GEORGIA DOT RESEARCH PROJECT 11-15

FINAL REPORT

WORK ZONE TECHNOLOGY TESTBED

Georgia Department of Transportation

OFFICE OF RESEARCH

15 Kennedy Drive

Forest Park, GA 30297-2534

TECHNICAL REPORT STANDARD TITLE PAGE

1.Report No.: FHWA-GA-1115	2. Government Accession No.:	3. Recipient's Catalog No.: N/A
4. Title and Subtitle: **Work Zone Technology Testbed**		5. Report Date: February, 2016 6. Performing Organization Code:
7. Author(s): Wonho Suh, Ph.D., Randall Guensler, Ph.D., Michael Hunter, Ph.D., Angshuman Guin, Ph.D. , James Anderson, Kathryn Colberg, and Stephanie Zinner		8. Performing Organ. Report No.: 11-15
9. Performing Organization Name and Address: Georgia Transportation Institute/UTC Georgia Institute of Technology 790 Atlantic Drive Atlanta, GA 30332-0355		10. Work Unit No.: N/A 11. Contract or Grant No.: 0010423
12. Sponsoring Agency Name and Address: Georgia Department of Transportation Office of Research 15 Kennedy Drive Forest Park, GA 30297-2534		13. Type of Report and Period Covered: Final; May 2011 – September 2013 14. Sponsoring Agency Code: N/A
15. Supplementary Notes: Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		

16. Abstract: In this research project, travel time data collection technologies were reviewed and three different technologies, Bluetooth®, Automatic License Plate Recognition (ALPR), and iCone® system, were selected for field testing deployment in Metro Atlanta. After successful initial testing in controlled conditions, the systems were deployed into I-285 freeway work zones and real-time travel time data were collected. This research project evaluated the capability of the selected technologies to provide accurate real-time travel time information. The data from the systems were selectively compared with travel time data collected via manual means. The selected technologies were found to report reasonably accurate travel time data in free flow conditions and congested traffic conditions. However, travel times derived from all three methods were biased toward collecting more data from slower moving lanes during congested traffic conditions. As such, work zone travel times were biased high from all three methods. However, the overall results showed that all three methods are technologically feasible, and biases can be overcome with proper equipment placement and deployment configurations.

17. Key Words: Travel Time, Work Zone, Bluetooth®, Automatic License Plate Recognition, ALPR, iCone®		18. Distribution Statement: No Restriction	
19. Security Classification (of this report): Unclassified	20. Security classification (of this page): Unclassified`	` 21. Number of Pages: 53	22. Price: N/A

Form DOT 1700.7 (8-69)

GDOT Research Project No. RP 11-15

Project Report (Final)

Work Zone Technology Testbed

By:

Wonho Suh, Ph.D.
Randall Guensler, Ph.D.
Michael Hunter, Ph.D.
Angshuman Guin, Ph.D.
James Anderson, Kathryn Colberg, and Stephanie Zinner
(Graduate Research Assistants)

School of Civil and Environmental Engineering
Georgia Institute of Technology

Contract with

Georgia Department of Transportation

February 2016

Table of Contents

List of Tables

List of Figures

Executive Summary

Work zones are a major source of non-recurrent congestion. Real-time information regarding travel time and delays in and around work zones is a critical component of traveler information systems. Through the Georgia NaviGAtor system, the Georgia Department of Transportation has been providing invaluable traffic information for commuters on the Georgia freeway network. With the advancement of the 511 traffic information system, the demand on the Traffic Management Center to provide more detailed and accurate information regarding work zone travel time is becoming more important and will be expanded.

In this research project, travel time data collection technologies were reviewed and three different technologies, Bluetooth®, Automatic License Plate Recognition (ALPR), and the iCone® system, were selected for field testing deployment in Metro Atlanta. After successful initial testing in controlled conditions, the systems were deployed into I-285 freeway work zones and real-time travel time data were collected. This research project evaluated the capability of the selected technologies to provide accurate real-time travel time information. The data from the systems were selectively compared with travel time data collected via manual means.

The selected technologies were found to report reasonably accurate travel time data in free flow conditions and in congested traffic conditions. However, travel times derived from all three methods were biased toward collecting more data from slower moving lanes during congested traffic conditions. As such, work zone travel times were biased high from all three methods. Nevertheless, the overall results showed that all three systems are technologically feasible, and that biases can be overcome with proper equipment placement and deployment configurations. In addition, a high bias in travel time estimation is not necessarily problematic; actual travel times experienced by drivers that are less than the reported travel times will cause less driver angst than will travel times that are greater than anticipated. Strength and weakness of each system and corresponding recommendations are discussed in the report.

Acknowledgments

The authors of this report wish to thank the Georgia Department of Transportation for its support and assistance throughout this effort, in particular the efforts of David Jared, Binh Bui, Mark Demidovich, and W. Grant Waldrop.

1 Introduction

Work zones are a major source of non-recurrent congestion. Real-time information regarding travel time and delays in and around work zones is a critical component of traveler information systems. Through the Georgia NaviGAtor system, the Georgia Department of Transportation has been providing invaluable traffic information for commuters on the Georgia freeway network. With the advancement of the 511 traffic information system the demand on the Traffic Management Center to provide more detailed and accurate information regarding work zone travel time is becoming even more important and will be expanded to major arterials.

Efficient communication of work zone information to motorists is also critical. Receipt of accurate travel time information can reduce motorist angst associated with delays. In addition, strategically utilized information delivery systems, such as changeable message signs, cell phone alerts, etc., can also encourage travelers to change travel decisions or take alternative routes, thereby reducing congestion and improving worker safety.

The accuracy of travel time information in work zones is heavily dependent on: 1) the precision and accuracy of detection equipment; 2) deployment configuration, including number of detectors, location, and layout of detectors etc.; 3) equipment calibration and calibration stability; and 4) detector robustness, in terms of accuracy degradation under different weather conditions (e.g., fog or rain) or location challenges (e.g., placing a detector at a distance or near objects that may interfere with detector signals). Commercially-available detection and communications systems are numerous, costs vary widely, and manufacturer claims of accuracy and robustness may not have independent 3rd party validation. Hence, evaluating travel time data collection technologies and their data communications systems will help inform equipment selection decisions and provide for efficient use of scarce resources.

This project assesses three travel time data collection technologies that are amenable for use in work zones: Bluetooth®, Automatic License Plate Recognition (ALPR), and the iCone® system. The research team successfully tested these technologies under controlled conditions, and then deployed the systems in I-285 freeway work zones to collect real-time travel time data and compare the travel times with traditional manual methods. This research project evaluated the capability of the selected technologies to provide accurate real-time travel time information. The three selected technologies provided reasonably accurate travel time data under free flow conditions and congested traffic conditions. However, travel times derived from all three methods were biased toward collecting more data from slower moving lanes during congested traffic conditions. Hence, work zone travel times were biased high from all three methods. All three systems are technologically feasible, and the travel time biases can be overcome with proper equipment placement and deployment configurations. Strengths and weaknesses of each system and corresponding recommendations are discussed in the report.

2 Literature Review

Lack of reliable real-time travel time or delay information in work zones is a significant source of motorist angst [1]. Current traffic information sources, such as changeable message signs, may not adequately address motorist needs, if the information arrives late in the travel planning process, if the data are obsolete, or if the information is not sufficiently detailed to be helpful in travel planning. A primary goal of detection and communication systems in work zones is to provide accurate and timely information to motorists to support trip diversion decisions and improve mobility through work zones [2-4].

A wide variety of turnkey systems can be deployed in work zones for the purpose of obtaining travel time and traffic congestion information. These systems are characterized by a number of parameters including data collection equipment types (e.g., portable video detection, portable radar detection, RFID, wireless vehicle detection, etc.), types of outputs provided (e.g., current speed, current travel time, predictive travel time based on current traffic conditions, etc.), and reporting methods that provide data to planners, engineers, and ultimately motorists. Many current systems are advertised as off-the-shelf, ready for deployment, and can theoretically be tied directly into the Georgia NaviGAtor framework to provide usable data.

Alternative detection technologies used in other fields (e.g., law enforcement, manufacturing, cargo logistics, etc.) may also be amenable to transportation applications. For example, portable video detection, portable radar detection, RFID, wireless vehicle detection, license plate detection, etc., could be deployed independently and tied into the NaviGAtor framework for the collection and transmission of such traffic information as travel times, queue lengths, etc.

Some reports focused on data quality for turnkey equipment systems are available from manufacturer-sponsored studies and from some independent studies [5-8]. Some studies also provide results for comparative concurrent deployments of several systems [9]. Some of the literature also focuses on the impact of the information on people within the work zone or those approaching the work zone with no rerouting alternatives [10-12]. However there are limited cross-cutting comparisons across the variety of available technologies that identify deployment challenges related to each technology and report comparative testing results under uniform test conditions. Also, equipment manufacturers often do not openly publish the detailed characteristics of travel data that are provided. For example, manufacturers often do not report whether reported travel time data comprise real measurements or whether the 'data' comprise predictions of travel times, based on derived estimates of current traffic conditions. In addition, it is often impossible to determine how data are processed (e.g., data quality control and outlier removal) and how final travel time outputs are calculated (e.g., formula to estimate travel time based on speed and traffic counts). This research project is intended to provide comparative testing across the selected technologies and recommendations for selecting and testing systems.

3 Technology Review

This section identifies and presents a systematic review of technologies that are currently available to collect travel time data in work zones. This review considers three major aspects in work zone technology: data collection, data processing, and output data formatting. Technologies deployed in other fields, such as portable video detection, portable radar detection, radio-frequency identification (RFID), wireless vehicle detection, etc., are also investigated when manufacturer specifications indicate that such applications appear promising. This review includes available peer-reviewed and company-produced studies documenting the performance of these work zone monitoring systems. Also, this review identifies operational characteristics for each technology. For example, the report assesses the types of data collected, data accuracy, equipment calibration, calibration stability, detector robustness (across environmental conditions and location characteristics), sensor interference issues, deployment configuration requirements, data processing requirements, data output formats and post-processing needs, automation capabilities, communications requirements, etc. This review provides a detailed discussion on the relevant advantages, disadvantages, and expected challenges associated with implementation and data collection. This section also overviews how each technology is best suited for specific roadway configurations and operating conditions.

Travel time data collection technologies either measure travel times directly, or measure travel times indirectly. Direct travel time measurement systems include: probe vehicles, radio frequency identification systems, license plate matching, vehicle magnetic signature matching, Bluetooth® signal monitoring, and GPS-based cell phone and navigation system reporting. Each technology employs different methodologies and hardware systems. Furthermore, technologies within the same class often have unique operating characteristics. Technologies that appear to be well-suitable for work zone operation are further evaluated for their ability to provide supporting data for given conditions.

3.1 Indirect Travel Time Estimation

Indirect travel time estimation technologies translate sensor measurements into travel time estimates using pre-programmed algorithms. Systems may employ intrusive sensors (e.g., inductance loop detectors, piezoelectric sensors, magnetic sensors, etc.) or non-intrusive sensors (e.g., active/passive infrared sensors, vehicle image detection systems, microwave sensors, passive acoustic sensors, pulse ultrasonic detectors, etc.). These sensors can be deployed within existing networked infrastructure or take the form of independent equipment. Because travel time is not collected directly, algorithms are required to translate sensor measurements into travel time estimates [13]. These algorithms [14] include:

> Stochastic Queuing Methods: Queuing methods use vehicle count data to estimate speeds. Average travel times are estimated based on the cumulative arrivals and cumulative departures curves. This method works better in a “closed” system where all vehicles are counted.
>
> Section Density Algorithms: Density algorithms estimate speeds and travel times using measured traffic volumes and estimated average section density (estimated based on cumulative vehicle counts and hypothesized speed-flow relationships).

Multi-Regime Algorithms: Different travel time estimation methods are applied for three traffic states: (1) lane closures, (2) incident conditions, and (3) normal operations.

Indirect methods can utilize existing equipment to collect data. For example, traffic counts from existing inductance loop detectors or vehicle image detection systems can be used to provide traffic volume inputs. Such monitoring units are commonly deployed in many areas to continuously gather traffic data. Many of these devices have already been tied into traffic management centers (TMCs) to provide live traffic data and in turn report travel times and traffic conditions to the general public. However, these indirect methods, although proven to work in uncongested traffic conditions, present significant potential inaccuracies when converting sensor measurements into travel time estimates. Furthermore, some of these devices require significant capital, operation, and maintenance costs. Although some of these products have been converted into portable equipment, such as RTMS sensors, many of them are not portable and require construction and calibration. For example, inductive loops require work crews to cut into the pavement to place coils of wire to initially set up the sensor. Video detection systems (VDS) for traffic counts require existing poles or new poles to be placed so that cameras are high enough to accurately detect vehicles passing the camera.

Because indirect methods are a simplified way of estimating average travel times from measured traffic parameters, travel time extrapolation can be inaccurate. FHWA [13] stated to "Exercise caution when using point detection devices for estimating travel times. Freeway detectors may provide reasonable estimates in light traffic, but using detector estimates is not recommended in heavy congestion or on arterial streets." The research team opted not to investigate any of the indirect methods as part of the research effort due to the noted dis-benefits of these approaches, limited resources, and a desire to focus on more accurate methods.

3.2 Speed to Travel Time Conversion

Speed to travel time conversion methods assume that individual spot speed measurements (i.e., speed measurements at specific points in space) can be converted to travel times. That is, for specific segments of roadway given speed measurement stations that are set at a specific distance apart, the speeds at each location and distance separating the locations can be used to predict the travel time between the locations. The method assumes that speeds between the measurements are relatively uniform, or follow some pre-determined speed gradient. Provided that non-linear congestion impacts on speed are not present within the analysis zone (i.e., congestion waves are not forming or dissipating), or that analysis zones are sufficiently small such that the impact of a single zone is low, such assumptions may be reasonable. Spot speed measurements can be provided by radar stations, laser stations, video detection systems (VDS), etc.

3.3 Direct Travel Time Data Collection Methods

Direct travel time measurements involve repeated measurement of vehicle presence with time stamps that can be used to estimate travel time between measurements. A variety of technologies can be employed to identify specific vehicles at multiple locations, ranging from prove vehicles to cell phone tracking. Each technology is addressed in the subsections that follow:

3.3.1 Probe Vehicles

Probe vehicles equipped with GPS (Global Positioning System) or AVL (Automatic Vehicle Location) technology navigate the transportation network and report their travel times between stations. Deployment of probe vehicles can be explicit, where the agency assigned specific vehicles to specific routes, or incidental, where large volumes of data from commuters are provided under contract. Initial capital costs of this method are low, because on-board GPS equipment is relatively inexpensive and there is no additional infrastructure requirement. Additionally, real-time data transmission can be provided via cellular connectivity and routes can be easily modified. However, this method is labor-intensive for explicit deployments when a statistically representative sample is required. In explicit deployments, three commonly used probe vehicle driving styles are employed:

> Average Car - Probe vehicle driver travels according to the driver's judgment of the average speed of the traffic stream;
>
> Floating Car - Probe vehicle driver "floats" with the traffic by attempting to safely pass as many vehicles as pass the test vehicle; and
>
> Maximum Car - Probe vehicle driver travels at the posted speed limit unless impeded by actual traffic conditions or safety considerations.

Probe vehicle methods can be highly effective for collecting travel time data. GPS systems are quite accurate as speeds are satellite signal based (derived from a Doppler shift in satellite signals and not based upon changes in latitude and longitude) and individual vehicle deployments are fairly low cost. Furthermore, using smart phones, probe vehicle data can be transmitted in real time without making any modifications to vehicles. Cellular reporting also allows flexibility in route planning and the ability for a driver to easily modify his/her route to collect data on other routes which may not have infrastructure set up to collect live traffic data.

However, probe vehicle methods allow agencies to collect only a small sample of actual travel times unless a large number of probe vehicles are employed. Hence, the sampling method may not appropriately account for speed variability in the traffic stream. For statistically representative samples, many drivers need to be hired, which usually proves to be unsustainable in terms of cost. Furthermore, if agencies wish to collect data from participating public who volunteer to provide their vehicle data through in vehicle equipment or smart phones, issues over privacy of volunteers' location and trips can arise (see Section 3.3.6, GPS Reporting via Cell Phone).

3.3.2 RFID Tag Readers

Radio frequency identification (RFID) readers identify specialized RFID tags affixed to vehicles, typically for use in tolling operations (e.g., Georgia Peach Pass toll tags). RFID readers broadcast a radio signal which powers the transmitter in the RFID tag, which uses the signal power to respond with a message that includes the unique identification number of the RFID tag. By configuring a system of two or more units placed at user-defined distances, travel times can be monitored between the stations by comparing the time stamps of each unique RFID tag at each reader. RFID and toll tag readers provide continuous and automated collection of data and are highly accurate, given the known distance between specific reader locations. RFID systems are also known for high equipment reliability. However, RFID systems carry significant equipment and installation costs. RFID and toll tags uniquely identify each vehicle. There is no easy way to link the RFID tag to an individual user, because user identification information is classified as personally-identifiable information by the tolling agency and not released to the public due to privacy restrictions. Nevertheless, potential privacy issues arising around the ability of a monitoring agency to identify users' repeat trips and locations. Furthermore, a sampling bias may occur in using travel times from only the subset vehicles that carries RFID or toll tags.

3.3.3 License Plate Matching

License plate matching systems read license plates at upstream and downstream locations via optical character recognition, and pair the data via license plate matching algorithms. Once these systems obtain a unique reading at two locations, the travel time is taken as the elapsed time between identifications. License plate data can be collected continuously and these systems yield very accurate travel times. Furthermore, license plate data collection systems can collect large numbers of vehicles passing the field of view, allowing for large sample size. Because almost all vehicles display license plates, the method addresses the potential sampling bias issues associated with monitoring RFID tags or other technologies that may only be present in a subset of the passing vehicle fleet.

Significant initial capital costs are required to implement automatic license plate recognition (ALPR) cameras. Furthermore, due to the high volume of data collected, significant real-time data processing efforts are required. Not only do the license plates need to be matched, but filtering processes must be employed to handle partial or incorrect license plate readings.

There is usually no easy way to link individual vehicle license plates to individual users, because vehicle ownership information is classified as personally-identifiable information by state agency and is typically not released to the public due to privacy restrictions. Nevertheless, potential privacy issues arising around the ability of a monitoring agency to identify users' repeat trips and locations.

3.3.4 Magnetic Signature Detection

Magnetic signature systems monitor changes in a magnetic field above a sensor embedded in the roadway to detect the unique magnetic signature of the vehicle at multiple locations. Once these systems obtain a unique reading at two locations, the travel time is taken as the elapsed time between identification. Magnetic signature sensor data can be collected continuously to provide accurate travel times. Furthermore, the data collection systems can collect very large numbers of vehicles passing the field of view, potentially improving data representativeness. However, equipment deployment can be very costly as systems require embedding of hardware in the roadbed. The equipment required for magnetic signature recognition was not tested by the research team; hence, manufacturer claims regarding accuracy of signature re-acquisition have not been independently verified. The need to embed the sensor in the pavement is a potentially significant drawback of this technology where only a temporary deployment is desired. On-pavement (surface) systems do exist; however such systems are only recommended for low speed areas due to sensor durability issues at high speeds. If these systems are of interest to the Georgia Department of Transportation, the research team recommends that these systems be tested in subsequent research, rather than relying on results from manufacturer-sponsored studies.

3.3.5 Bluetooth® Systems

Bluetooth® devices are quite common in cell phones, headsets, and global positioning system (GPS) units. Because each Bluetooth® device constantly transmits its unique Media Access Control (MAC) address, there is an opportunity to capture and anonymously identify a significant portion of the traffic stream at a relatively low cost [15-17].

