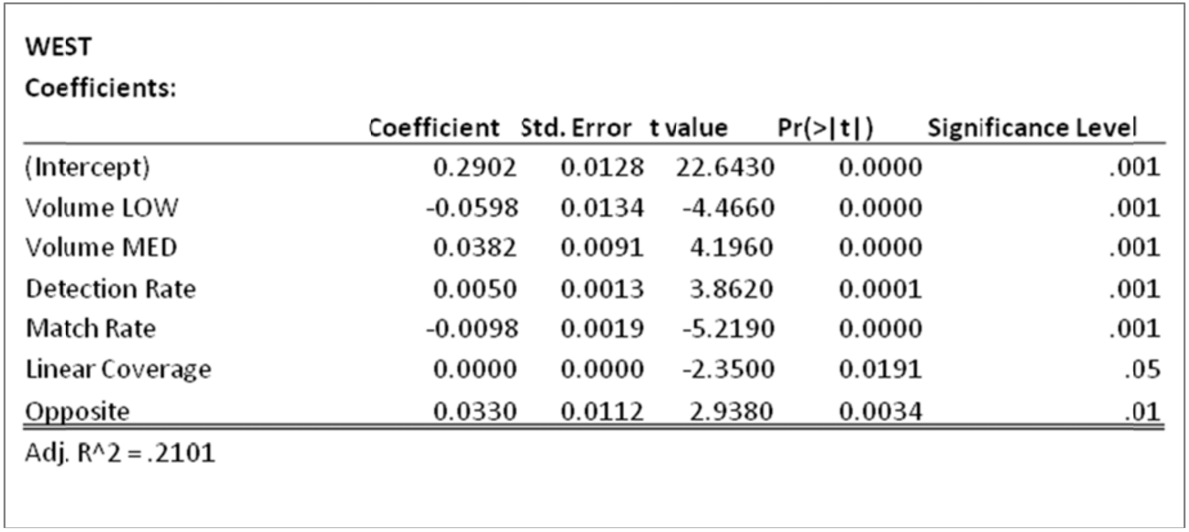
(10) Sensor 4 Antenna Strength (Categorical[dBi]: 7,9,12)

A generic model was first attempted using all variables:

$$E_k = \beta_0 + \beta_1 V + \beta_2 D + \beta_3 M + \beta_4 L + \beta_5 R + \beta_6 O + \beta_7 S_1 + \beta_8 S_2 + \beta_9 S_3 + \beta_{10} S_4 + \epsilon_k \quad (5)$$

where E_k is the absolute error in fractional minutes, V is the volume in veh/hr, D is the detection rate in percent, M is the matching rate in percent, L is the sensor lane-ft coverage, R is the directional variable, O is the opposite side variable and $S_{1\text{-}4}$ are antenna strengths of sensors in dBi 1-4. ϵ_k is the regression error term. The resulting model for the westbound direction and their variables, with relative significance levels is presented in Table 6-1.

Table 6-1: Westbound error regression model results



WEST

Coefficients:

	Coefficient	Std. Error	t value	Pr(>|t|)	Significance Level
(Intercept)	0.2902	0.0128	22.6430	0.0000	.001
Volume LOW	-0.0598	0.0134	-4.4660	0.0000	.001
Volume MED	0.0382	0.0091	4.1960	0.0000	.001
Detection Rate	0.0050	0.0013	3.8620	0.0001	.001
Match Rate	-0.0098	0.0019	-5.2190	0.0000	.001
Linear Coverage	0.0000	0.0000	-2.3500	0.0191	.05
Opposite	0.0330	0.0112	2.9380	0.0034	.01

Adj. R^2 = .2101

The resulting model confirms some of the anticipated concerns regarding volume, with lower volumes resulting in more accurate travel times. This can be attributed to the fact that the lower volumes accumulate less signal delay, as vehicles do not back up or wait as long on approaches. Medium volumes increased error in the westbound direction, implying that volumes over 500 veh/hr resulted in additional intersection delays that were passed on to the MACAD system. Higher detection rates were shown to increase the error. This is also expected because, under the same volume level, a higher detection rate is typically associated with a larger detection zone and a larger detection zone will lead to a larger spatial error. Matching rates had a negative correlation, implying that improving matching rates will reduce error by providing a larger sample size. Linear coverage played a similar role to detection, larger zones contributed to the error. Opposite-side tandem mounting was found to have an increasing effect on error in the westbound direction. This may be caused by the fact that the opposing side sensor at 61st St NE was mounted close to the eastbound ALPR detection zone, which allowed it to capture westbound vehicles waiting at the light. The NE 170th location was configured to avoid this issue.

6.2 ERROR ANALYSIS EASTBOUND

6.2.1 Descriptive Analysis Eastbound Direction

The eastbound side of the test bed shows greater variations and errors. In Figure 6-3, the single sensor configuration (shown in orange) is notably farther from the ALPR trend than the tandem configuration data obtained concurrently.