MAC addresses are unique to each particular Bluetooth® device and are employed in according to the Institute of Electrical and Electronics Engineers (IEEE) rules. MAC addresses are arranged in six pairs of two hexadecimal digits, each separated by a colon (e.g., 00:02:G2:20:67:2A). Because each MAC address corresponds to a unique device, and the code is continuously transmitted, the address can be identified multiple times along a roadway when multiple Bluetooth® detection systems are deployed. At the time of detection, the MAC address, detection time, and location information can be stored. Based on the information, the travel time between locations can be calculated for each unique MAC address.

Compared with many other travel time data collection technologies, the capital costs of Bluetooth® data collection is fairly low. Bluetooth® sensors can be deployed as permanent or temporary systems. The equipment is highly portable and can be operated on battery power or solar panel during temporary deployment, or connected to power for the permanent installation.

The total number of unique MAC addresses read divided by the total traffic volume over the same time period is defined as “Fraction read” [16] or “Detection rate” in other studies [17]. Most studies found this rate between 3-10% (per location), which implies a significantly lower matching rate between two locations. Furthermore, as Bluetooth® is also using potentially personally identifiable information to match time stamps at each location. Although there is no current means to associate a specific MAC address with a specific individual or household, the possibility of privacy issues might arise in the future.

3.3.6 GPS Reporting via Cell Phone and Navigation Systems

Numerous private companies currently provide speed data for major roadway links (and estimated travel times for origin and destination pairs using the speed data) using non-infrastructure-based methods. Most of these companies sample cell phone position and speed data from the fleet of vehicles using their services (e.g., Google monitors such data when the user opts in to Maps and position data usage on their smartphone), or GPS speed and position data reported by navigation systems (e.g., TomTom). Such private-sector speed and travel time data are not free, but can be licensed by agencies to add to their ITS system coverage [2].

GPS-based methods for collecting travel time data do not require any additional equipment to be installed in a vehicle and can provide continuous and automatic data collection. Furthermore, large amounts of data are accessible from this method because a high percentage of the population uses cell phones, and many are using navigation software on their phones which have the ability to provide the user with travel times and provide the service provider with location and speed information to gather travel time information from users.

GPS-based methods provide private entities with data which can be linked back to specific users. Many users may not even be aware that the private entities are monitoring their specific locations and vehicle speeds. This method could raise potential privacy concerns when raw data are transmitted. But, these private companies generally will not transmit any data to the public agency that can be used to link activity back to individual users. Additionally, a sampling bias may occur due to only gathering travel times from a subset of the vehicle population that carries multiple users (for example, bus) or multiple equipment systems (for example, a commercial truck with multiple wireless devices).

3.3.7 Summary

Numerous technologies exist for measuring or estimating travel time data. Many of the off-the-shelf systems are provided by private entities. Providers tend not to disclose the raw data or their data processing methods to the public or state DOTs. Even when using the same underlying technology, travel times from different providers may have large variations and inaccuracies. Also, providers are constantly updating their collection and data processing methods. Thus, a key outcome of this study will be the development of performance based recommendations that should be met by a travel time provider for any new device and an understanding of potential sources of bias that can be found across many technologies.

4 Technology Selection

In this project, three different travel time data collection technologies were selected for field deployment and detailed evaluation. Important factors considered in selecting the technologies used in this study are listed in Table 1.

Table 1: Factors Considered in Selecting Technologies

Factor	Detail
Real-time Data	The technology needs to provide real-time data.
Setup Requirement	The technology should not require extensive setup and installation.
Portability	The technology should be portable.
Power	The technology should work without external power.
Maintenance	The technology should not require extensive maintenance.
Sampling Rate	The technology needs to provide sufficient data points.
Proven Technology	The technology has been successfully deployed in other locations.

After reviewing strengths and weakness identified in the technology review, Bluetooth®, Automatic License Plate Recognition (ALPR), and radar (speed detection) were selected for deployment. Multiple Bluetooth® technology vendors were contacted and technical specifications were reviewed. All vendors provide deployment and data management services. BlueMAC® was selected, primarily because the system allowed the research team to access the data stream for detailed evaluation, rather than viewing only the results provided online by the contractor (which allowed the team to perform more thorough statistical comparisons). Four Automatic License Plate Recognition vendors were initially identified. ELSAG North America (ELSAG) was selected based on the system features and capability. ELSAG has the potential to share and integrate real-time data with other state agencies, since its ALPR systems have been deployed by the State Road and Tollway Authority (SRTA) and law enforcement agencies. For radar speed-detection-based travel time systems, the iCone® system was selected, primarily because their devices are pre-packaged in traffic control barrels specifically designed for use within work zones. Detailed information regarding the selected technologies is addressed in the subsections that follow.

4.1 *Bluetooth®: BlueMAC®*

The BlueMAC® Bluetooth® sensors are designed and assembled by Digiwest, LLC. According to the manufacturer, the BlueMAC® devices can be used as a portable short-term system or as a permanent long-term solution that can be integrated into existing systems or used as a standalone core technology, and can report conditions to the Traffic Operations Center without an expensive communications infrastructure [18].

In addition the manufacturer intends that BlueMAC® can provide travel time data with little effort required for setup. The portable system (Figure 1) includes a battery for 20 days of continuous service. Currently, BlueMAC® runs continuously in North Carolina and Florida using power from a solar attachment. BlueMAC® also provides wireless data transmission and an onboard GPS to self-identify map location. BlueMAC® has extensive live, online, real-time reporting capabilities (Figure 2).

Figure 1: BlueMAC® Device (Web)

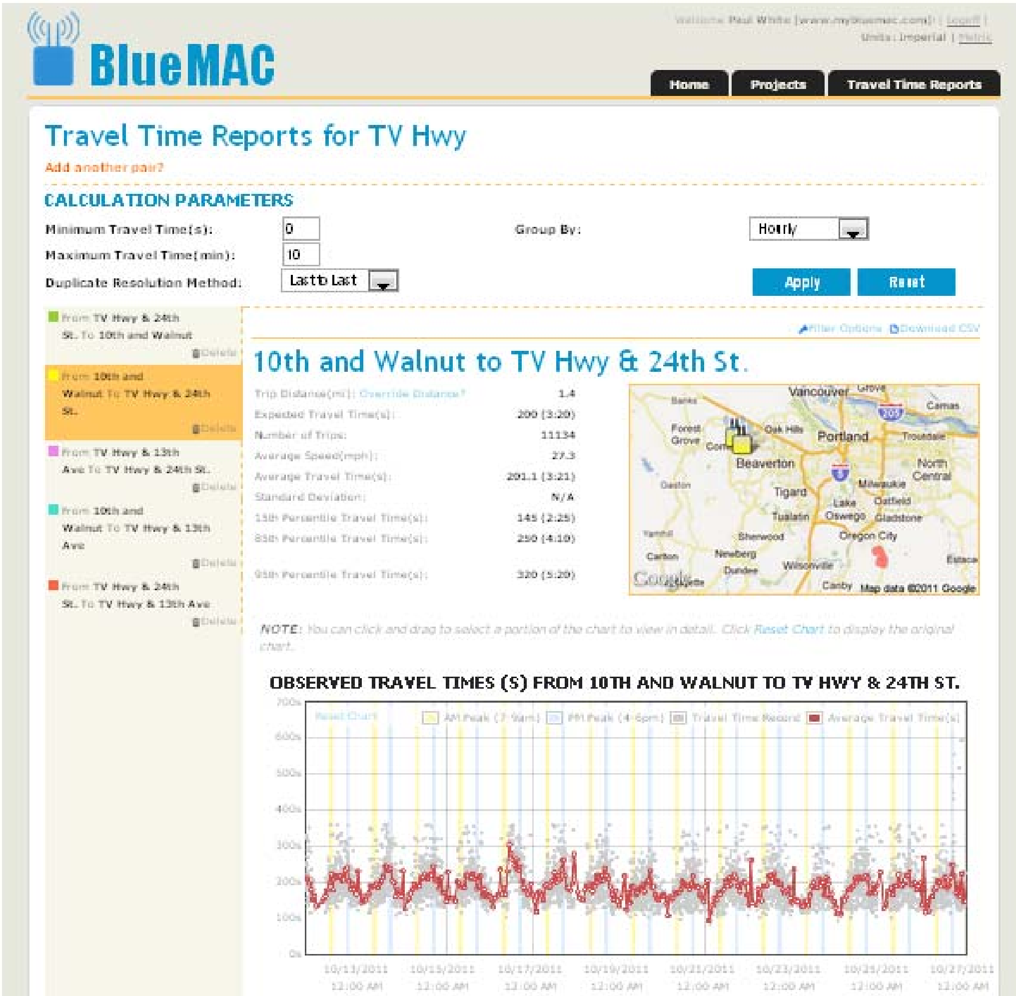

Figure 2: BlueMAC® Travel Time Output (Web)

4.2 Automated License Plate Recognition (ALPR): ELSAG

ELSAG North America specializes in development and sales of law enforcement systems. The ELSAG Mobile Plate Hunter-900 (MPH-900) is a fixed ALPR system that can be mounted permanently to structures, such as bridges or overpasses, or can be mounted in a mobile configuration, typically on police vehicles. According to the manufacturer, the MPH-900 ALPR system can read up to 1,800 plates-per-minute at 99% accuracy [19]. The MPH-900 is used by hundreds of law enforcement agencies and in all fifty states in the United States [19].

In the greater Atlanta area, ELSAG ALPR systems are used by police departments in Atlanta, Alpharetta, Sandy Springs, Gwinnett County, and DeKalb County, and by the Georgia State Patrol. For research purposes for this project, two sets of three cameras (25mm, 35mm, and 50mm focal lengths), and two processing units, were procured and evaluated.

4.2.1 ELSAG Equipment Modifications

As ELSAG's primary clients are law enforcement agencies, ALPR cameras are equipped with three circular magnets attached to the base so that they can be mounted on the trunk of a police vehicle. To increase the portability of the system for use in work zone deployment, square metal plates were fabricated as tripod mounts. The magnetic camera attachments were mounted to the magnetic plates so that they could be deployed in the field as shown in Figure 3 below. External 12 volt gel cell batteries were used to power the equipment during field deployments.

Figure 3: ELSAG ALPR Cameras Mounted to Tripods

4.2.2 ELSAG ALPR Car System® Program

The ELSAG ALPR system includes Car System® software as the user interface for the ALPR system. The main function of the Car System® program is to record and display the captured license plate and vehicle information in real-time. For each captured license plate, the program records the date and time stamp of capture, the camera ID, the recorded license plate number, a black and white image of the license plate and back of the vehicle, and a zoomed-in infrared image of the license plate. When each license plate is captured, the program can be set to produce a beeping sound, momentarily display the infrared license plate image, and add the license plate information to the running display of the captured license plate information. A screen shot showing the display of the Car System® program during the data collection process is shown in Figure 4 below. In addition to displaying the data, the program also stores an archive of ALPR readings and allows the user to export the data collected during specified time periods as an HTML (Hypertext Markup Language) file. A screen shot showing the data export interface within the Car System ® program is shown in Figure 5.

Figure 4: Data Collection Screen within Car System® program

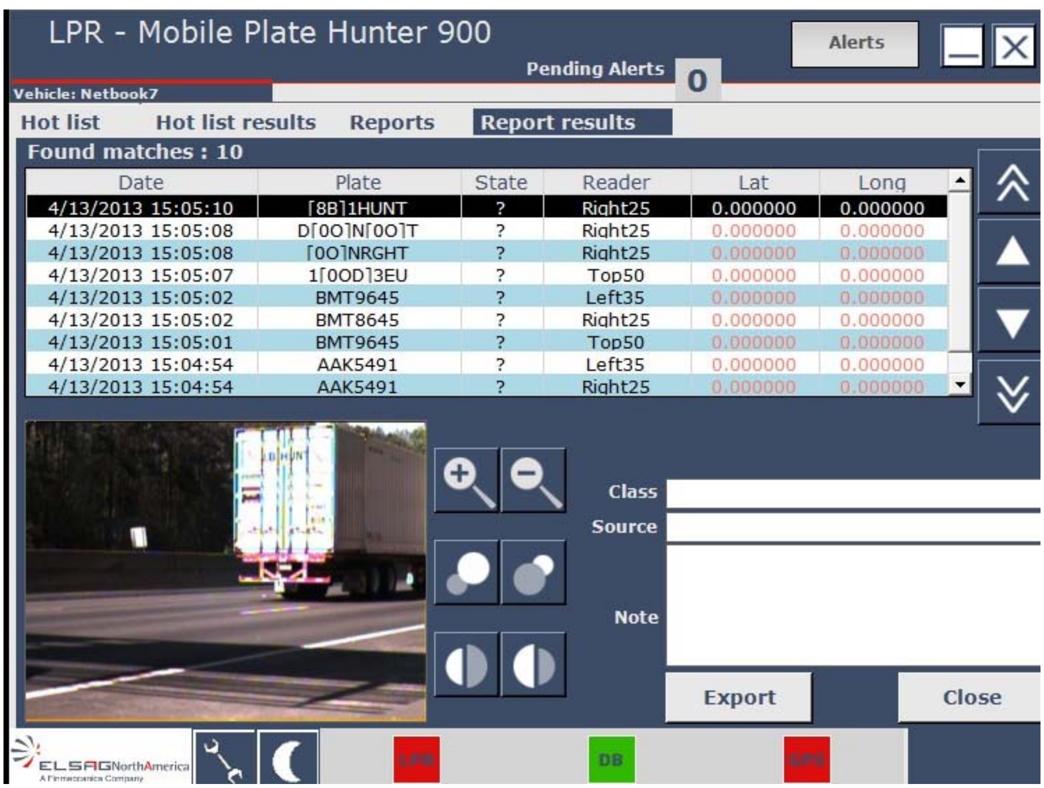

Figure 5: Data Export Screen within Car System® Program

The ELSAG Car System® program also has a setup mode that allows the user to check and adjust the view of each camera connected to the system. In setup mode, the user can select a specific camera to the display the camera's view in the window, allowing the user to adjust the positioning of the camera until the view is set to the desired area. This feature is useful when establishing the deployment. The Car System® program also allows users to label each of the cameras in a manner that corresponds to which port on the processing unit the camera is connected to via the camera connection cable.

4.3 iCone®

The iCone® is a radar-based vehicle monitoring system developed by iCone® Products, LLC. The system consists of a Type I/III traffic barrel containing a speed radar sensor, computer, GPS, wireless modem, Iridium Satellite modem, and an Absorbed Glass Mat battery [20]. Figure 6 shows the location of these hardware elements within the iCone®. Vehicle speeds are collected via radar and aggregated to 2-minute or greater time intervals. Location of the iCone® is established by GPS and vehicle speeds and location are reported by cell modem or satellite modem to a server. The server then locates the iCone® units on a map, creates links between multiple iCone® units, and calculates the current travel time based on spot speed measurements and distance between the iCone® devices. According to the manufacturer, the system calculates the current delay based on the distance between each iCone® unit and vs. normal speeds.

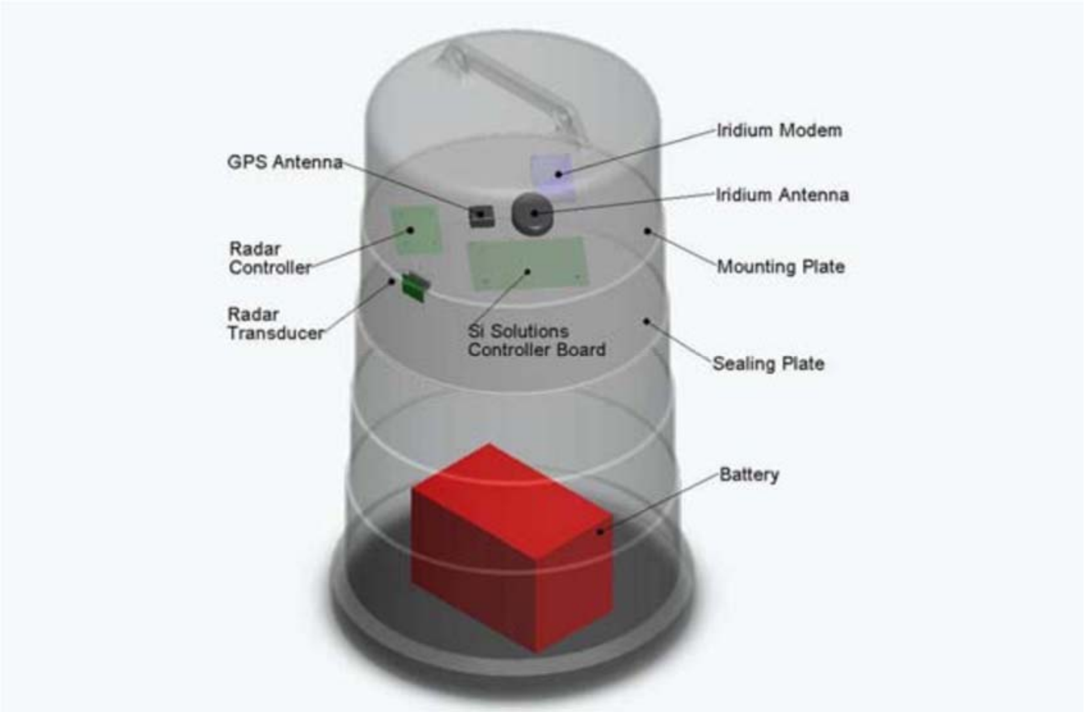

Figure 6: iCone® Internal Hardware Configuration [21]

Placement of iCone® devices consists of aiming the iCone® at a point 30' downstream for every foot away from the roadway. According to the vendor, individual iCone® units must be located at least 300' apart to reduce the possibility of interference. Typical iCone® setups space each iCone® between 0.75 miles and 1.5 miles apart before the construction taper, to track queue lengths, and at the midpoint of the lane closures, to track speeds in the work zone. Where speeds within the work zone are expected to be fairly consistent, because vehicles have passed the bottleneck created by the taper and the flow is capacity constrained, one iCone® placed within the lane closure is believed to be enough to track speeds and calculate travel times through the length of the lane closures. However, additional iCone® devices may be desirable within the work zone when variability is noted as necessary. Figure 7 illustrates a Typical iCone® setup.

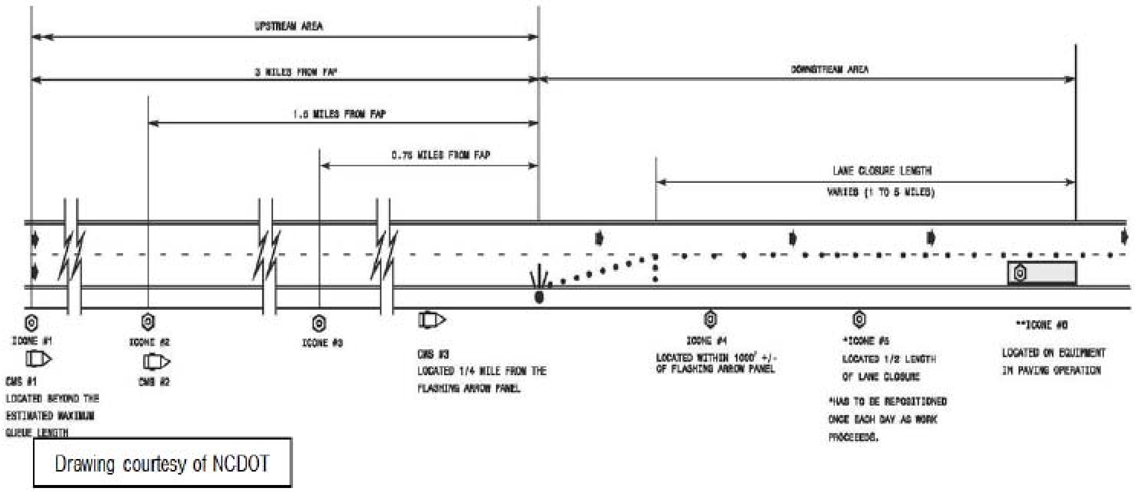

Figure 7: Typical iCone® Setup with 6 iCone® Units [22]

When the iCone® is powered on, the system with the Windows CE operating system begins to run the iCone® software. A self-test of all components is run and the battery level is tested. Communication connectivity is established by either wireless cell modem or satellite modem, depending on availability. The iCone® then finds its location by GPS and reports the latitude and longitude position to the server. Next, the custom configuration file is downloaded to define the metrics for data gathering and reporting intervals (see below). Finally, the iCone® collects data, transmits data to the server, and displays calculated travel times in real-time [21].