As can be seen in Figures 6-4, there is a greater effect of volume on the accuracy of the Bluetooth MAC address readers due to the signal delay. Eastbound travel times are affected much more than westbound ones, as most of the configuration's mountings have the detection zone centered near the eastbound signal approaches. This results in more reads near the approach areas and progressively less as the vehicle leaves the detection zone. This skews the results towards reflecting the intersection delay.

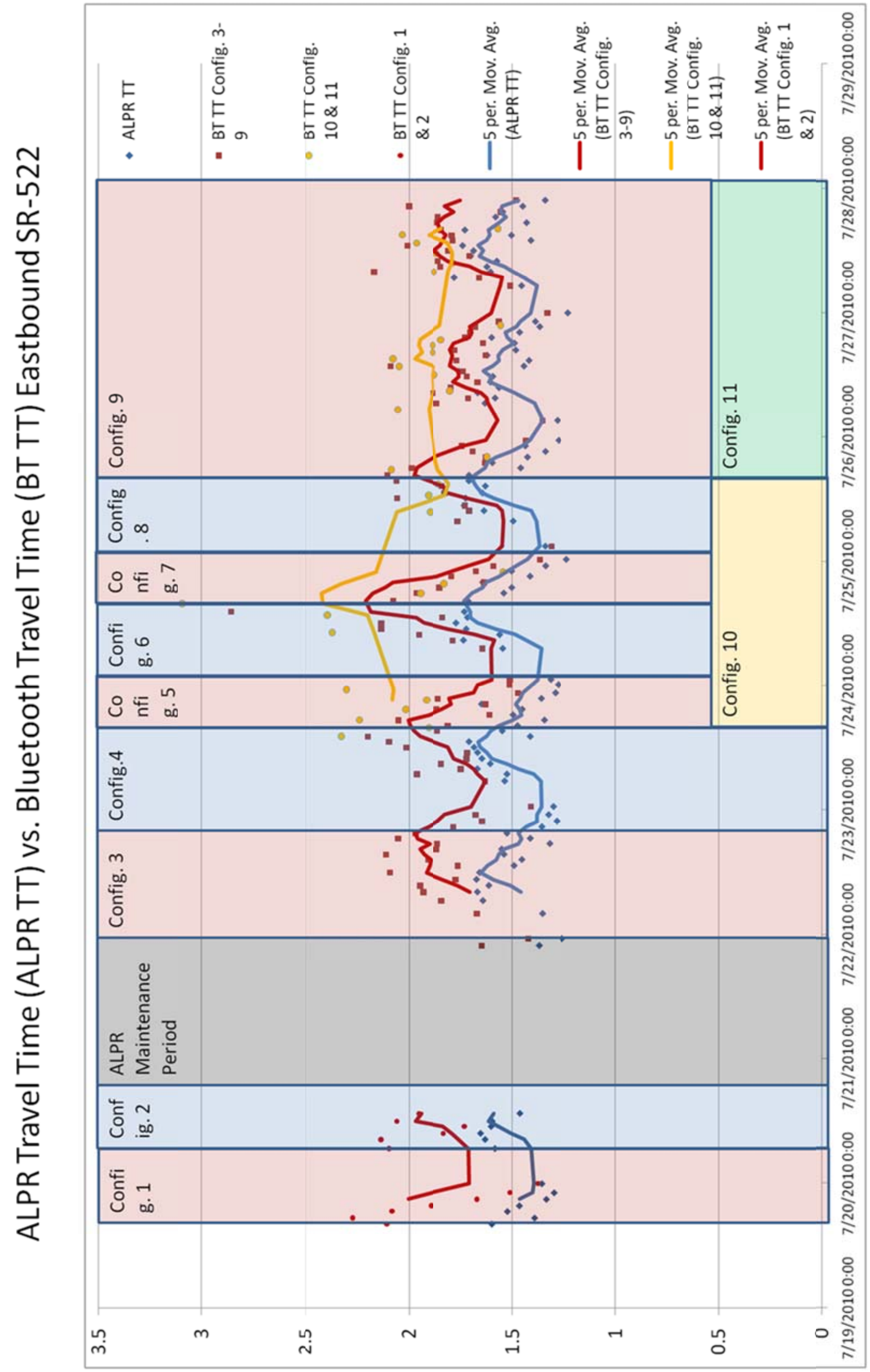


Figure 6-4: Travel time comparison eastbound SR-522 (ALPR – blue, BT – red + orange) (1hr averages)

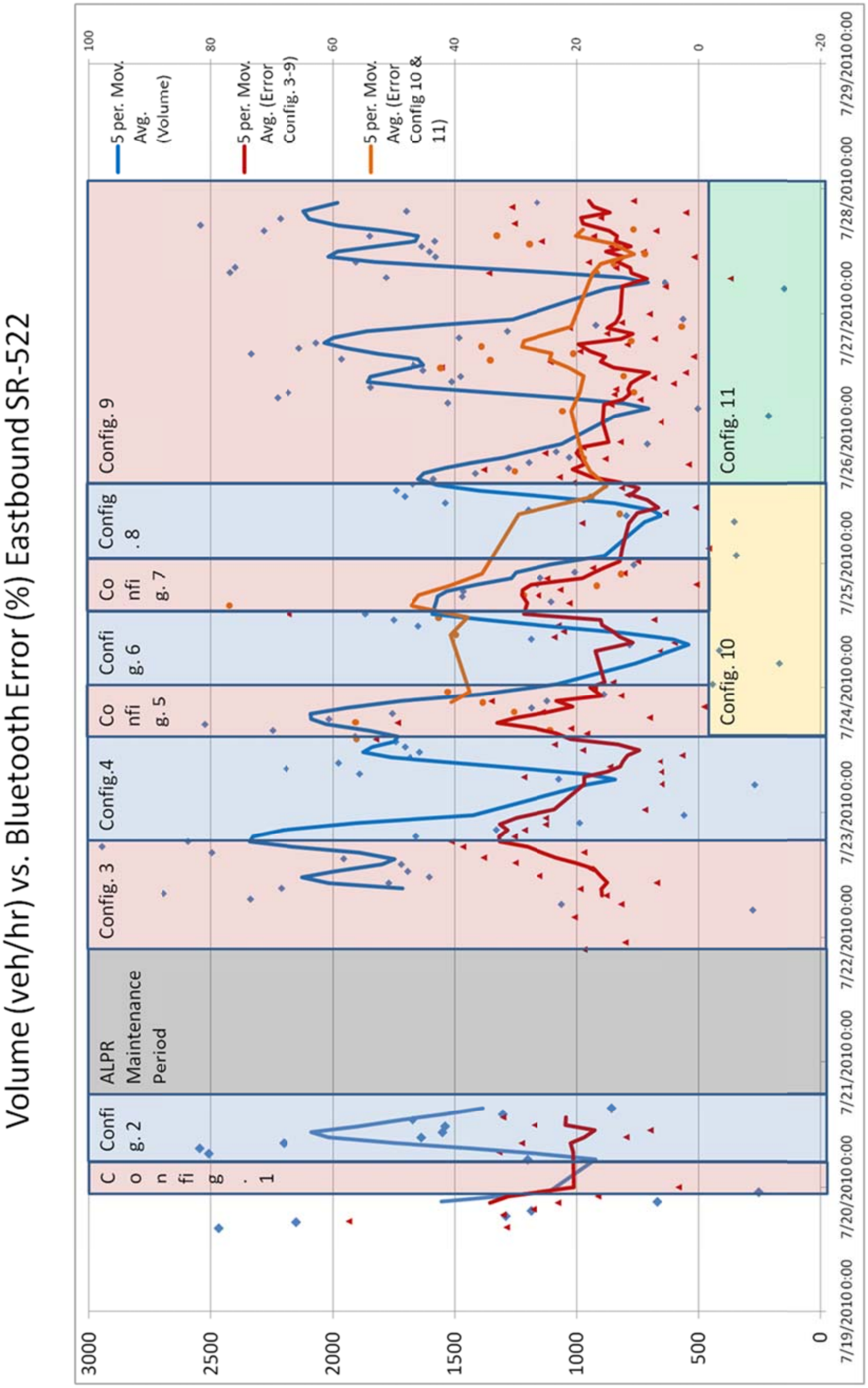
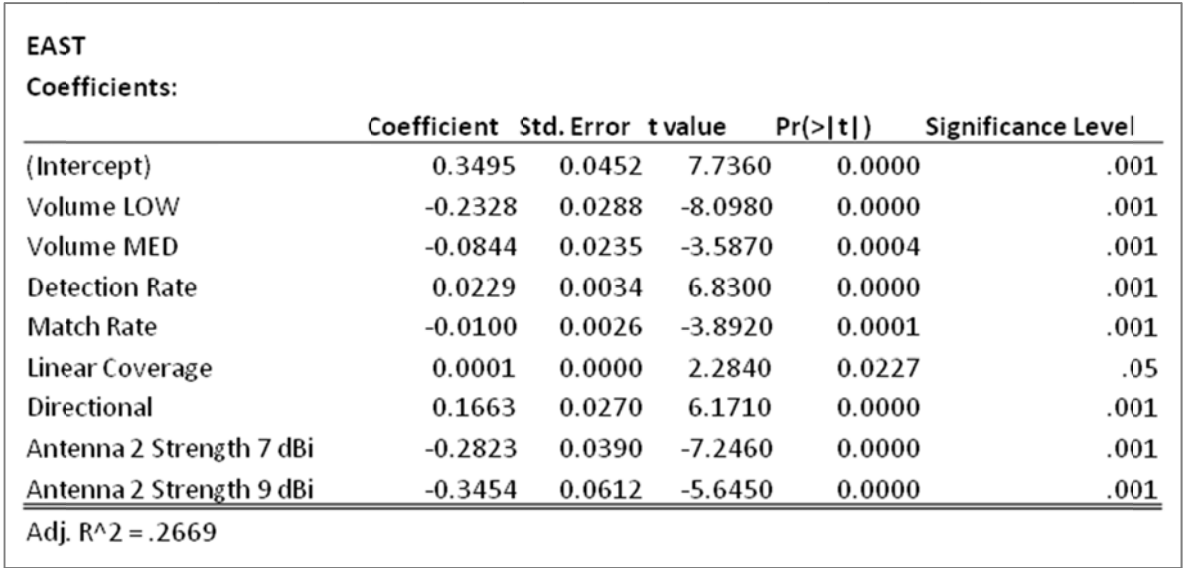