The iCone® configuration file allows the user to configure the Radar, GPS, Wireless Cell Communication, Satellite Communication, and Temperature Messages. The following are details of the options for each piece of hardware [21]:

1. Radar
    a. Message Interval – Time (minutes) between iCone® radar message transmissions.
    b. Start Interval – Time (seconds) between starting radar collection intervals.
    c. Read Time – Time (seconds) to leave radar on for a collection interval.
    d. Read Delay – Time (milliseconds) to sleep the radar after a valid read.
    e. Max Read Count – Maximum number of valid radar reads to accept during a collection interval.
    f. Standard Message Flag – Option to select an aggregated radar report message.
    g. Bin Message Flag – Option to collect 5 mile-per-hour bin reports.

2. GPS
    a. Message Interval – Time (minutes) between location messages.
    b. Maximum Dilution of Precision (DOP) – Minimum GPS accuracy for a location message (1=ideal, 1-2=excellent, 2-5=good, 5-10=moderate, 10-20=fair, greater than 20=poor).
    c. Maximum Attempts – Time (minutes) to try to achieve maximum DOP for a location message.
3. Wireless Cell Communication
    a. Message Interval – Time (minutes) between data transmissions.
    b. Fails – Number of transmission fails before satellite transmission is attempted.
    c. Failure Lock-out – Number of times the fails counter is allowed to roll over before wireless cellular communication transmission is no longer attempted.
4. Satellite Communication
    a. Message Interval – Time (minutes) between transmissions.
    b. Message Timeout – Time (seconds) until unsuccessful transmission attempt stops.
5. Temperature Messages
    a. Message interval – Time (minutes) between transmissions.
    b. Message timeout – Time (seconds) until unsuccessful transmission attempt stops.

The iCone® systems have been crash tested at 100 km/hour according to the guidelines set forth by the National Cooperative Highway Research Program (NCHRP) Report 350 Category 2 [21]. Crash testing verifies that the device components will not break away and enter the vehicle's driver compartment, will not scatter or throw debris in the area of roadway workers, and will not exceed crash-related driver impact standards [22]. The system uses an Absorbed Glass Mat (AGM) battery, which is a "dry" type battery. AGM batteries are similar to a traditional lead acid battery, except that the acid is absorbed into sheets of fiberglass. With this design, battery acid will not spill on the roadway in the case that the battery is crushed. Moreover, this battery will not explode, as it is not sealed and compressed, as would be the case with a Lithium Ion battery. Finally, all other components are small enough and light enough to be crushed and or contained in the inside the barrel cone upon impact.

5 Data Collection

After the initial testing and evaluation in Metro Atlanta, BlueMAC® Bluetooth® and ELSAG ALPR systems were deployed into I-285 freeway work zones in September, October, and November 2012 and the iCone® system was added to the evaluation in April 2013. Discussion and analysis of the extensive initial testing may be found in [17] and [23]. To conduct an unbiased evaluation of the reported travel times from the selected technologies, it is essential to collect comparable baseline travel time data via traditional manual methods (baseline data). Although such data cannot be considered "ground truth," as errors in manual baseline data will occur, the manual baseline comparative data are generally considered accurate and can be manually re-confirmed by a second party. Video cameras at overpasses in the study zones were employed to collect the baseline comparative data. The team manually captured time-stamped vehicle license plate data, and paired the license plated numbers and timestamps for two locations to generate baseline travel time and speed data. The following sections describe how manual baseline travel times were obtained to for comparison with selected travel time data collection technologies.

5.1 Travel Time Observation – Overpass Video Recording

Video collection of license plates has been used in variety of travel time, demographic, and fleet characterization studies (emissions). For example, in evaluating the conversion of the I-85 carpool lanes in Atlanta to a high-occupancy toll lane, the research team collected and processed more than 1.5 million license plate observations. In the work zone project, high-definition video cameras were used to concurrently collect comparative baseline travel time data alongside the test systems. Baseline data collection was conducted using Panasonic HDC-TM700X video cameras mounted on tripods. Video cameras are a reliable means of manually collecting travel time data for nearly the entire vehicle population along the corridor (when license plates are present in the camera field of view). License plates of each passing vehicle in the video are manually recorded by undergraduate assistants, which is a labor-intensive method. To record clear images of the vehicle license plates, high-definition video cameras were placed on the downstream side of the overpass bridges, aimed at the backside of passing vehicles. Each camera recorded the license plates for two freeway travel lanes at the same time. At site locations with an odd number of freeway travel lanes, the last camera was used to record only one freeway travel lane.

For the I-285 freeway deployments, the high-definition camera tripods were positioned with two legs on the concrete wall of the overpass and one leg on the sidewalk to position the camera as close to the side of the overpass as possible. This setup also ensured that the wire fence did not block significant portions of the view by minimizing the distance between the camera lens and the wire fence. Figure 8 below shows an image of the camera placement on the freeway overpass during the deployments. The camera views of the two lanes were set up by zooming them in completely and then panning and tilting the camera until the two freeway travel lanes were centered on the screen with the outside lines disappearing from view in the middle of the shot. Figure 9 below shows an example of the camera zoom view for a camera recording two lanes of travel.

Figure 8: High-definition Video Camera Setup

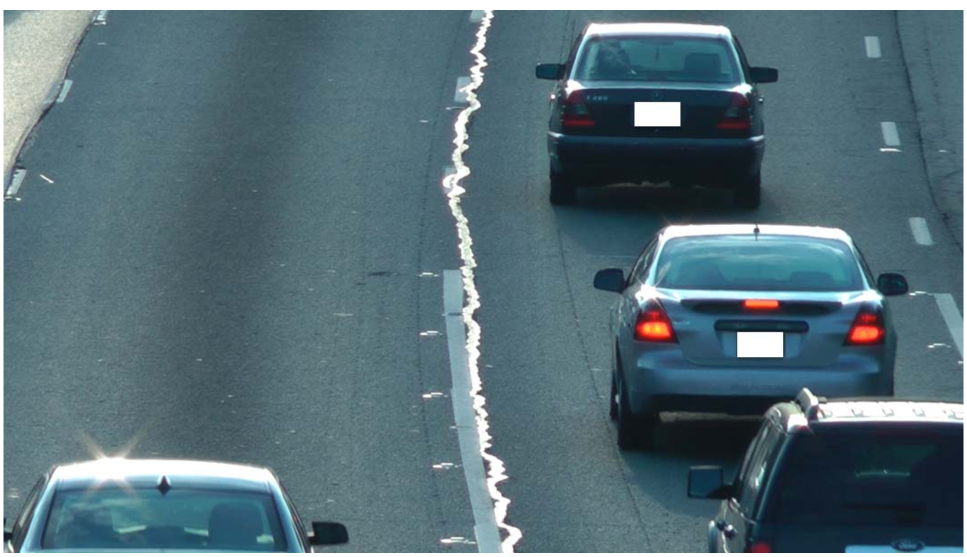

Figure 9: Optimal Camera Zoom View

5.2 *Baseline Travel Time Data Extraction*

Video footage was recorded at two locations and travel time data between the two locations were obtained by matching the license plate detection at each site. Because the freeway deployments involved large vehicle volumes, the video footage from the deployments was processed using a proprietary software program developed by Georgia Tech.

The high-definition video files collected during the field deployments were run through a freeware program called Free Video to JPG Converter available from DVDVideoSoft (http://www.dvdvideosoft.com). This program reduces the video files into a series of screen shots every 30th frame, equivalent to approximately two frames per second. The reduced video images were sent through the Georgia Tech video-processing program. The video-processing program has a user interface that allows data processors to enter the license plate number for each vehicle seen in the images. The video-processing program uses the frame grabs, rather than the rolling video, allowing data entry staff to tab through the images rather than needing to pause and re-start a video file. The image processing interface results in faster processing times. Figure 10 below shows an image of the license plate video-processing program interface.

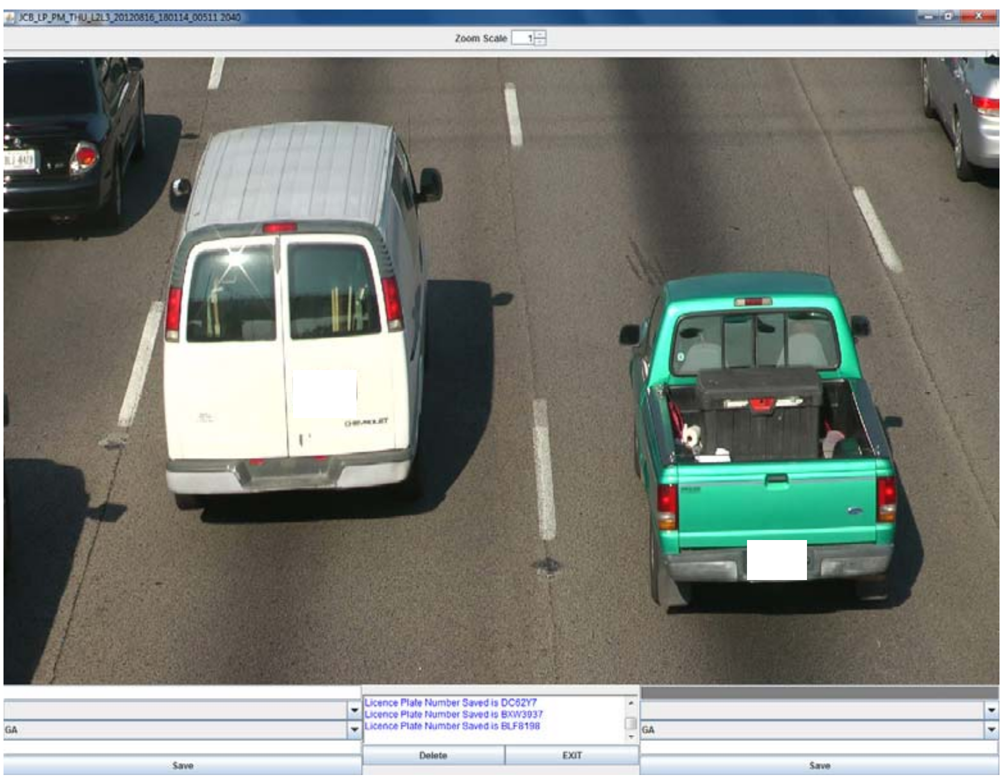

Figure 10: Georgia Tech's Proprietary License Plate Video-Processing Program

The Georgia Tech video-processing program automatically assigns time stamp to each input vehicle license plate. The time stamps are assigned to vehicles using the end time of the video file and counting backwards in time using the frame number as a proxy for elapsed time. The data entry staff (students) input license plate numbers to the best of their ability and indicate difficult to read license plate digits as question marks. If a license plate is completely unreadable, or blocked by another vehicle or object such as a tow ball or trailer, the video processors input the word "miss" into the box for the license plate number, which is necessary to maintain continuity of total vehicle counts. Additionally, data entry staff input specific information about the reason for license plate obstructions, such as the presence of trailer hitches, bike racks, etc. From the series of the procedures, baseline comparative travel times as well as traffic volume were collected and compared to selected test system travel times and volumes to identify potential biases. Table 2 summarizes data collection for the I-285 freeway deployments.

Due to the extensive time involved in manually processing license plate data, the full data processing efforts were only performed for the September 7th, October 20th, and November 10th deployments. For the evaluation of the selected technologies, data sets with larger variability in travel times were employed, as this was expected to improve the chances of identifying data collection differences across the selected systems, compared to free-flow conditions. Plus, the primary benefit of work zone monitoring systems is expected to be achieved under congested, rather than free flow, conditions. September 7th was chosen because the data were collected during the weekday morning peak period and the data therefore reflected a transition from congestion during the peak period to free-flow conditions after the end of the peak period. October 20th was chosen because it was during active work zone conditions during which heavy congestion was captured at the Paces Ferry Road site and free-flow conditions were captured at the Northside Drive site. November 10th was chosen because BlueMAC® Bluetooth® data were collected during that deployment. Therefore, a comparison between the observed data, ELSAG ALPR data, and BlueMAC® Bluetooth® data was possible for that day.

Table 2: Summary of the Data Collection for the I-285 Freeway Deployments

Day	Date	Sites	Equipment Present	Baseline Data Extraction	Work Zone?
1	Sep. 7th, 2012	I-285 Eastbound Paces Ferry Road-Northside Drive	ELSAG ALPR, HD video	Yes	No
2	Sep. 12th, 2012	I-285 Eastbound Northside Drive-Roswell Road	ELSAG ALPR, HD video	No	No
3	Sep. 14th, 2012	I-285 Eastbound Paces Ferry Road-Northside Drive	ELSAG ALPR, HD video	No	No
4	Sep. 29th, 2012	I-285 Westbound Riverside Drive-Pace Ferry Road	ELSAG ALPR, HD video	No	No
5	Oct. 20th, 2012	I-285 Eastbound Paces Ferry Road-Northside Drive	ELSAG ALPR, HD video	Yes	Yes
6	Nov. 10th, 2012	I-285 Eastbound Roswell Road-Chamblee Dunwoody Road	ELSAG ALPR, HD video, Bluetooth®	Yes	No
7	April 13th, 2013	I-285 Eastbound South Cobb Drive - Mt. Wilkinson Parkway	ELSAG ALPR, HD video, Bluetooth®, iCone®	No	Yes
8	April 20th, 2013	I-285 Eastbound Northside Drive-Roswell Road	Bluetooth®	No	Yes

6 Accuracy and Timeliness of Data Delivery

To perform an evaluation of the selected technologies, the system-reported travel times were compared with travel time data obtained by manually matching vehicle license plates from overpass video cameras (see Chapter 5). While BlueMAC® Bluetooth® and iCone® systems are off-the-shelf and readily provide real-time travel time data via the service provider's webpage, the ELSAG ALPR system currently stores the license plate readings on the processing unit. ELSAG travel time data are currently obtained by extracting the data post-data-collection; however, the equipment is capable of streaming data (as deployed in police enforcement systems) and could be readily adapted for widespread field deployment with minimal software modification. The evaluation of the selected systems addresses the following two aspects: 1) accuracy of the reported travel time and 2) timeliness of data reporting.

"Accuracy" of travel times relates directly to the quality of the travel time data provided by each system. This evaluation assesses whether the selected technology provides sufficiently accurate and reliable travel time data. The reported travel time data from all the selected systems are compared against the manual baseline travel time data. "Timeliness" relates to the responsiveness of the system to capture dynamically changing travel time data and report results to the web page in a timely manner with minimal communications lag. Timely data are critical for providing real-time traffic information to motorists. The following sections present initial analytical findings based upon the field deployments and comprehensive evaluations of the selected systems in terms of accuracy of the reported travel time and timeliness of the data.

6.1 Travel Time Bias

As mentioned in Chapter 5, I-285 data from September 7th, October 20th, and November 10th deployments included manually-processed license plate observations to serve as baseline travel time data for comparison. The October 20th, 2012 data collection deployment was conducted on a Saturday morning on I-285 from Paces Ferry Road to Northside Drive during active work zone conditions; traffic was significantly congested. The series of travel time plots for the deployment data (manual baseline and ELSAG ALPR) are shown in Figure 11.

In Figure 11, the majority of the travel times through the work zone typically ranged from about 8 minutes to 25 minutes over the course of the deployment period. Looking more closely at the data, two separate bands of travel times appear in the manual baseline travel time data, one band appears for about a 10-minute travel time and another for about a 17-minute travel time. It was hypothesized that these two separate travel time bands in the video data develops because of the presence of distinct travel time differences across the various freeway travel lanes [23]. The work zone lane closure for this corridor was a one mile stretch of the leftmost inside lane of the freeway. Indeed, the video data indicated that vehicles in the left lanes of the freeway (inside lanes) traveled faster than vehicles in the right lanes (outside lanes). The outside lane included more trucks and experienced significantly more queuing than the inside lane. Significantly different travel time patterns also developed by lane, due in part due to increased back-ups resulting from vehicles merging at work zone lane closure locations. Thus, travel times can be significantly different across lanes and average travel times can be potentially biased depending upon which lane is monitored, and whether more vehicles from one lane are monitored than from other lanes.

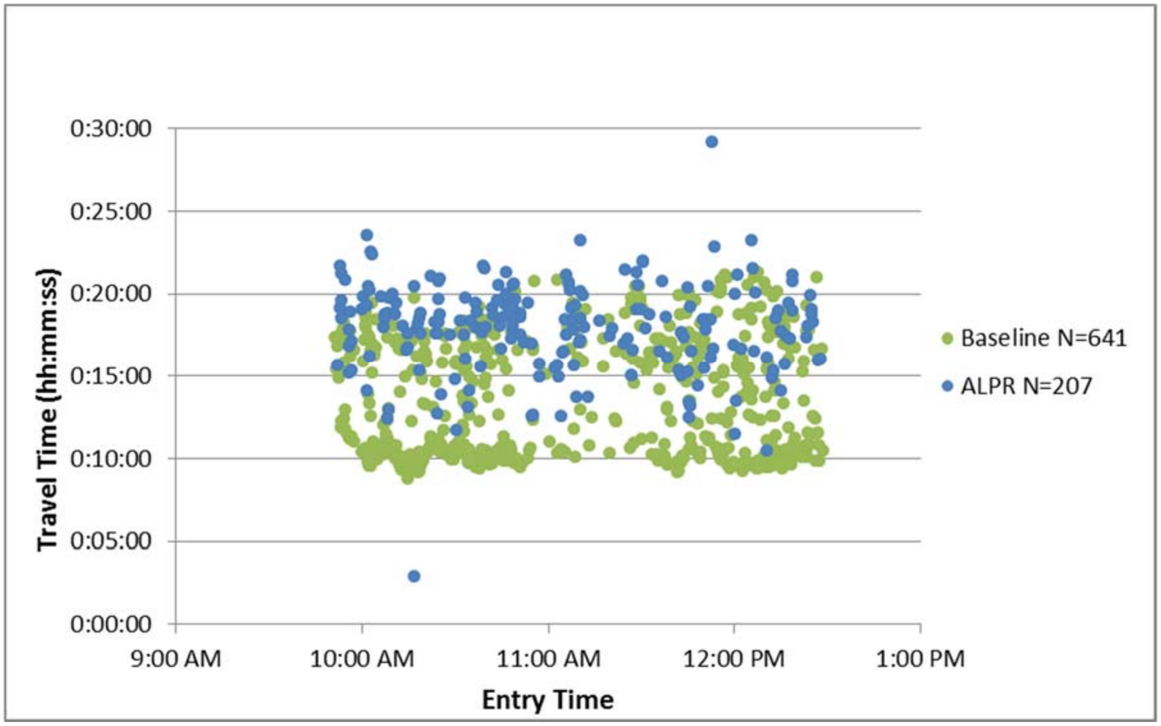

Figure 11: Manual Observation vs. ELSAG ALPR Travel Times (10/20/12)

Further emphasis is added to the lane bias potential, given that the ELSAG ALPR travel time plots are more in line with the higher band of manual baseline travel times (Figure 11). Given the placement of the ALPR cameras, the research team concluded that the ALPR system detected more vehicles travelling in the slower (outside) lanes of the freeway. This would be expected for the ELSAG ALPR cameras because vehicles in the outside lane occlude the longer sight distances to the inside lane, preventing the cameras from capturing as many of the license plates from vehicles on the inside freeway lanes. In essence, the ALPR system is inherently weighting the speeds captured from the lane closes to the cameras. In this instance, the right lane (outside lane) was the slower lane, and the ALPR captured a higher percentage slower vehicles.