Figure 6-5: Eastbound SR-522 error and volume (1hr averages)

6.2.2 **Error Modeling Eastbound**

An eastbound model was developed using the same approach and the same initial set of variables as the westbound direction. However, the resulting set of significant variables turned out to be slightly different, with more variables playing a role. Since the relationship between the ALPR zones and MACAD zones was more complex, this is to be expected. Volume, detection rate, match rate and linear coverage still play a significant role however. Table 6.2 shows the regression model for the eastbound direction.

Table 6-2: Eastbound error regression model results



EAST
Coefficients:

	Coefficient	Std. Error	t value	Pr(>|t|)	Significance Level
(Intercept)	0.3495	0.0452	7.7360	0.0000	.001
Volume LOW	-0.2328	0.0288	-8.0980	0.0000	.001
Volume MED	-0.0844	0.0235	-3.5870	0.0004	.001
Detection Rate	0.0229	0.0034	6.8300	0.0000	.001
Match Rate	-0.0100	0.0026	-3.8920	0.0001	.001
Linear Coverage	0.0001	0.0000	2.2840	0.0227	.05
Directional	0.1663	0.0270	6.1710	0.0000	.001
Antenna 2 Strength 7 dBi	-0.2823	0.0390	-7.2460	0.0000	.001
Antenna 2 Strength 9 dBi	-0.3454	0.0612	-5.6450	0.0000	.001

Adj. R^2 = .2669

For the eastbound direction, directional antennae and antenna strength was found to have an increasing effect on error. Since the directional antennae were focused on the westbound side ALPRs, an increase in error is to be expected due to misalignment. Reduced error due to antennae strength (the stronger the lower the error – 7 dBi has less of a decreasing effect than 9 dBi) at sensor 2 (NE 170th St) can interpreted as creating a larger sample size. The eastbound direction was further from the mounted sensors away for most configurations – in such cases, antenna strength makes more of a difference, as smaller antennae have a harder time collecting samples.

It is worth noting that detection rate was not shown to be significant in either direction. This was somewhat unexpected, and discouraged the use of the initial detection-based model outlined in the proposal. There may be a couple explanations for this occurrence. First, there may have been too much noise from non-vehicular sources that increased the detection rate without providing subsequent matches. Second, the diversion rates for the corridor may have been too high, once again resulting in detections without matches. Discussion of detection and match rates for each configuration is presented in the following section.

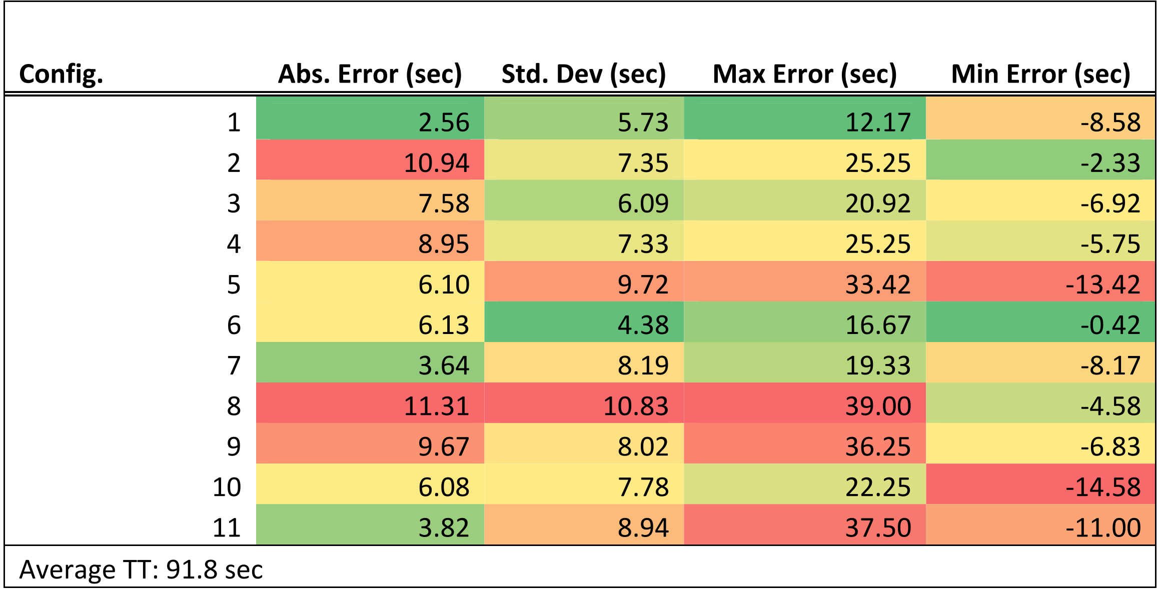
6.3 CONFIGURATION COMPARISON

Further insights into the performance of the MACAD devices can be gleamed from comparing the different configurations tested. In doing so, one can determine the most successful setup that was capable of providing the most accurate results, despite of the additional issues caused by the signal delay. A discussion of the performance of each configuration is given in the following section, once again separated by direction. While examining the data, it is imperative to recall that the tested corridor is less than 1-mile long, which results in the largest footprints taking up nearly 20% of the corridor.