Lane capture bias, however, can also be present in the baseline data travel times produced by the license plate video processing. Even though all of the license plate video cameras were placed on freeway overpasses with the same view of all travel lanes, a lane bias may exist in the baseline travel times derived from the video data, because more tractor trailer trucks travel in the outside lanes of the freeway than in the inside lanes. Due to their height, tractor trailer trucks can sometimes block from camera view the license plates of a vehicle preceding the truck, especially if the truck is following closely behind the vehicles (as is the case during congested conditions). This means that during the video processing a greater percentage of the vehicles in the outside lanes may be recorded as “misses” in the program, because they are blocked from view. The result is that video processing travel times may be biased towards faster moving left lanes because there is a higher likelihood of finding license plate matches in these lanes. This drawback is relatively straightforward to address in assessing lane-by-lane average speeds and overall speed statistics by binning the travel time data (e.g., five minute bins) per lane. Because the manual method provides accurate vehicle counts [24], average travel time can be weighted properly by lane.

A y-y plot comparing the travel times produced by the manual baseline data collection and the ELSAG ALPR during this deployment is presented in Figure 12 below. Again, the y-y plot was produced by plotting the average travel times (not weighted by volume) produced by each technology over the same five-minute bin periods. The ELSAG ALPR vs. manual baseline y-y plot shows that the ELSAG ALPR produces slower travel times on average than those produced by video license plate processing. Using the raw data for both the manual baseline and ELSAG ALPR it is not immediately possible to distinguish between how much of the bias can be attributed to ALPR detection of a greater number of slower moving vehicles, and how much of the bias can be attributed to manual video processing bias towards faster moving vehicles. A lane by lane analysis is performed in section 6.2 to further investigate this issue.

Even if ELSAG ALPR travel times are biased towards slower moving vehicles, this may not be a fatal flaw with respect to communicating expected work zone travel times to motorists. Drivers are less likely to be upset by experiencing a faster travel time than the travel times advertised. However, it appears that the ELSAG ALPR data are biased towards capturing travel times from the vehicles using the lanes closest to the camera location. This means that ELSAG ALPR travel times would be biased in the opposite direction if the cameras are set up adjacent to the fastest moving lanes in a work zone (e.g., on the median shooting into the fast lane rather than in the work zone shooting into the slower lane). Motorists also do not realize that there may be significant travel time differences across lanes. If ALPR cameras are deployed on the faster work zone lanes, motorists may respond negatively when they experience slower travel times than advertised.

This potential lane-bias drawback is not limited to the ELSAG ALPR but must be taken into consideration for any technology with a near-lane over sampling bias. For instance, the research team conducted several independent studies using Bluetooth® equipment (other than BlueMAC®) for field accuracy [25]. It was seen that the Bluetooth® had a potential to sample closer and slower moving vehicles at a higher rate. Under generally homogeneous conditions this would not significantly impact findings but where high speed differentials exist between lanes this could result in significant bias.

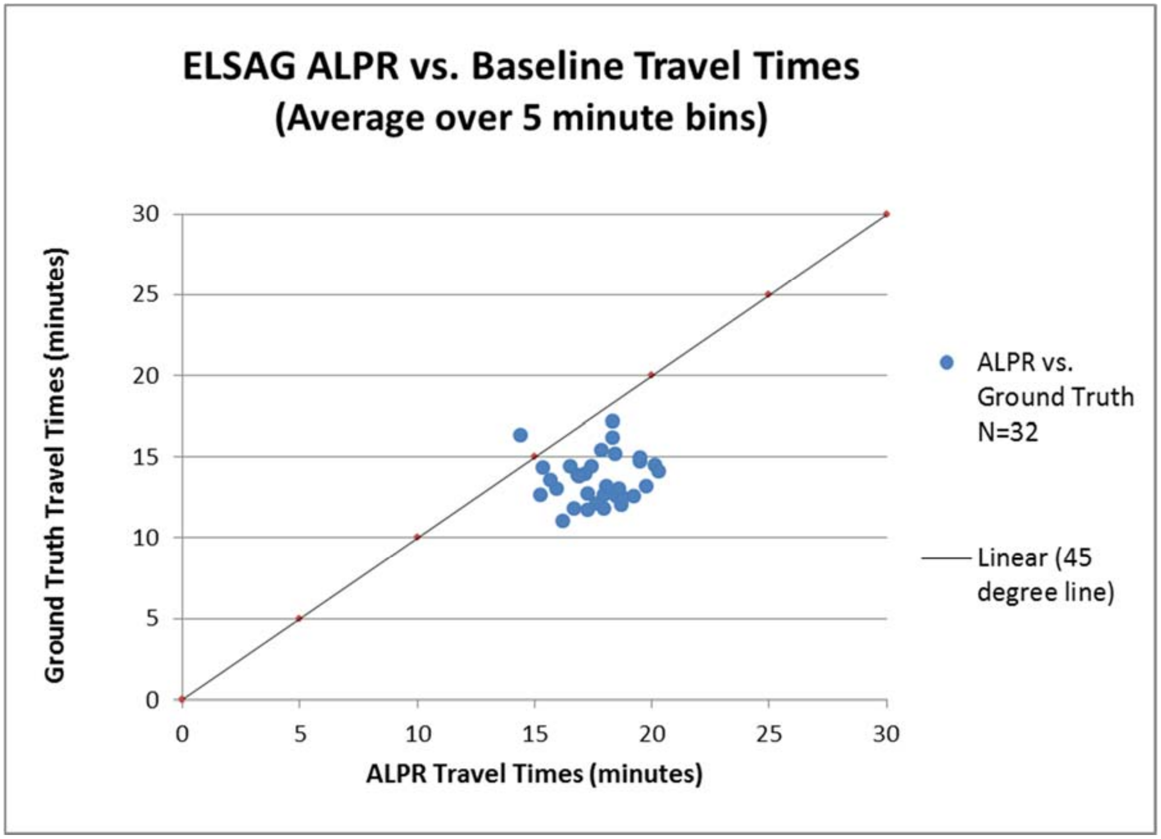

Figure 12: Comparison y-y Plots (10/20/12)

The possible reduction in discrepancy is investigated in the free-flow data. The November 10th, 2012 deployment was conducted on a Saturday morning during non-work zone conditions in the I-285 corridor from Chamblee Dunwoody Road to Roswell Road. The series of three travel time plots from this deployment for manual baseline, ELSAG ALPR, and BlueMAC® Bluetooth® data are shown below in Figure 13. The corridor experienced free-flow conditions throughout the deployment period with travel times averaging around three to four minutes. Even though this corridor experienced free-flow conditions throughout the deployment, the travel time plot shows that the ELSAG ALPR and Bluetooth® devices produced slightly slower travel times than those produced by the license plate video processing. This was also the case with the October 20th work zone deployment. Because the corridor was not congested during this deployment, the ALPR occlusion limitation should have been reduced but the limitation due to distance of vehicles in farther lanes from ALPR equipment could have still prevented the ALPR cameras from picking up the faster moving vehicles in the inside lanes.

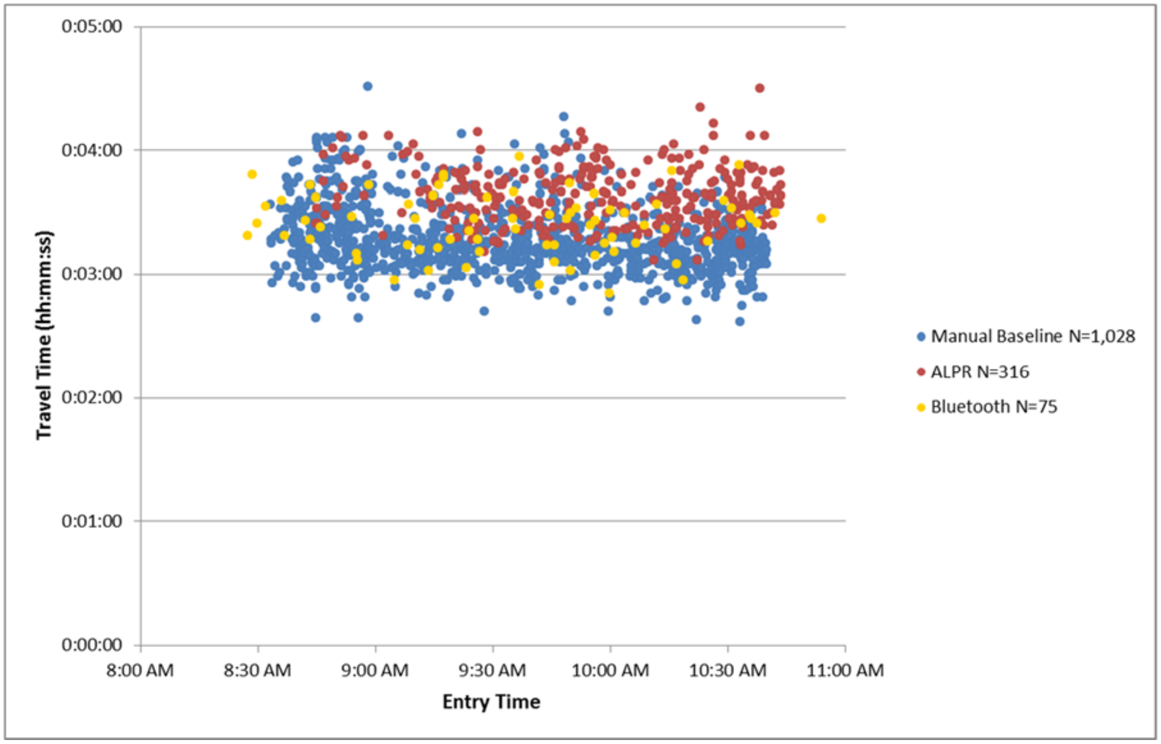

Figure 13: Travel Time Plots (11/10/12)

The y-y plots comparing each pair of the two technologies against the manual baseline data are presented in Figure 14 below. These y-y plots were again created by plotting the average travel times produced by the technologies over five-minute bin periods. The y-y plots confirm that the ELSAG ALPR travel times were, on average, slower than travel times based upon manual video license plate processing. The BlueMAC® travel times were also on average slower than the video license plate processing travel times, but not as significantly as the ELSAG ALPR travel times. The video processing travel times may again be slightly biased towards faster travel times due to differences in the license plate data entries across the different freeway lanes. However, for the free flow conditions all methods reported travel times within a minute of each other. Finally, the y-y plot comparing the ELSAG ALPR travel times to the Bluetooth® travel times shows that the ELSAG ALPR travel times were slower, likely indicating a similar bias in the data sets. The research team has conducted several independent studies using Bluetooth® equipment (other than BlueMAC®) for field accuracy [25]. Hence, the Bluetooth® equipment had a potential to sample closer and slower moving vehicles at a higher rate.

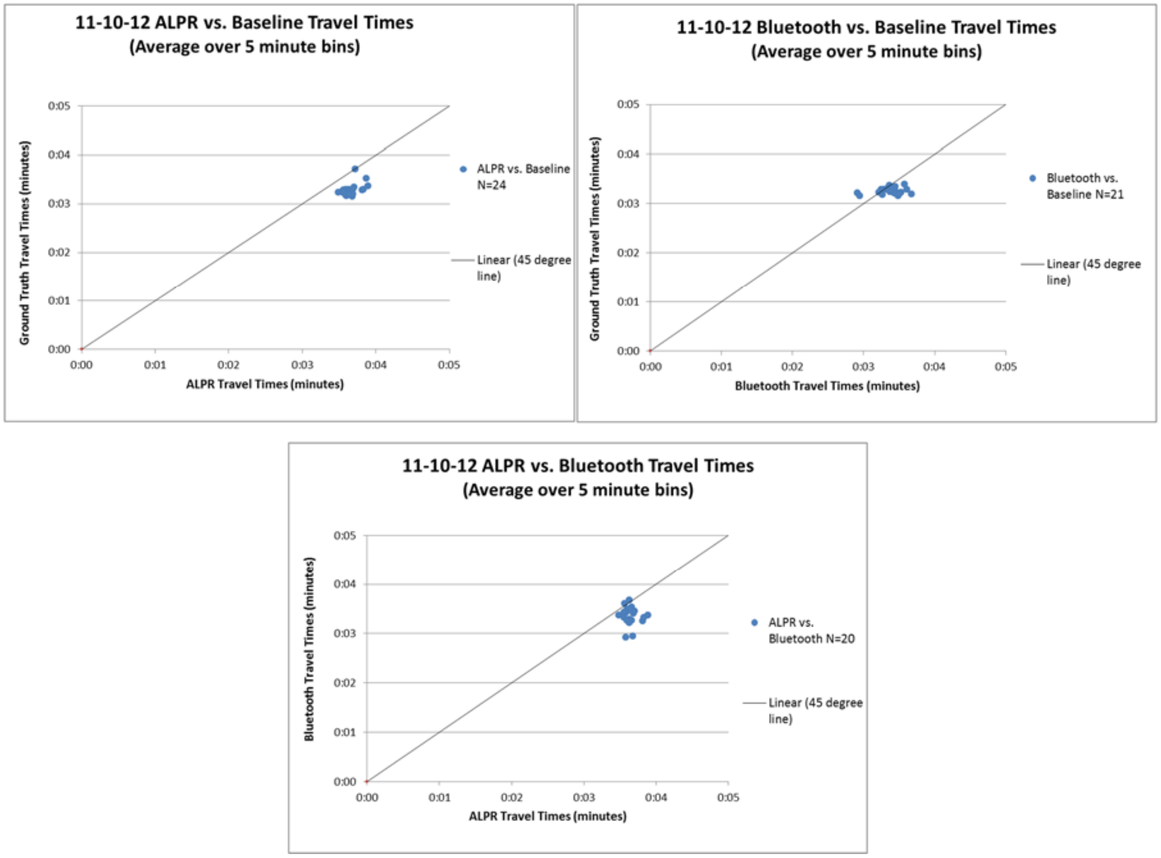

Figure 14: Comparison y-y Plots (11/10/12)

6.2 Lane Sampling Bias

Given the findings discussed in the previous section, a detailed lane bias analysis was conducted using the October 20th, 2012 deployment data. The goal was to investigate whether travel time differentials across freeway lanes might introduce a bias into the travel times produced by the various technologies if they detect different percentages of vehicles travelling in each freeway lane. Table 3 below shows the breakdown by lane at Site A (Paces Ferry Road) for the video and ELSAG ALPR travel time matches from the October 20th deployment. The 2nd through 5th columns in the table show, for each freeway lane, the number of vehicles that passed each site, the number of travel time matches that were made between these vehicles using the video processing license plate data, and the average travel time for these travel time matches. The 6th through 9th columns show the total number of unique ELSAG ALPR license plate detections at each site and, for each lane, the number of ELSAG ALPR travel time matches, and the average travel time for these travel time matches.

Table 3: Lane Breakdown for Manual Baseline and ELSAG ALPR Travel Times

Saturday, October 20th, 2012 (Active Work Zone)	Lane at Site A	Total Vehicle Volume at Site A	Total Vehicle Volume at Site B	Percent of Plates Transcribed Site A	Percent of Plates Transcribed Site B	# of Manual Matches (by lane at site A)	Avg. Manual Travel Time (by lane at site A)	# of Unique ALPR Detections (Site A)	# of Unique ALPR Detections (Site B)	# of Corrected ALPR Matches (by Lane at site A)	Avg. ALPR Travel Time (by lane at site A)
	Lane 1	2,260	559	73.58%	93.92%	338	10:29	unknown	unknown	2	17:08
	Lane 2	791	928	47.91%	70.01%	59	14:56	unknown	unknown	6	18:04
	Lane 3	802	1,814	55.24%	73.10%	78	17:15	unknown	unknown	48	19:19
	Lane 4	1,243	1,574	84.07%	65.69%	166	16:14	unknown	unknown	152	17:43
	Lane 5	N/A	948	N/A	91.35%	N/A	N/A	unknown	unknown	N/A	N/A
	Total	**5,096**	**5,823**	**69.27%**	**75.02%**	**641**	N/A	**3,157**	**1,663**	**208**	N/A

The average manual baseline travel time column of the table shows distinct travel time differences for vehicles identified in each of the four freeway lanes at Site A. The fastest travel times were experienced by the vehicles in lanes one and two at Site A, the next fastest travel times were experienced by the vehicles in lane four, and the slowest travel times were experienced by the vehicles in lane three. These results show that there are distinct travel time differences across the various freeway lanes. Furthermore, Figure 15 below shows a travel time plot of each of the travel time matches from the video license plate processing at Site A, color coded by lane number. On average, this travel time plot shows faster travel times experienced by vehicles travelling in the left lanes as compared with vehicles travelling in the right lanes.

For the ELSAG ALPR lane bias analysis, the total number of unique ELSAG ALPR detections for each lane at each of the sites is unknown, because ELSAG ALPR detectors do not provide a corresponding lane number. However, the average ELSAG ALPR travel times for vehicles in each of the four lanes at Site A were calculated using the 208 ELSAG ALPR travel time matches that were manually assigned to their lane at Site A. These average ELSAG ALPR travel times do not show as much of a difference across freeway lanes as the average manual baseline travel times and tend to be higher. The explanation for this is that the vehicles that were detected by the ALPR cameras at Site A from the inside lanes were detected in one of the outside freeway lanes at Site B. Only a small percentage of the vehicles travelling in the inside lanes are detected by the ALPR cameras due to occlusion and sight distance limitations. Hence, the probability of a vehicle traveling continuously on the left lane being identified at both sites is very low. When reviewed in the video, these eight ALPR matches from lane one and lane two at Site A were detected in the outside lanes at site B. Thus, the vehicles likely had longer travel times as they spent some time in the slower moving outside lanes rather than completing the entire trip on the inside lanes. Additionally, some differences between the travel times produced by the manual matches and the ALPR matches may be attributed to these two sets of travel times not being measured between the same two points in the freeway. Because the ALPR units were set up in advance of the interchange overpasses, and the video cameras were aimed beyond the overpasses, there are a few hundred feet of difference in the length of the travel paths.

This analysis further demonstrates the potential bias introduced when a technology under-samples one or more lanes. The impact of differing lane-detection sampling probabilities is exaggerated as a vehicle must be sampled at least twice to determine a travel time. For example, if a vehicle has an 80% probability of being sampled in the near-lane the probably of that vehicle contributing a travel time is (0.80 X 0.80) or 64%. If a vehicle has a 20% probability of being sampled in the far lane the probably of that vehicle contributing a travel time is (0.20 X 0.20) or 4%. Thus, in this example a factor of 4 in detection probability (80% versus 20%) results in the vehicle being 16 times less likely (64% versus 4%) in contributing a travel time.

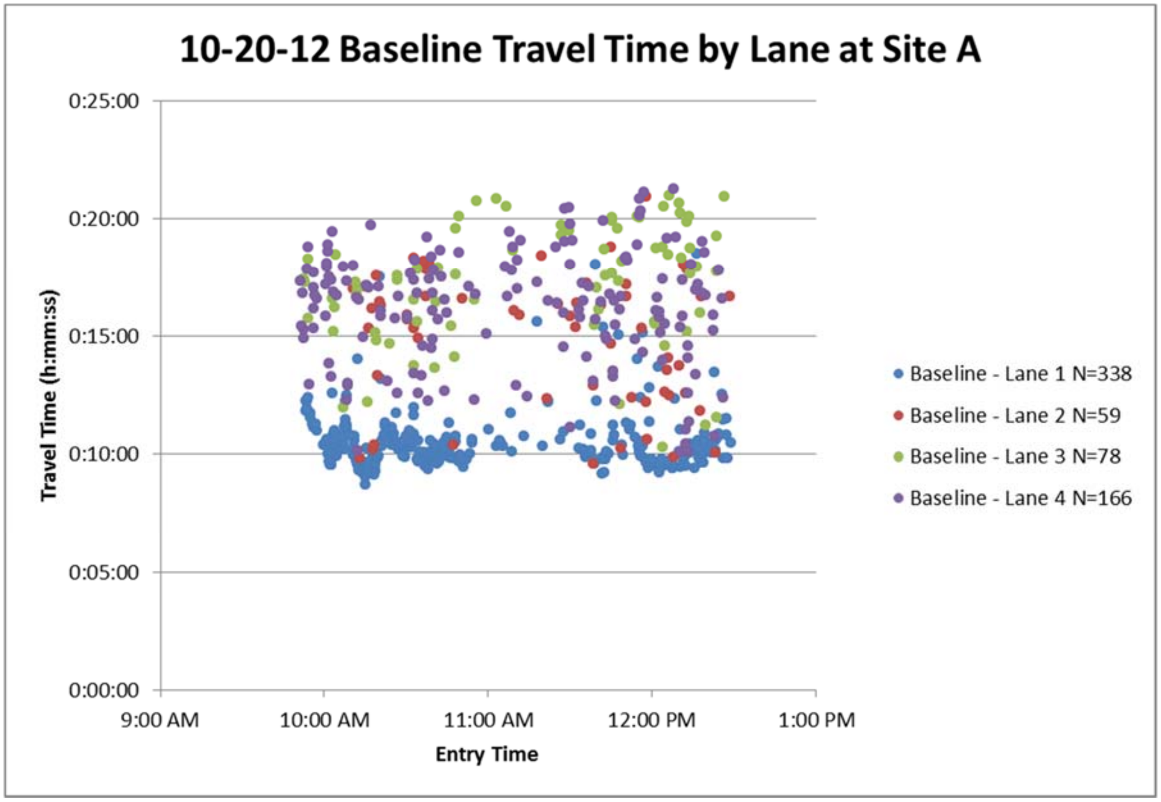

Figure 15: Travel Lane Breakdown of Travel Time Matches (10/20/12)

The more striking takeaway from the lane bias analysis is that the greatest percentage of the baseline manual travel time matches was in lane one (inside lane), and the greatest percentage of ALPR travel time matches was in lane three (outside lane). The video cameras are biased towards producing travel time matches between vehicles in the inside freeway lanes for several reasons. For example, there are fewer tractor trailer trucks in the inside lanes; therefore, less license plate occlusion occurs on these lanes. In addition, the vehicles travelling in the inside lanes are less likely to exit the freeway within the corridor; so, a higher percentage of these vehicles complete the travel through the entire monitored corridor and have a higher probability of being re-identified on the videos. As was previously discussed in the travel time results section, there are also several reasons why the ALPR cameras would be biased towards producing travel time matches for the vehicles travelling in the outside freeway lanes, such as being restricted to these outside lanes, due to occlusion, and camera sight distance limitations. The occlusion limitation was particularly present during the October 20th deployment because the Paces Ferry Road (Site A) ALPR set-up location experienced heavy congestion, with very small headways between vehicles for the majority of the deployment period.

6.3 Accuracy Analysis

It is common practice among many state agencies to report longer travel times to motorists when a large variation in travel times is observed. Drivers are not as likely to be bothered by experiencing faster travel times than they expect, based upon a message they receive. As presented previously, ELSAG ALPR and BlueMAC® Bluetooth® travel time data for these specific deployment configurations were found to be biased towards reporting longer travel times, likely due to longer travel times on the lanes adjacent to the equipment. In this accuracy analysis, the travel times reported from ELSAG ALPR and BlueMAC® Bluetooth®, and iCone® for the April deployment, are compared to the longer travel times of the manual baseline data. First, average manual baseline data are derived by taking the average of data points at each one-minute interval throughout the data collection period. Then all data points above this average will be taken and used to get another one-minute interval average (i.e., the average for the upper travel time band). The resulting average at one-minute intervals are assumed to represent the longer travel times (baseline upper-bound) that may be commonly designed to be reported by state agencies and compared with the ELSAG ALPR and BlueMAC® Bluetooth® travel times. This is a simplistic way of separating the modes. Further research needs to be done to perform a modal analysis to identify the underlying distributions for a more rigorous test.

6.3.1 ELSAG ALPR Results (October 20th, 2012)

The October 20th, 2012 data collection deployment was conducted on a Saturday morning in the I-285 corridor from Paces Ferry Road to Northside Drive during active work zone conditions. The travel time plots from this deployment for ELSAG ALPR, manual baseline upper-bound, and manual baseline average are shown in Figure 16 below. The majority of the one-minute travel times typically ranged from approximately 10 to 20 minutes over the course of the deployment period. The mean percent difference for the overall collection period was 33.7% (vs. one-minute average manual baseline travel time) or 14.9% (vs. one-minute average upper-bound manual baseline travel time). The absolute percent difference was 35.8% (vs. one-minute average baseline travel time) or 22.2% (vs. one-minute average upper-bound manual baseline travel time). These percent differences indicate that the ELSAG ALPR was likely over-estimating travel times most of the time. This can be attributed to the lane bias issue when the ALPR is set up in a congested area as discussed in Section 6.2 previously.

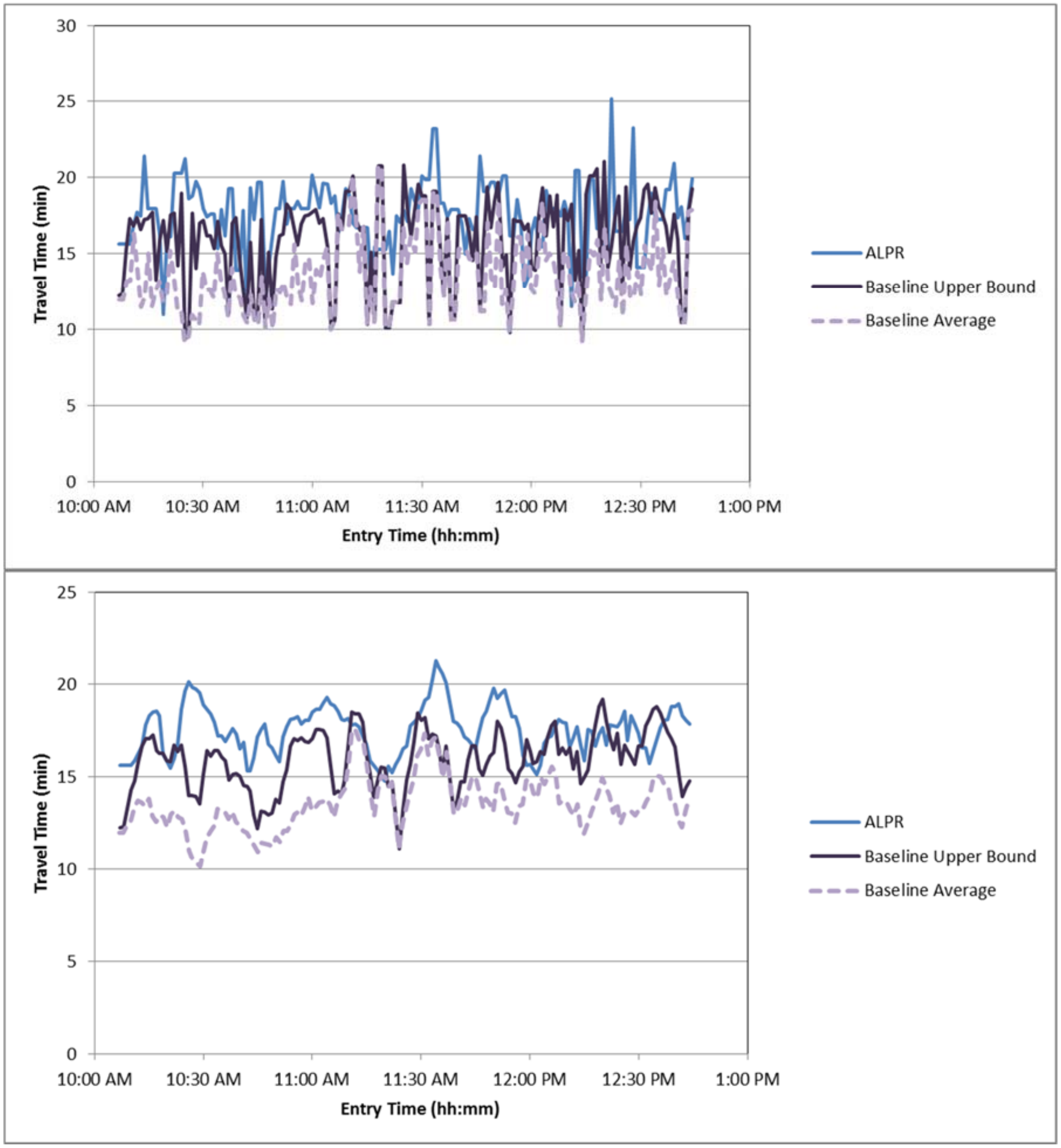

Figure 16: One-minute and Five-minute Average Travel Times (10/20/12)

6.3.2 BlueMAC® Bluetooth® and ELSAG ALPR Results (November 10th, 2012)

The November 10th, 2012 deployment was conducted on a Saturday morning during non-work zone conditions in the I-285 corridor from Chamblee Dunwoody Road to Roswell Road. BlueMAC® Bluetooth® and ELSAG ALPR travel times were included in this data collection. The travel time plots from this deployment for BlueMAC® Bluetooth®, ELSAG ALPR, manual baseline upper-bound, and manual baseline average are shown in Figure 17. Given the free-flow traffic conditions, the average travel times ranged from 3 to 4 minutes over the course of the deployment period.

The mean percent difference for ALPR vs. one-minute average manual baseline data was 15.8% and the mean absolute percent difference was 15.9%. Furthermore, the mean percent difference for ALPR vs. one-minute average manual baseline upper-bound for the entire data collection period was 9.3% and the mean absolute percent difference was 9.8%. Here it is apparent that the ALPR is over-estimating the travel times even in free flow conditions. As discussed earlier, the ALPR system is suspected of being significantly biased toward slower moving traffic in the adjacent right lanes. The traffic in the right lanes has a higher probability of being detected because these vehicles are occupying the ALPR cameras field of view without blockage, while views to the traffic in the left lanes have a higher probability of being obstructed.

The mean percent difference for BlueMAC® Bluetooth® vs. one-minute average upper-bound manual baseline data for the entire collection period was 4.9% and the mean absolute percent difference was 8.4%. Furthermore, the mean percent difference for BlueMAC® Bluetooth® vs. one-minute average upper-bound manual baseline data was -1.1% and the mean absolute percent difference was 7.5%. This shows that while the BlueMAC® Bluetooth® has a much smaller sample size than the ELSAG ALPR, but its sample population may contain less bias toward slow traffic during uncongested conditions than the ELSAG ALPR.

Figure 18 shows the average travel time by minute for each lane, a total weighted average by volume for each minute, and the ALPR average travel time by minute for the November 10, 2012 data collection. This plot shows that the ALPR travel times more closely match those of lane 4 and lane 5 (the outside, right-most lanes) due to the sampling bias caused by the equipment being set up on the right side of the freeway. When comparing the ALPR travel times to the weighted average travel time by volume, one can see that that ALPR is consistently over-estimating the travel times by about 10 to 15 seconds.

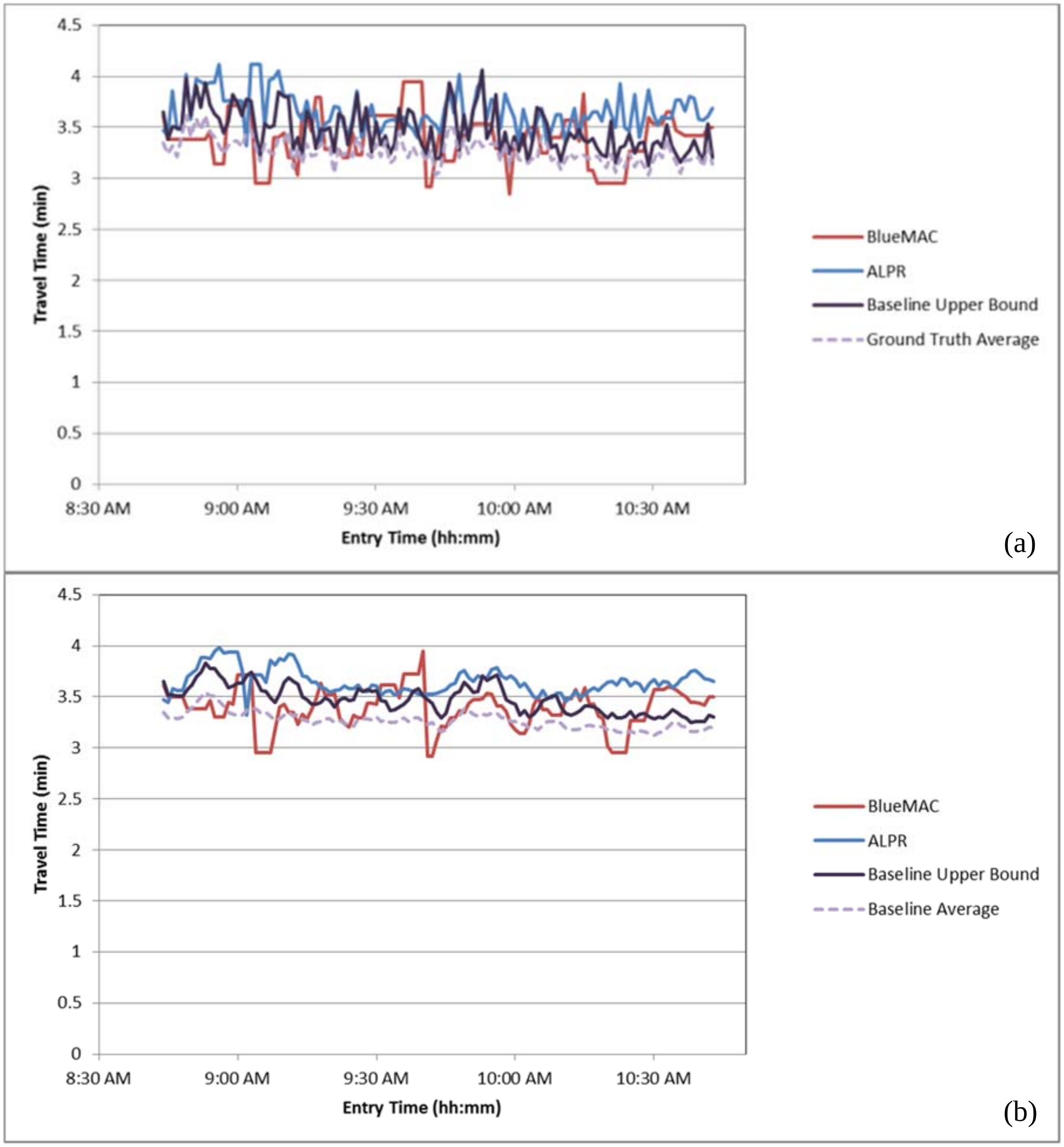

Figure 17: One-minute (a) and Five-minute (b) Average Travel Times (11/10/12)

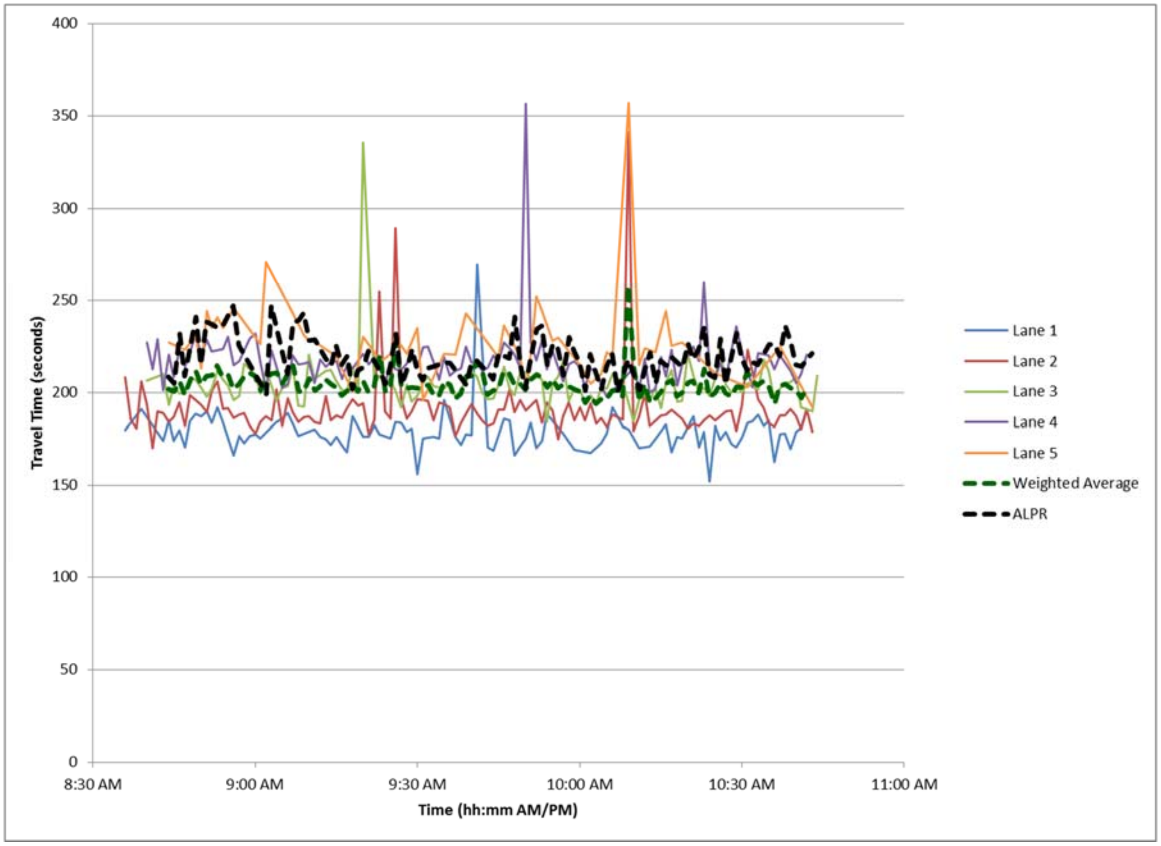

Figure 18: One-minute Weighted Average Travel Time by Lane and ALPR (11/10/12)

6.3.3 iCone®, BlueMAC® Bluetooth®, and ELSAG ALPR Results (April 13th, 2013)

The April 13th deployment included ELSAG ALPR, BlueMAC® Bluetooth®, and iCone® in parallel. These devices were set up at South Cobb Drive and Mount Wilkinson Parkway along I-285 in Atlanta, GA. In addition to these two sites, iCone® units were set up at 4 additional locations (Riverview Road, Atlanta Road, Orchard Road, and the Chattahoochee River Bridge) and BlueMAC® Bluetooth® units were set up at 2 additional locations (Atlanta Road and the Chattahoochee River Bridge). The iCone® and BlueMAC® Bluetooth® units were deployed on Friday April 12th, 2013, prior to the April 13th deployment, and retrieved on Tuesday, April 16th, 2013. ELSAG ALPR cameras were deployed on April 13th, 2013 from 9:30 AM to 3:00 PM. Each system used in this experiment directly revealed inherent advantages and limitations in the travel time results.