6.3.1 Westbound

Table 6-3 presents a basic comparison of the tested configurations based on error statistics – average error, standard deviation of error, and min and max error in terms of minutes. The statistics are computed on 15-min intervals. Of the configurations tested, configuration 6 (9 dBi omni and 12 dBi directional) appears to have some of the best results, with a low average error and the lowest deviation in both the westbound and eastbound directions. Configuration 1 (a mix of 7 and 9 dBi antennae as singles) also fares well with the lowest absolute error, low standard deviation and a low maximum error. It can be seen from Table 6-3 that the absolute value of the max error is significantly higher than the absolute value of the minimum error, supporting a case for positive bias.

Table 6-3: Westbound 15-minute aggregate error statistics by configuration



Config.	Abs. Error (sec)	Std. Dev (sec)	Max Error (sec)	Min Error (sec)
1	2.56	5.73	12.17	-8.58
2	10.94	7.35	25.25	-2.33
3	7.58	6.09	20.92	-6.92
4	8.95	7.33	25.25	-5.75
5	6.10	9.72	33.42	-13.42
6	6.13	4.38	16.67	-0.42
7	3.64	8.19	19.33	-8.17
8	11.31	10.83	39.00	-4.58
9	9.67	8.02	36.25	-6.83
10	6.08	7.78	22.25	-14.58
11	3.82	8.94	37.50	-11.00

Average TT: 91.8 sec

Figure 6-6 shows the detection and matching rates for each configuration in the westbound directions. The matching and detection rates proved to be consistent with earlier studies (e.g. Malinovskiy, 2010), although certain configurations, notably tandem ones, had significantly higher detection and matching rates. The rates were obtained by counting the number of detections or matches happening within a particular 15-minute time window and normalizing the value by the sum of ALPR volumes in both directions. As ALPR data was available for only one lane, the values were doubled in an attempt to reflect the total volume in all four general purpose lanes. Transit volume was ignored in this study. The westbound direction captured an average of 10.8% of the total estimated volume with 4.1% of the estimated volume matched.

It is worth noting that both matching and detection rates can be over 100% theoretically, as contamination from non-vehicle sources may occur and vehicles can contain more than one device, resulting in an over-estimation.

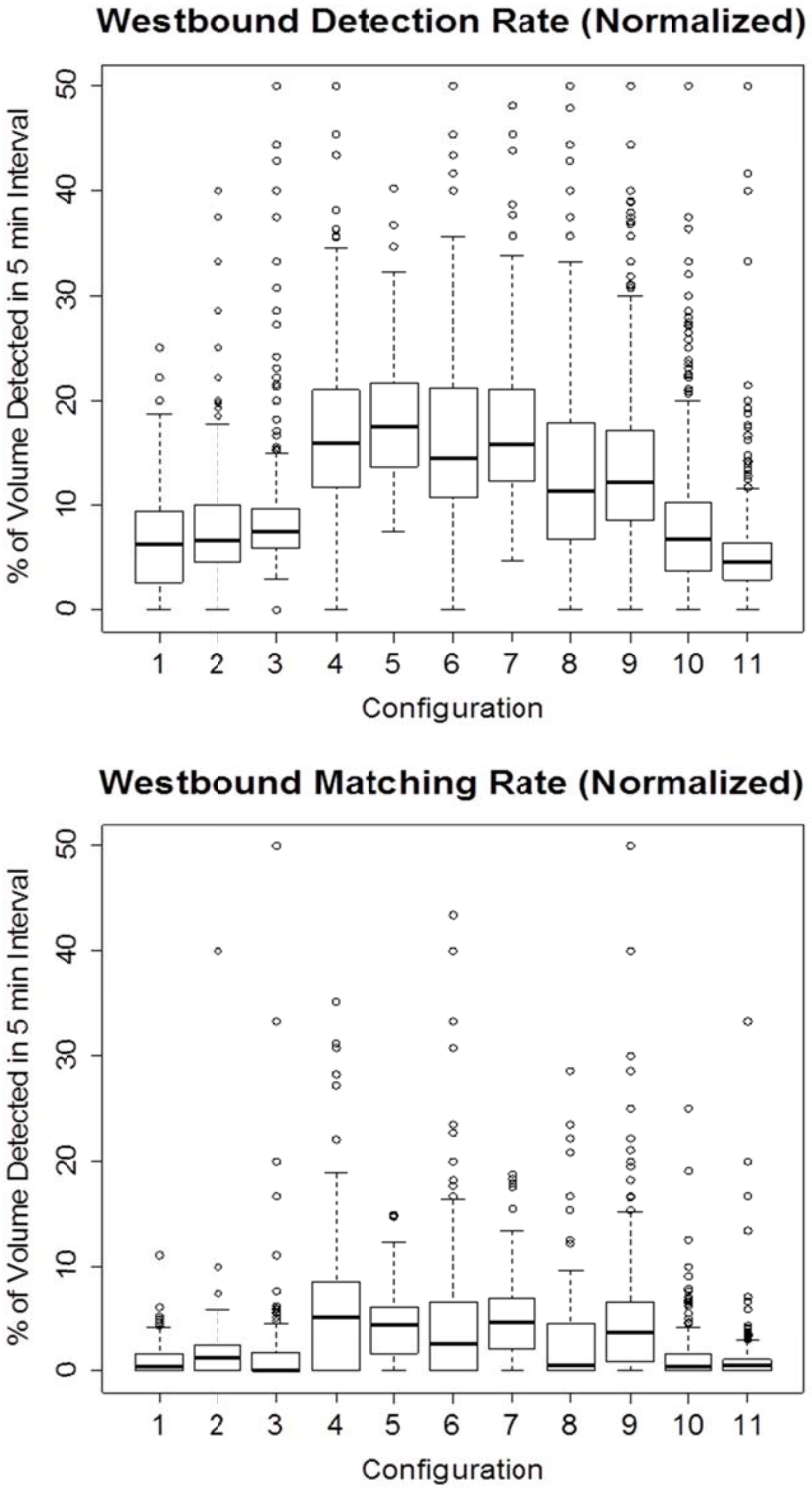
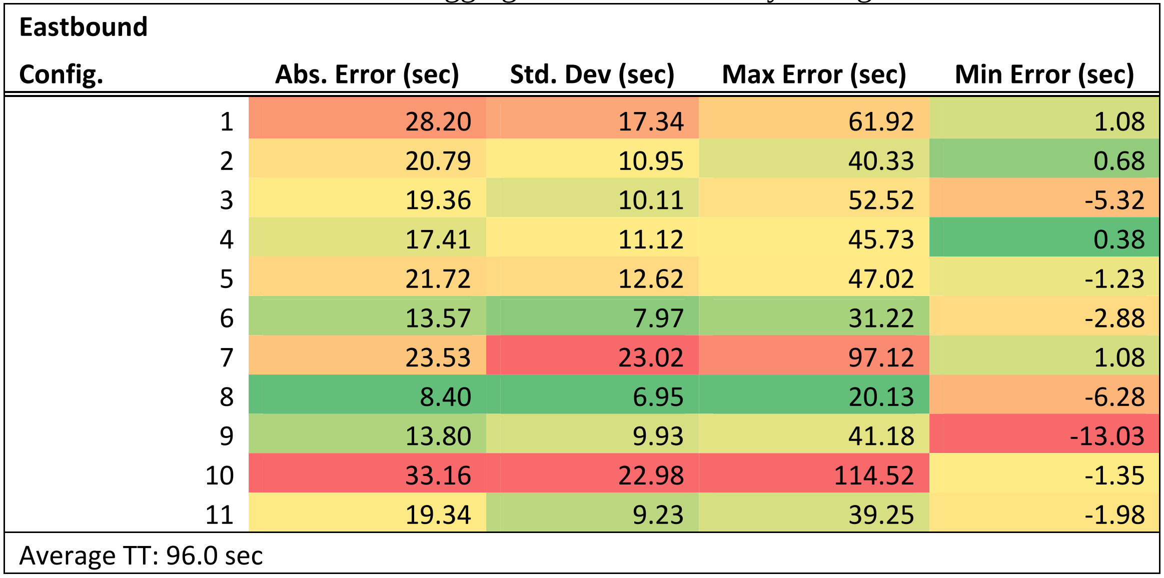


Figure 6-6: a) Westbound detection rates normalized by ALPR volume b) Westbound matching rates normalized by ALPR volume

6.3.2 **Eastbound**

Table 6-4 presents the basic configuration comparison for the eastbound direction. As expected, the results are different. The average error increases from 7.2 seconds to 19.8 seconds, reflecting the additional error from the intersection delay. However, it should be noted that configuration 6 still manages to demonstrate a relatively low error of 13.6 seconds, although this is still higher than any westbound configuration.

Table 6-4: Eastbound 15-minute aggregate error statistics by configuration



Eastbound Config.	Abs. Error (sec)	Std. Dev (sec)	Max Error (sec)	Min Error (sec)
1	28.20	17.34	61.92	1.08
2	20.79	10.95	40.33	0.68
3	19.36	10.11	52.52	-5.32
4	17.41	11.12	45.73	0.38
5	21.72	12.62	47.02	-1.23
6	13.57	7.97	31.22	-2.88
7	23.53	23.02	97.12	1.08
8	8.40	6.95	20.13	-6.28
9	13.80	9.93	41.18	-13.03
10	33.16	22.98	114.52	-1.35
11	19.34	9.23	39.25	-1.98
Average TT: 96.0 sec				

For this direction, the sensors captured an average of 11.4% of the estimated volume. The detections resulted in travel time matches for 5.2% of the total estimate volume. Figure 6-7 shows the detection and matching rates of the 11 configurations for the eastbound direction. Similar trends as the westbound direction persists, with tandem configurations having significantly higher detection and matching rates.