The ELSAG ALPR showed a significantly higher number of matches between the two sites than either of the other two systems. The ELSAG ALPR collected 2,308 paired observations between South Cobb Drive and Mount Wilkinson Parkway (due to the high volume of effective sampling), while the BlueMAC® only collected 256 paired Bluetooth® observations (Figure 19). The figure clearly shows that the speed differential was being experienced roughly after 12:00 PM. The team concluded that the definitive separation between faster travel times and slower travel times was caused by faster vehicles with a lower number of trucks in the two left lanes and slower vehicles in the two right lanes with a higher number of trucks. This phenomenon can also be seen in the data from the BlueMAC® Bluetooth® system, which detected this speed differential as well. This is further evidence of Bluetooth® system bias toward slower moving vehicles that remain in the detection zones for longer periods of time. Further independent research by the researchers with a variety of Bluetooth® based detection systems have confirmed this finding [25].

Also in Figure 19, iCone® travel time estimations had the high spikes in travel times (as high as 60 minutes) when ELSAG ALPR and BlueMAC® Bluetooth® were reporting closer 28 minutes. The differences between the iCone® travel times and ELSAG ALPR and BlueMAC® Bluetooth® travel times may be caused by the iCone® travel time estimation methodology, which assumes spot speed data on two measurement points are representative of traffic condition between the two points. This assumption may generate some unrealistic travel times under congested conditions, when traffic is in stop-and-go conditions or shockwaves are passing the measurement points. For example, travel time based on 5 mph spot speed can result in predicted travel times that are twice as long as travel times based upon 10 mph spot speeds.

Also, it is possible that vehicles in the slower moving right lanes were blocking faster moving vehicles in the left passing lanes. In Sheckler's 2010 report [21], researchers stated that the low profile of the iCone® will primarily sense vehicles in the lane nearest to the iCone®. Furthermore, during medium to high volumes of traffic, the farther lanes will also be blocked out by the nearest lane. Sheckler's final statement on this effect is "an iCone® set on the right shoulder will primarily be measuring the speed of vehicles in the slower driving-lane and shouldn't be expected to reflect the passing-lane speeds [21]."

The April 13th, 2013 data collection does not have manual baseline data available; therefore, the BlueMAC® Bluetooth® and iCone® systems were compared against the ELSAG ALPR data for purposes of mean percent difference and mean absolute percent difference calculations. The mean percent difference for BlueMAC® Bluetooth® vs. ELSAG ALPR for the entire data collection period was -6.7% and the mean absolute percent difference was 25.2%. As seen in the November data collection, the ELSAG ALPR reported higher travel time over the BlueMAC® Bluetooth® implying the ELSAG ALPR is more biased toward slow moving travel times.

The percent error for iCone® vs. ELSAG ALPR for the entire data collection period was 9.5% and the mean absolute percent difference was 33.1%. The mean percent difference shows that on average the iCone® system estimated significantly higher travel times compared to the ELSAG ALPR. Furthermore, the mean absolute percent difference shows that there is more variation occurring with the iCone® data than two other technologies. The iCone® travel times are expected to have more variation, since they are calculated based on the spot speed of limited locations. Once a significant variation in spot speeds begins to occur, iCone® travel times can vary significantly; this would be more apparent when traffic speeds are unsteady in the areas where iCone® units are located. Hence, it is critical to analyze the deployment zone's flow in advance and deploy sufficient iCone® units upstream and downstream of bottlenecks to cover both the congested and uncongested flows in order to obtain a representative travel time.

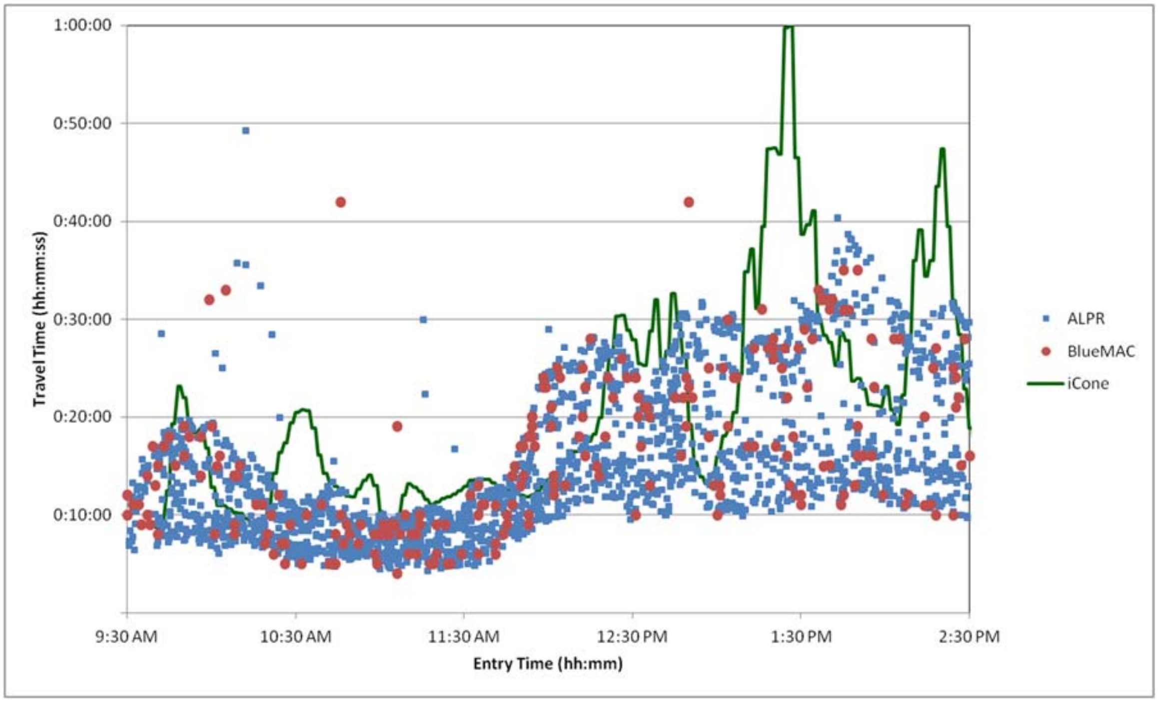

Figure 19: Travel Time Data (04/13/13)

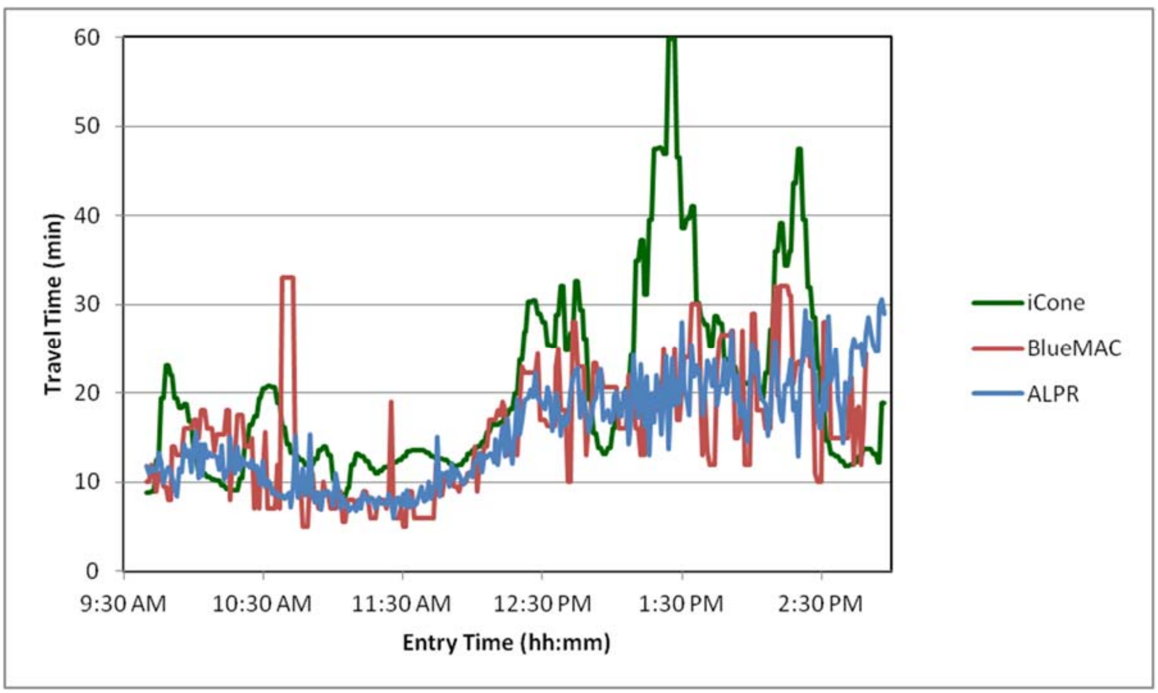

Figure 20: One-Minute Travel Time (04/13/13)

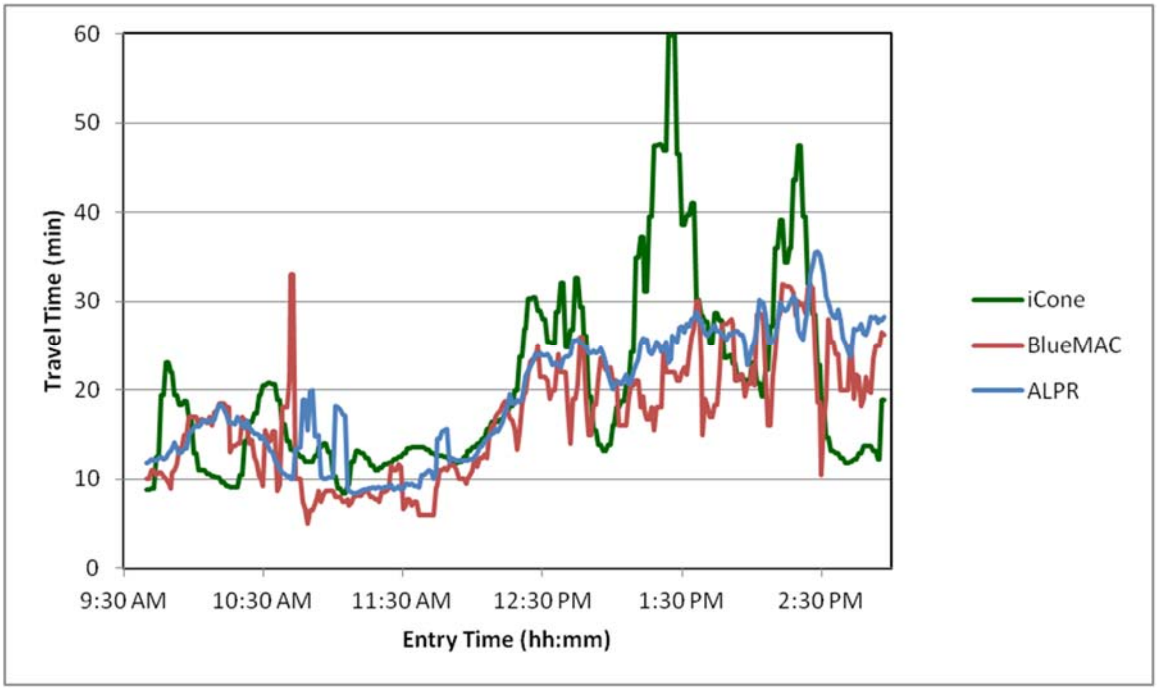

Figure 21: Five-Minute Travel Time (04/13/13)

6.3.4 Aggregate Statistic Plots

The five minute average, median, and 85th percentile travel times were plotted for each device for each day of data collection, to visually identify the data variability for each device under the respective conditions present during each data collection. Large departures between the median and average lines indicates that extreme values that are skewing the average. Furthermore, when the 85th percentile is distant from the average or median line, the travel times collected exhibit larger variability.

Figure 22 shows the descriptive statistics plots for the October 20th, 2012 data collection. This was an active work zone and congested conditions were experienced. For the ALPR, the average line follows the median line from about 10:00AM to 10:30AM and 11:00AM to 12:00PM. After 12:00PM, the average line departs from the median. In the travel time plot for the ALPR, during the times that the median and average lines are nearly the same, the travel time points are much closer to each other and there are no extreme values. Before 10:00AM and after 12:00PM the travel times are more separated and two extreme values can be observed. The 85th percentile line in this plot also shows an increase in variability when the average and median lines depart.

Figure 22b shows the statistics plot for the baseline travel times. It was previously shown that the baseline travel times for this day had some bias due to oversampling from the inside lane (lane 1). Lane 1 not only showed much lower travel times, around ten minutes, but also had a much higher number of matched plates (Lane 1 = 338 vs. Lane 2 = 59). Therefore, the average and median lines are showing lower travel times (about 13 minutes) than the ALPR (about 17 minutes) which is biased to the outside lane. Interestingly, between about 11:15AM and 11:45AM in

Figure 22b the median line drops below the average line and the 85th percentile line departs upward from the average line. At the same time, the match frequency for lane 1 goes down. Lane 1's match frequency drop is most noticeable in the travel time plot. The drop of the median line suggests that a separation in travel times also began occurring at that time. A larger and more equally weighted separation in travel times allows the median to drop while the 85th percentile line increases.

Figure 23(a-c) shows the aggregate statistic plots for ALPR, BlueMAC®, and the baseline travel times on November 10th, 2012. This was a non-work zone day and no congestion was experienced. Consequently, travel times remained steady, at around 3.5 minutes, and departure between the average and median lines was not expected. Furthermore, it was expected that the 85th percentile line would maintain a consistent gap above the average and median lines. When viewing the ALPR statistics the hypothesis held that the average and median lines would remain close and that the 85th percentile line would maintain a fairly constant gap between the average and median lines. However, this was not the case for the BlueMAC® travel times.

Due the low penetration of Bluetooth® devices, travel times collected by this method are bound to show more variation than ALPR, which has a very high penetration rate during free flow conditions. In

Figure 23b, the departures of the 85th percentile line and the median line between 9:00AM and 9:30AM are a sign that the travel times experience more variation during that time. More variation allows the 85th percentile line to depart and opens up the possibility for the median to depart from the average. Outside of this range, the travel times show less variability as all lines remain close to each other.

In

Figure 23c, the baseline data shows much less variation. Observing the travel time plot for November 10, 2012 it can be seen that matching frequencies, travel times, and lane sampling rates by lane remained stable throughout the data collection. Therefore, it would be expected that the resulting statistics plot should show very close average and median lines throughout. Furthermore, the 85th percentile line should maintain a fairly constant gap with the average and median lines. The baseline statistics plot as shown in

Figure 23c shows very close average and median lines as well as an 85th percentile line that exhibits a fairly stable gap from the average and median lines.

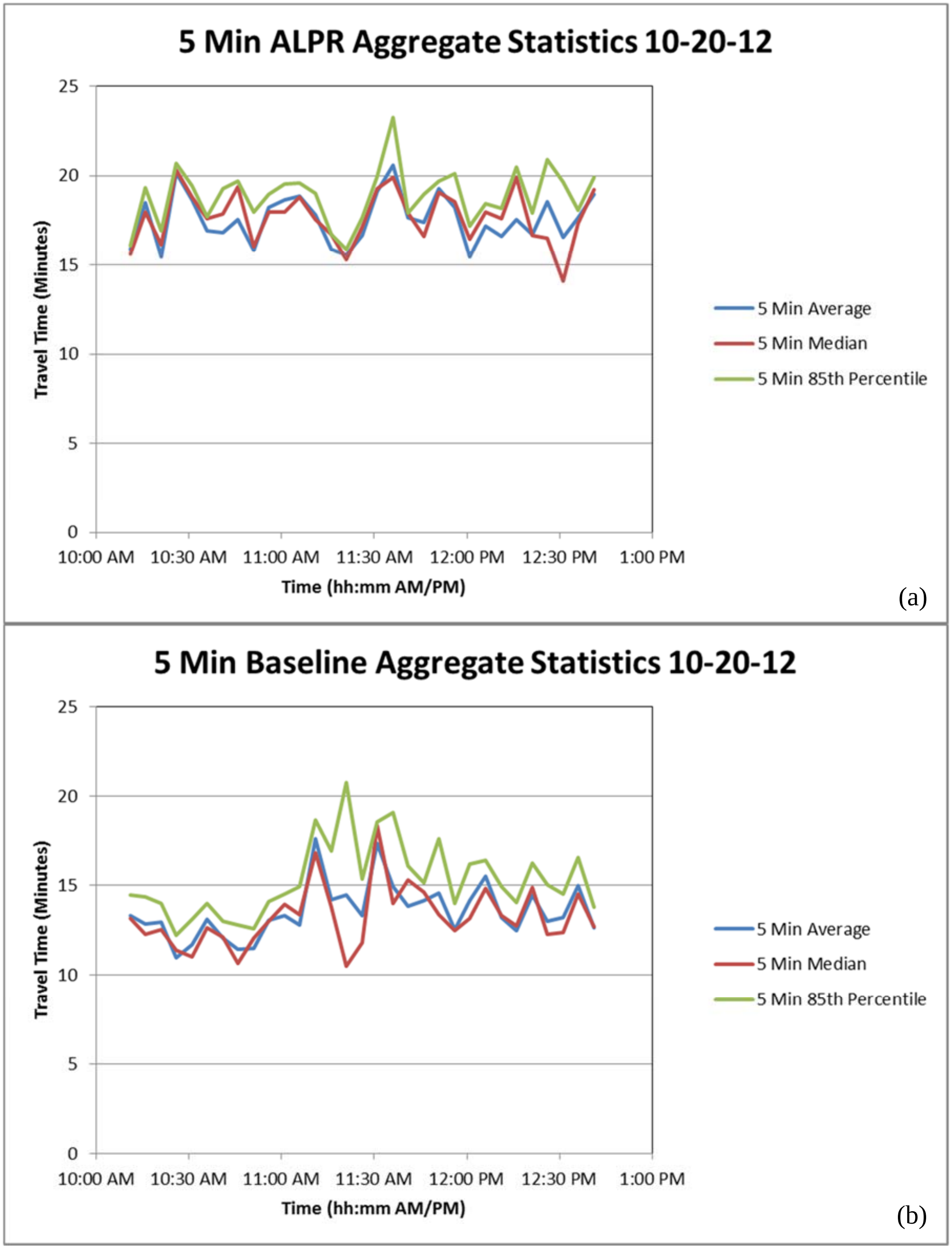

Figure 22: Five-minute Travel Time (a) ALPR, (b) Baseline (10/20/12)