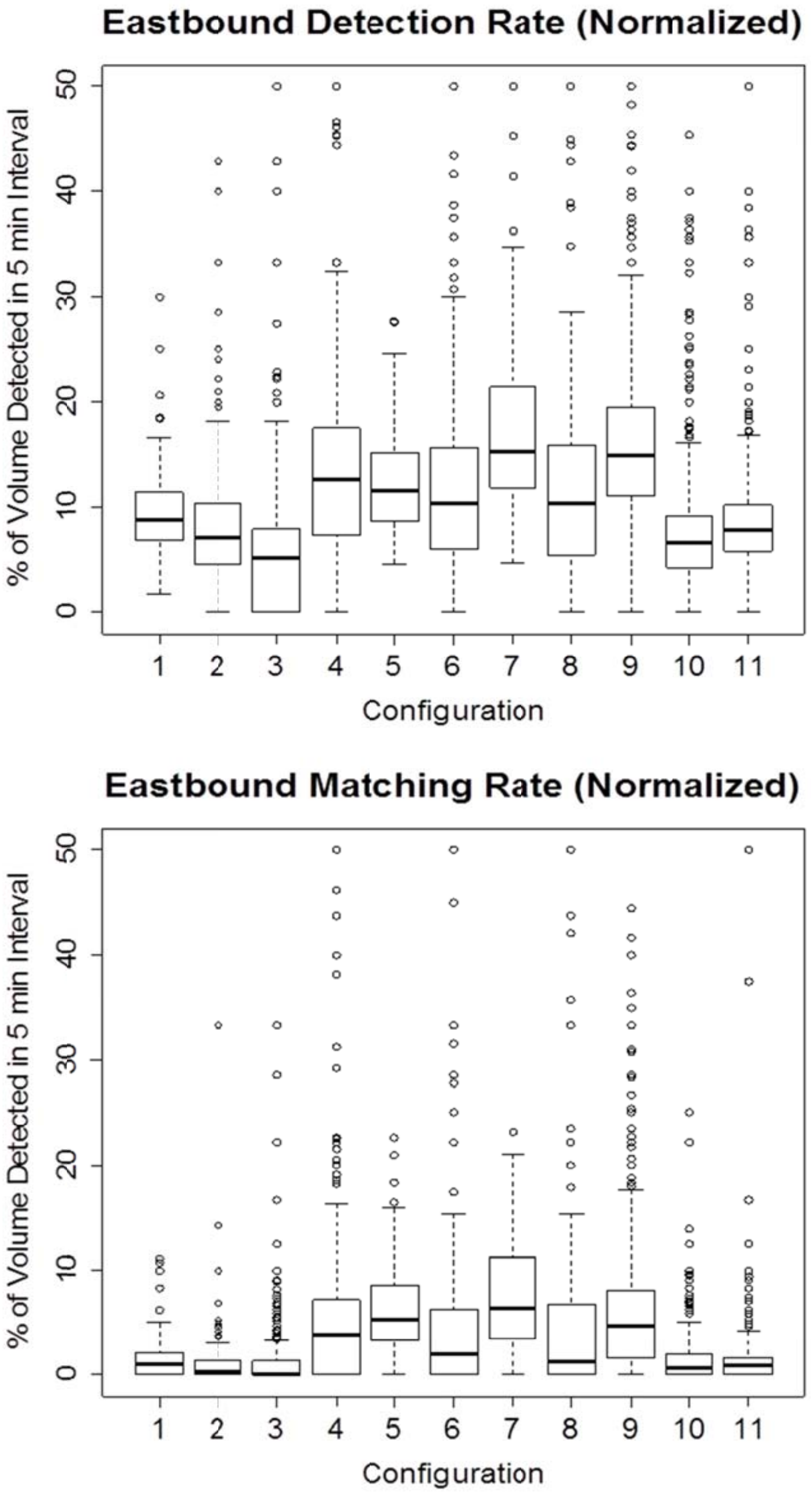


Figure 6-7: a) Eastbound detection rates normalized by ALPR volume b) Eastbound matching rates normalized by ALPR volume

6.3.3 **Configuration Comparison Summary**

In general, configurations with higher matching rates provided more accurate results, particularly in the better aligned westbound direction. An additional intersection (47th St) that allows for diversion from the westbound direction only is likely responsible for the lower matching rates in the westbound direction. Configurations 5 and 6, or combinations of 7 dBi and 9 dBi antennae with a 12 dBi directional antennae mounted in the same location did consistently well in both travel directions, obtaining some of the highest matching and detection rates. Configurations 5 and 6 were also among the most accurate, with 6 being the closest to ground truth in part due to its larger antennae which allowed it to obtain a lower error rate in the eastbound direction. Although there is a directional component to this which may increase error in the eastbound direction, the sensors are mounted at the same point in each location, improving the accuracy in the westbound direction. The linear coverage of the sensor footprints is also modest compared to fully omni-directional configurations. Therefore, the findings of the configuration analysis are fairly consistent with the modeling results.

7 CONCLUSIONS AND RECOMMENDATIONS

Considering the properly aligned westbound results only, a few conclusions can be made about the use of Bluetooth sensors for travel time extraction. The overall error, detection and matching rates, suggest that a combination of sensors is worthwhile. Detection and matching rates tend to increase with optimal MACAD configurations, which results in an increase in accuracy. In all the experiments conducted, the MACAD Bluetooth methodology provided estimates that were sufficiently accurate, with slight overestimates. The extent of the over-estimation highly depends on the configuration and antenna type and installation location, as shown by the results of this study. Errors ranged from 4% to 13%, but it should be noted that longer corridors (over one mile) would not experience such drastic differences, as the 10.24 sec protocol window plays a smaller role. In this study additional error sources also contributed to such a wide range of possible errors. The short SR-520 experiment, described in Section 4.1, serves as a good example of how precise Bluetooth sensors can be on longer corridors without intersection delay and other potential contaminants.

When using Bluetooth or other MAC-address readers, one has to be very careful of data contamination by intersection delay. Ideally, the sensors would be mounted mid-block to prevent such contamination, but the location of the ALPR sensors dictated Bluetooth device locations in this study. Another potential contamination factor was the proximity of bus stops near the detector locations – if a passenger's Bluetooth device was detected at the first location whilst they were on the bus, after which they have disembarked and walked past the first location, the travel times would be close to the vehicle travel times, yet contain an additional source of error. This problem is exacerbated in areas with high-volume bus stops.

7.1 CONCLUSIONS

The use of Bluetooth readers to measure travel time provides a comparable alternative to ALPR technology and can be used with significantly less effort and lower costs. Shorter corridors however, do pose challenges for the Bluetooth detection scheme due to the inherent “zone to zone” detection paradigm offered by these sensors. In such cases it may be tempting to reduce the detection area in order to decrease the size of the detection zones and thus reduce the error. However, when the zones are reduced, the matching rate drops dramatically. In the experiments described above, configurations that used just one detector per site (thus significantly reducing the detection zone size) had less than half the matching rate of configurations that used two detectors per site, regardless of antenna choice. Of all the configurations attempted, combinations of omni-directional antennae with large detection zones provided the best results, with low absolute error and high matching rates. Combination configurations (4, 5, 6, 7, 8, and 9) had average matching and detection rates of 7.92% and 15.35%, respectively; while single-sensor (at each location) configurations had rates of 3.43% and 9.37% respectively. The higher detection rates may also increase due to extraneous sources, but the matching rates were shown to be statistically significant in reducing error.

Across all configurations, the reported Bluetooth travel time was 8.0% higher than the actual travel times reported by the ALPR sensors. All error rates encountered were well within FHWA’s recommendation levels. Although reducing the overall error was a concern, the main goal of this study focused on determining which configuration will provide the lowest relative error, not minimizing the overall error. Lower overall errors can be accomplished using a more discerning filtering algorithm. The least error prone configurations (1,5,6 and 11) reported travel times that were, on average, 4-7% above the ALPR travel time.

For the eastbound direction, additional intersection delay not considered by ALPR sensors is likely to have played a very significant role that contributed to the alignment issue, severely degrading the results. However, about half of the configurations tested were still able to produce results well under the FHWA threshold.

Errors encountered during this study were almost always positive. This implies that there is still a bias towards slower vehicles within this corridor study. As alluded to in our prior studies (Malinovskiy et al., 2010), this is likely the result of the inherent nature of Bluetooth technology – there is bias towards slower vehicles that have a higher chance of being detected due to longer residence times within the detection zone.

7.2 RECOMMENDATIONS

Based on the obtained experimental results, several recommendations for error control of Bluetooth-base travel time collection can be made:

1. Bluetooth-based travel times are likely overestimates, the error rate is dependent on a number of variables, including match rate.

2. A site-specific evaluation may be necessary to ensure that the measured travel times reflect the desired delays – nearby signals may superimpose additional

travel time. Extraneous sources of delay, such as bus stops, should also be considered.

3. Combinations of sensors working in tandem help reduce error in most cases. Tandem setups greatly increase the detection and matching rates, which is important for time-critical applications such as real-time travel information.

4. Sensor configuration can significantly affect the performance of the Bluetooth-based travel-time collection system, especially if the chosen corridor has a short travel time. The travel time data collected using Bluetooth sensors along the 0.98 mile long corridor tested in this study produced average errors between 2.4 and 11.4 seconds (4% to 13%) when compared to aligned ALPR sensors.

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