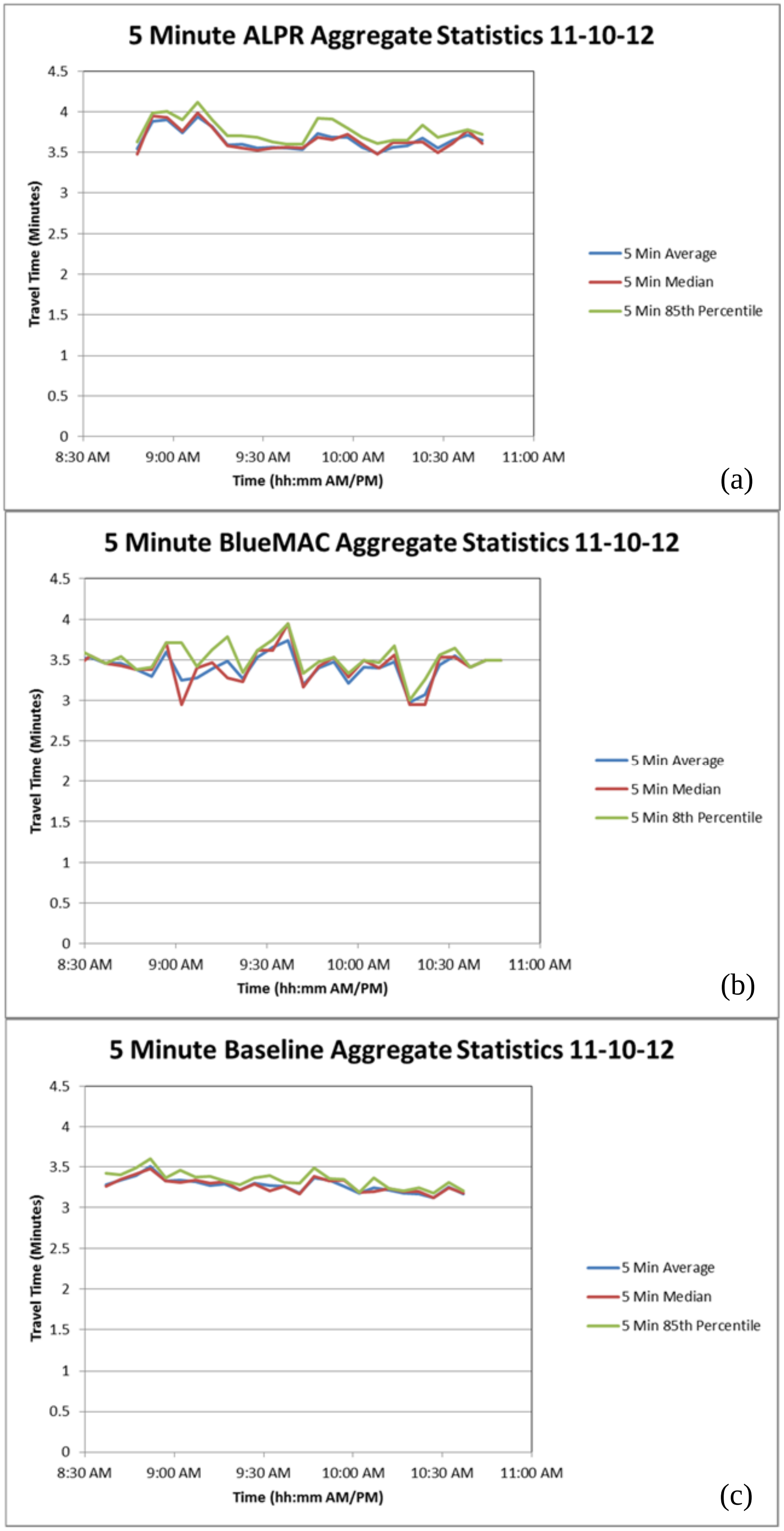

Figure 23: Five-minute Travel Time: (a) ALPR, (b) BlueMAC®, (c) Baseline (11/10/12)

Figure 24 through Figure 26 show the five minute aggregate statistic plots for the April 13, 2013 data collection. This day began in low volume traffic conditions, with queues building around 11:30AM. Here, it appears that during the earlier hours, before 11:30AM, there is less travel time variability than after 11:30AM. Furthermore, the ALPR showed much less variability throughout the day than the BlueMAC®. However, the iCone® travel times show much less variability throughout the day than either ALPR or BlueMAC®. The iCone® travel times show less variability because these travel times come from the XML live feed. This feed is only updated every two-minutes; therefore, the statistics plot show less variability (each five minute period examined includes repeat travel time data). In one five minute period, the first and second minute will use the same travel time, the third and fourth travel times will be the same, and the fifth travel time will be different. Although there is less variability within a small period of time for the iCone®, the variability of travel times compared to times captured by other devices is much larger.

Figure 24 shows the ALPR aggregate statistics for the April 13th, 2013 data collection. At approximately 10:30AM the 85th percentile line and the average line has some large deviations above the median line. This may be caused by some extreme travel time values occurring just before 10:30AM. Between 11:00AM and 12:30PM the average, median, and mean lines are very close together. After 12:30PM, the 85th percentile line begins to maintain a larger deviation from the average and median lines. This is caused by an evident separation in travel times shown in the travel time plot for April 13, 2013. As baseline data are not available for lane by lane travel time on this day, it cannot be determined if the separation in travel times is caused by different speeds in different lanes. However, the October 20, 2012 travel time by lane breakdown showed that when left lane closures occurred, travel times in the inside lanes were lower. From the previous observations, it can probably be assumed that the travel time separation here is also likely due to lower travel times in the left lanes than the right lanes.

Figure 25 shows the aggregate statistics plot for the BlueMAC® travel times for the April 13, 2013 data collection. The plot shows many areas where the 85th percentile line deviates largely from the average and median lines. Notable deviations are occurring at approximately 11:30AM, 12:45PM, 1:30PM, and 2:00PM. The large spikes at 11:30AM and 1:30PM are caused by some extreme values. Deviations occurring at 12:45PM and 2:00PM are caused by the separation in travel times. The average line deviations from the median line at 11:30AM and 2:00PM are caused by extreme values and the separation in travel times respectively.

Figure 26 shows that the data variability on a five minute basis from the iCone® system is fairly low. The only large deviations of the 85th percentile lines occur at approximately 9:45AM and 2:30PM. At 9:45AM, the deviation is occurring due to a short spike in travel times sensed by the system. Two of the five minutes in this period were 4 minutes larger than the previous (19 minutes to 23 minutes) which caused the 85th percentile line to deviate from the average and median lines. Furthermore, the deviations occurring at 2:30PM were also caused by a short term spike in travel times sensed by the system. Here a seven minute increase in travel time (36 minutes to 43 minutes) for only two out of the five minutes caused the 85th percentile line to deviate largely from the average and median lines.

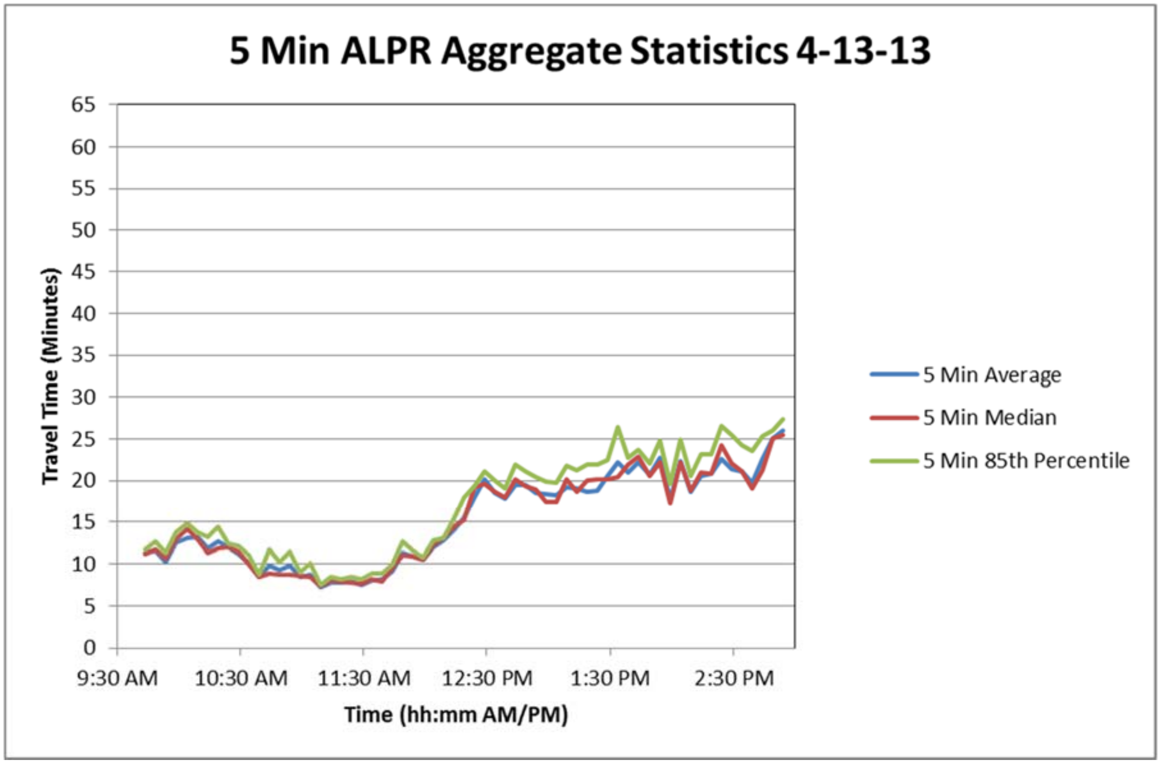

Figure 24: Five-minute Summaries: ALPR (04/13/13)

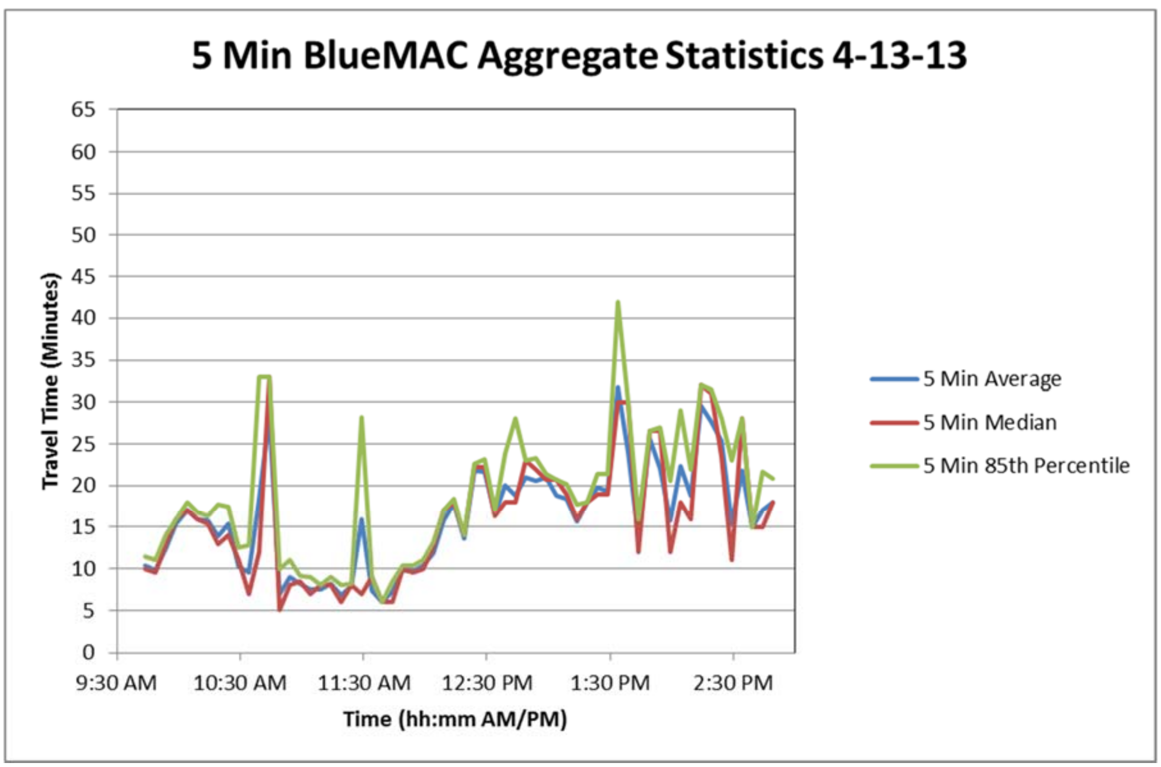

Figure 25: Five-minute Summaries: BlueMAC® (04/13/13)

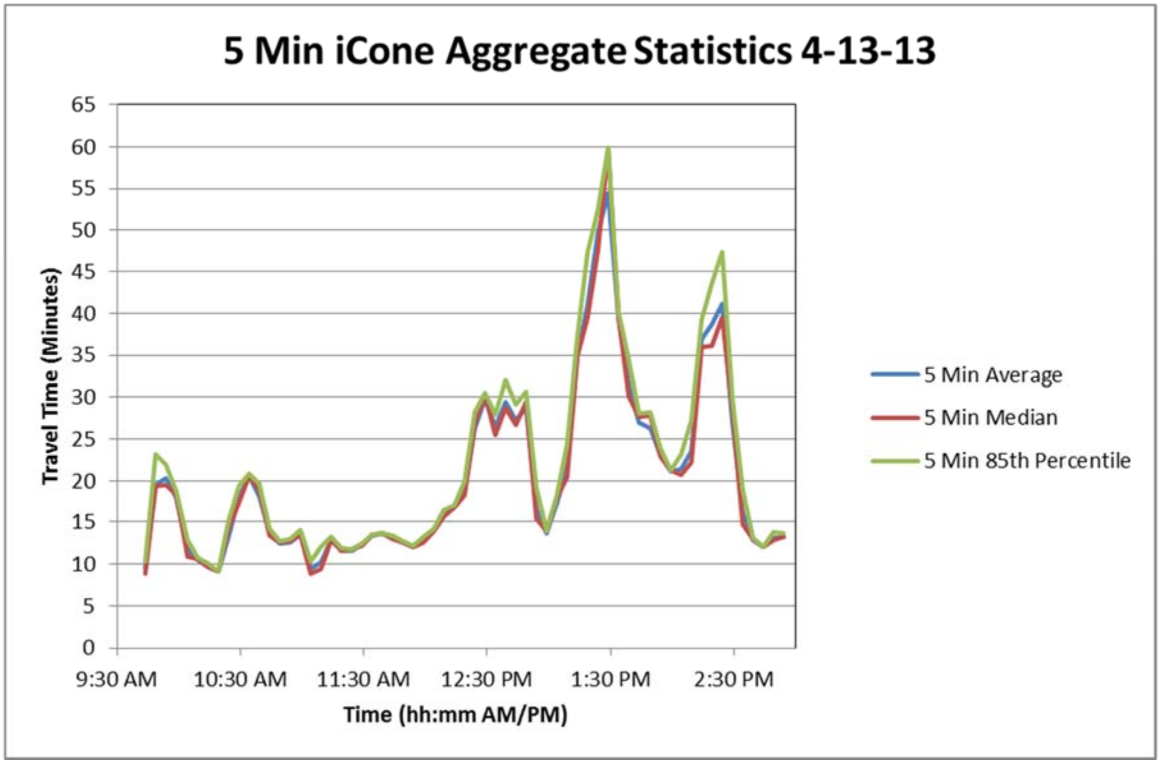

Figure 26: Five-minute Summaries: iCone® (04/13/13)

6.4 Timeliness of Delivering Travel Time Results

When travel time information is provided to users, many drivers may interpret the travel times as "predicted travel time". However, ELSAG ALPR, BlueMAC® Bluetooth®, and other systems do not claim to predict future travel times. There is a lag time in data reporting associated with every system. Hence, the "current" travel times reported by these systems are actually "previously experienced travel times," by other drivers at some point in the recent past. These reported travel times were relevant at the current time, minus the travel time of the user for which the travel times were reported (their monitored corridor entry time). Therefore, this lag is a function of travel time through the detection zone plus any data communications or processing time lag. During congestion, the lag time will be greater than during free flow conditions. This aspect can make ELSAG ALPR and BlueMAC® Bluetooth® much less responsive during congested periods with high variability in travel times.

The data reporting timeliness analysis compares the manual baseline travel time data based on entry time to the travel time data from each respective technology based on destination time for the October 20, 2012, and November 10, 2012 data. Destination- based travel times (i.e., timestamped by observed end of trip) from the ELSAG ALPR and BlueMAC® represent "experienced travel time" which would be delivered to drivers entering the monitored corridor. Entry-based travel times (i.e., timestamped for the start of trip) taken from the manual baseline travel data correspond to the actual travel time each driver actually takes through the system. Hence, experienced travel times can be compared to the destination-based travel times taken from the ELSAG ALPR and BlueMAC® Bluetooth®. In first-cut screening analyses, entry-based ELSAG ALPR and BlueMAC® Bluetooth® travel times were initially used to represent actual travel times drivers would experience and compared with the estimated travel times provided by the iCone® system.

The April 13th collection period does not have manual baseline data available. Figure 27 presents the travel time plot from October 20th, 2012 with the ELSAG ALPR destination-based travel time and the manual baseline entry-based data for trip entry time. This was an active work zone with congested conditions throughout the data collection period. Therefore, the lag time in reporting was expected to be between 10 to 20 minutes. However, the lag time did not present any significant problems because travel times were relatively stable and did not change significantly during the collection period.

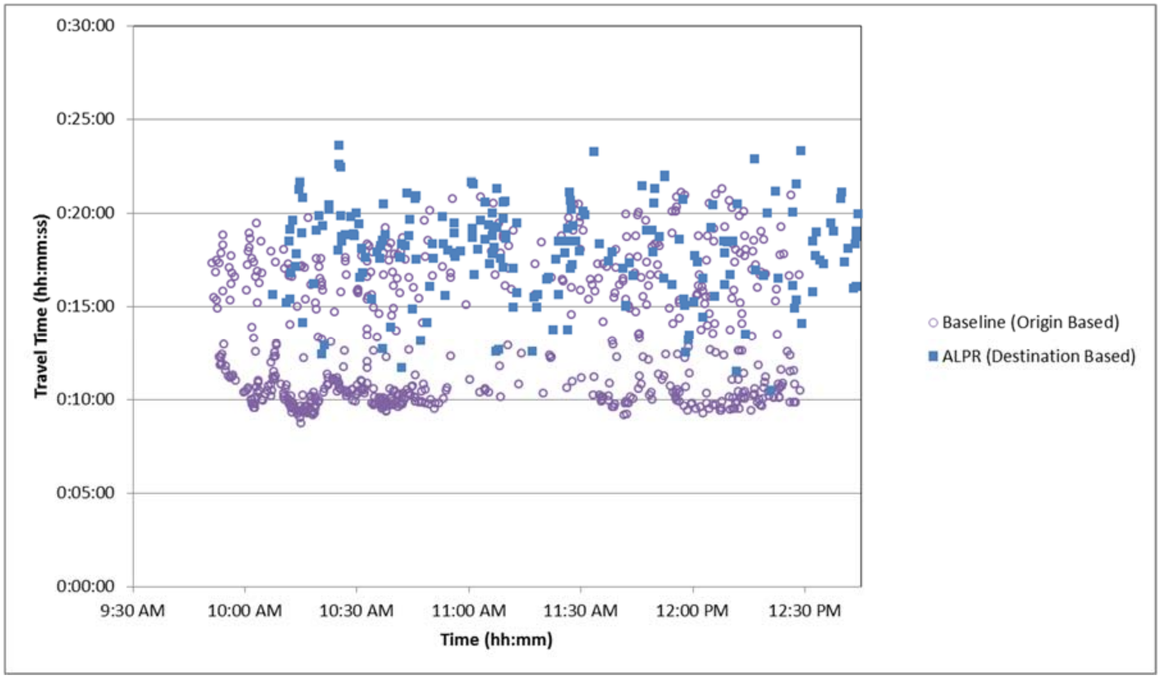

Figure 27: Travel Time Data (10/20/12)

Figure 28 presents the travel time plot from November 10th, 2012 with the ELSAG ALPR and BlueMAC® Bluetooth® data plotted with the timestamp from the destination time and the manual baseline travel time data plotted with the timestamp as the entry time. This was not an active work zone with uncongested conditions throughout the data collection period. Therefore, the lag time in reporting was as expected (between 3 to 4 minutes). Lag time issues did not arise, because travel times remained nearly constant throughout the collection period (i.e., any lag was irrelevant because the conditions remained constant throughout any lag period).

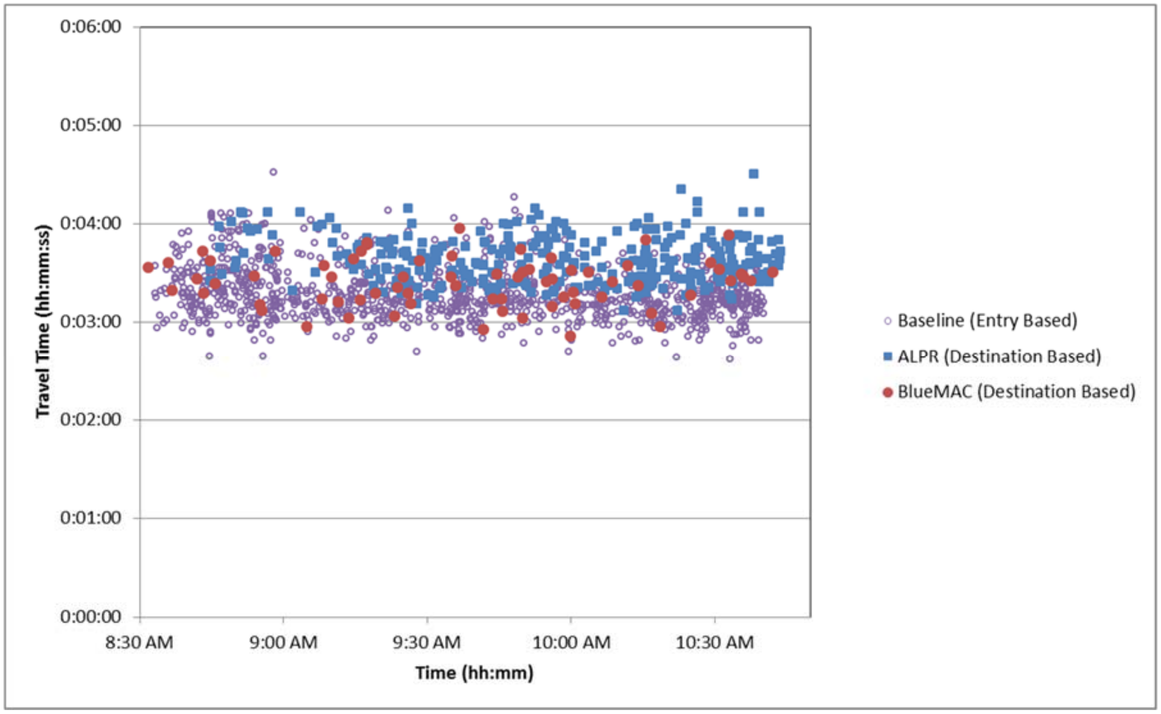

Figure 28: Travel Time Data (11/10/12)

Figure 29 (a) is the travel time plot from April 13th, 2013 with the ELSAG ALPR and BlueMAC® Bluetooth® data plotted with the timestamp from entry time and the iCone® data plotted with the timestamp as the systems reported time. This was an active work zone with varying conditions throughout the day, ranging from uncongested in the morning to highly-congested in the afternoon. Therefore, it is safe to assume the lag time in reporting for the ELSAG ALPR and BlueMAC® Bluetooth® systems varied throughout the day from 10 to 20 minutes in the morning to 10 to 40 minutes in the afternoon. Furthermore, when the ELSAG, ALPR and BlueMAC® travel times are plotted based on their destination timestamps (experienced travel times), the peaks of ELSAG ALPR, BlueMAC® Bluetooth®, and iCone® tend to align more closely (Figure 29 (b)). This shows that although the iCone® is theoretically more responsive to changing traffic conditions, it may also be experiencing some lag in calculating experienced travel times as well.

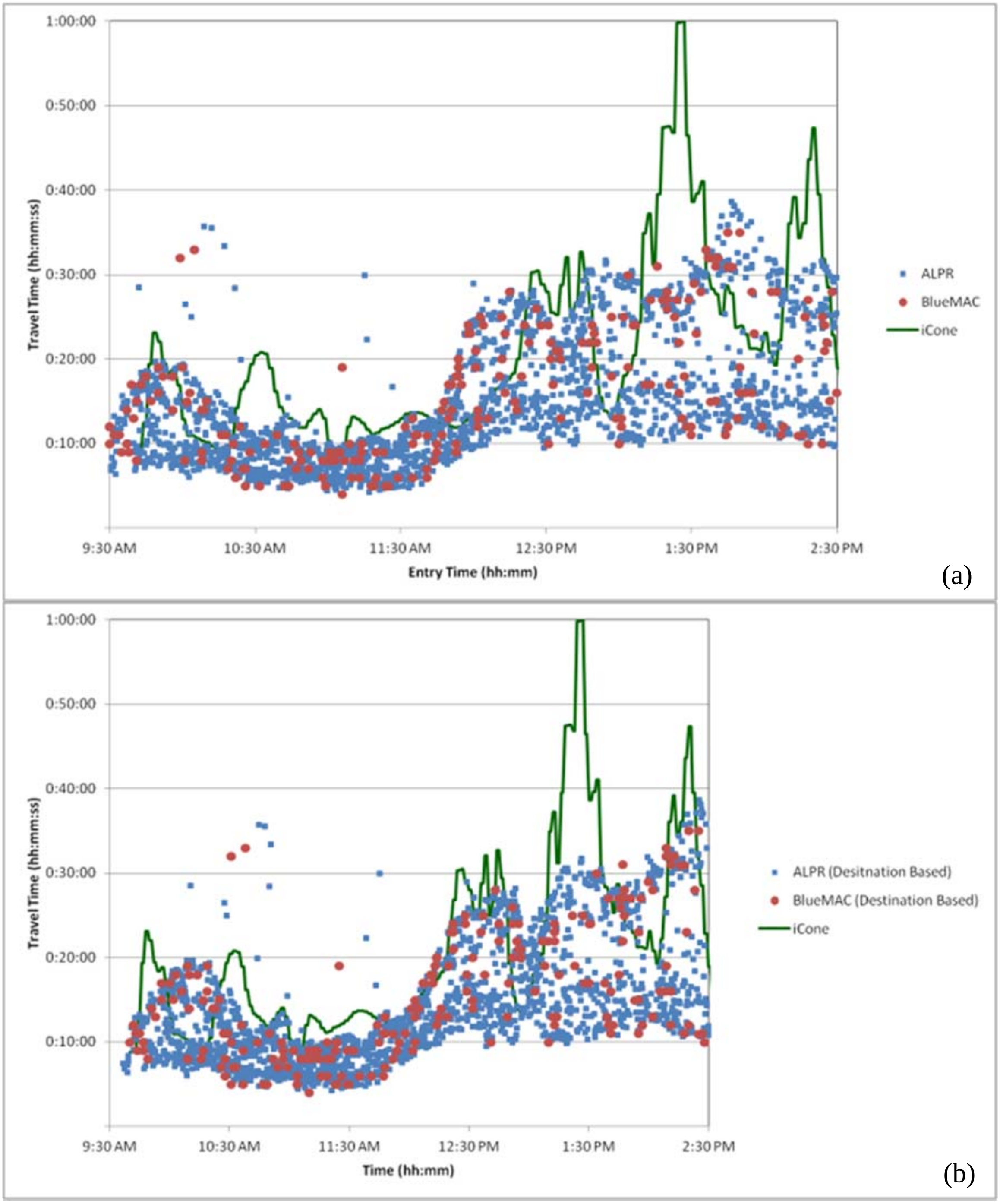

Figure 29: Travel Time Data (04/13/13)

To further illustrate this point, the rolling 5-minute average travel times were plotted in Figure 30 against their entry time and exit time. Entry time is the time that the vehicle was detected at the first location and exit time is the time that the vehicle was detected at the second location. In the plot, the horizontal offset between the lines represent areas where the lag is causing a departure between actual travel times of entering vehicles and the travel times experienced by the exiting vehicles.

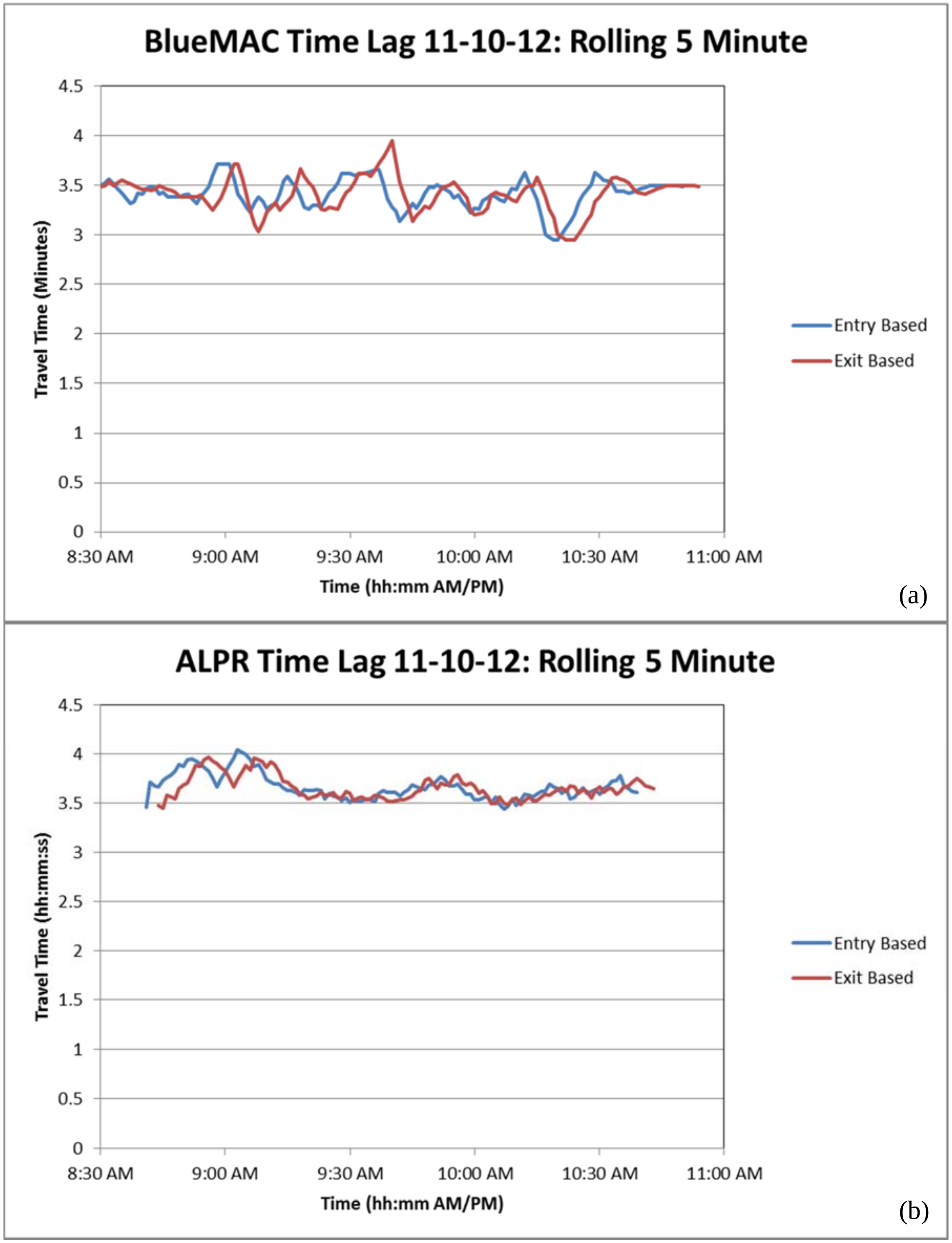

Figure 30: Time Lag Plots, Five-minute Travel Time, (a) ALPR, (b) BlueMAC® (11/10/13)

The above analysis reveals that all three technologies have the potential issue of latency of information to some extent. While the lack of ground truth data limited the ability to perform an enhanced comparison, a check of the reported exit time-stamped travel times against the entry time-stamped travel times revealed the nature of the lags. The amount of latency varies across technologies and is heavily correlated with the traffic conditions on the segments (i.e., non-homogeneous traffic conditions lead to more severe lag issues). The impact of the lags in the uniformly free-flowing conditions or uniformly congested conditions is not too severe since the lack of change in travel times makes the updates non-critical. However when the system is unstable (i.e., transitioning into congestion or recovering from congestion), the impact of the lag causes a significant difference of the reported travel times versus the travel times experienced by the motorists.

6.5 Technology Assessment Summary

To assess the accuracy of the selected technologies, travel times from these technologies were compared to baseline travel time data collected by manual means. These baseline travel times were collected by manual video license plate matching (and in one case, via MAC address matching). The analysis showed that the ELSAG ALPR and BlueMAC® Bluetooth® have the capability of providing reasonable “experienced travel times” although they are biased toward collecting data from slower moving vehicles. Travel times from the iCone® systems were also reasonable, despite the theoretical weakness of deriving indirect travel time calculations based upon spot speed data. Because iCone® data sometimes include unreasonably long travel times when congestion waves are present, placement of individual iCone® devices should be carefully managed, and data may need to be screened prior to transmittal to remove unreasonable results.

Although the ELSAG ALPR and BlueMAC® Bluetooth® are not designed to provide “predictive travel times”, many drivers are likely to interpret reported travel times as predictions of their travel times through a work zone. The timeliness of data delivery for the selected technologies were also evaluated to assess the lag between the “experienced travel times” and “actual travel time” that drivers will experience at the time when they enter the entering point. The analysis indicated that all of the selected systems experience some delay in providing travel times, depending on the traffic conditions and distance between sensors. Hence, travel times will be underestimated or overestimated, depending upon whether congestion is increasing or decreasing in the work zone. This section summarizes the strength and weakness of the selected technologies.

6.5.1 ELSAG ALPR Summary

The analysis indicated that the ELSAG ALPR has the capability to provide reasonable “experienced travel times,” although the data are biased toward slow moving vehicles and longer travel times during the field deployments when ALPR cameras are deployed adjacent to the slowest moving lanes. The ELSAG ALPR also experiences significant sampling bias issues in congested traffic conditions due to vehicle occlusion, and tends to have more bias compared to the BlueMAC® Bluetooth® despite the significantly larger sample size provided by ALPR. The ALPR technology requires an extensive data filtering process, because the raw data contains partial plate reads, non-plate reads, etc.

At this point, the ELSAG ALPR data are post-processed to extract travel times because the system does not come with any software that automatically generates travel times. Also, like the other technologies, ALPR provides “experienced travel times,” not “predictive travel times.” ALPR like the other technologies also has the weaknesses of data delays in “experienced travel times.” The results suggest that extra caution is necessary to use this data to provide drivers “predictive travel times”.

6.5.2 BlueMAC® Bluetooth® Summary

The analysis showed that the BlueMAC® Bluetooth® provided reasonable “experienced travel times,” although they were biased toward slow moving vehicles and longer travel times. The BlueMAC® Bluetooth® travel time data tended to have lower bias than the ELSAG ALPR data. However, sample size collected by this technology was significantly smaller than collected by the ELSAG ALPR. The Bluetooth® data are collected by monitoring Bluetooth® devices located inside vehicles and sample size is dependent on the penetration rate of these devices. In addition, slower moving vehicles remain in the detection zone longer and have a higher probability of being detected [23]. This limited sample size can lead to unreliable travel time data especially when traffic volume is low.

Because MAC addresses are usually collected in 16 digit uniform format, and the entire message is received, data do not require any extensive filtering processes (whereas the ELSAG ALPR requires a process to handle partial plate readings and non-plate readings). However, the Bluetooth® detection area is known to be within a 300 feet radius from the sensor and the location of a detected MAC address is not precisely known. Therefore, travel times contain some variation based upon uncertainty in the positions of consecutive readings. The sample size and detection zone limitations should be considered as important factors and caution should be exercised in using Bluetooth® technologies for deployment when exact detection location and significant sample size are prerequisites for the measurement, for example in a context of alternative routes and heterogeneous flows.

The BlueMAC® Bluetooth® system updates travel times once per minute on the webpage (Figure 31) and the location of each detection device is identified on a map. Also, travel time plots are available on the webpage which is easily accessible to users. However, BlueMAC® provides “experienced travel times,” not “predictive travel times.” The delay in reporting experienced travel times is a weakness that is a function of vehicle speeds and length of the monitoring zone. These results suggest that some caution should be exercised in using these data to provide drivers with “predictive travel times”.

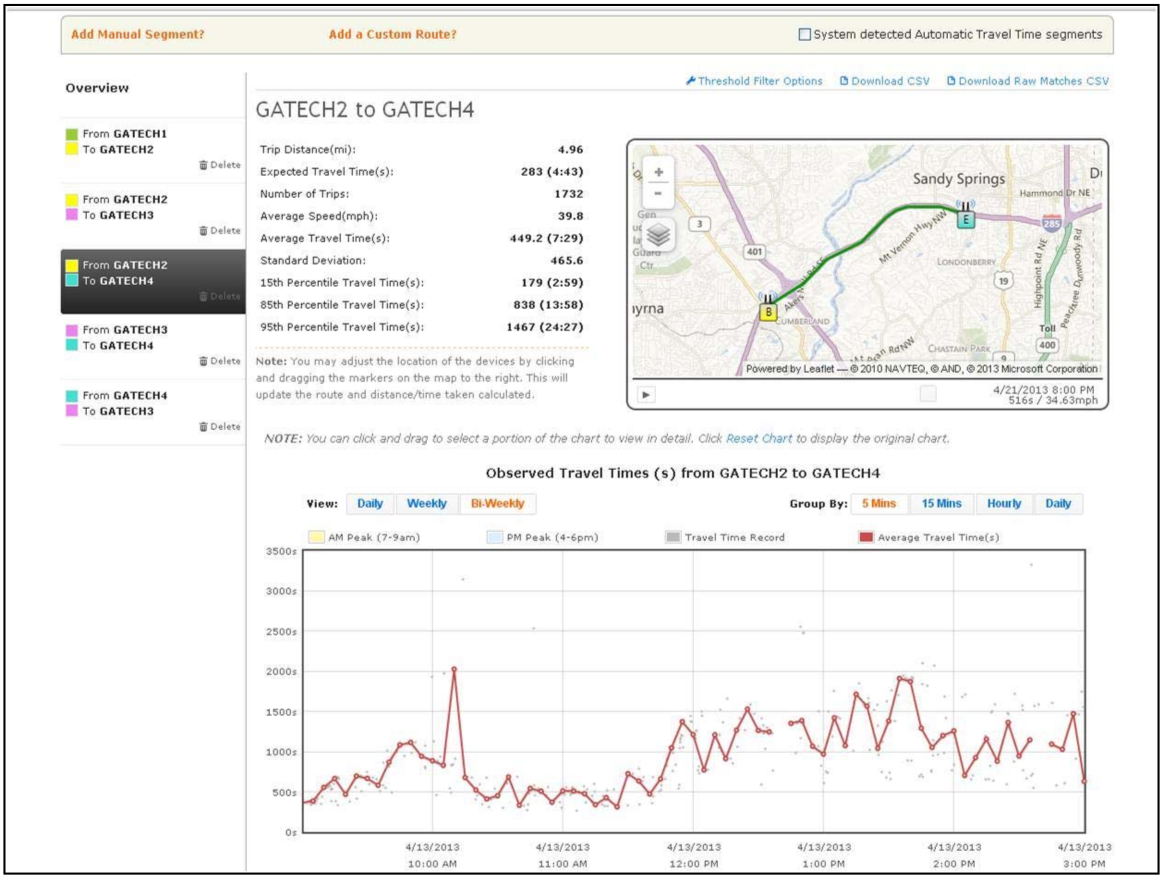

Figure 31: Sample BlueMAC® Live Travel Time Report

6.5.3 iCone® Summary

The iCone® technology estimates travel times based on the simple assumption that spot speed data at two measurement points are representative of traffic conditions between the two points. Because the iCone technology cannot capture the flow dynamics between the two measurement locations, estimated travel times may be inaccurate and may vary significantly as a function of measured spot speeds at specific times. As previously seen in Figure 29, the estimated travel time peaked at 60 minutes when low speeds were detected at the data measurement points around 1:20 PM. The estimated travel time quickly came back down after detecting faster speeds at the data measurement points. Spot speed technologies can provide unrealistic travel times under conditions of large speed variation; under congested conditions when traffic is experiencing stop-and-go conditions or shockwaves are passing the measurement point. For example, travel time based on 5 mph spot speed will produce twice the travel time compared to use of a 10 mph spot speed. In slow moving traffic conditions, with high speed variability, estimated travel times can vary significantly. Also, this technology would have time delay in detecting different traffic states until the new traffic states arrive at the measurement point. On the positive side, unlike the other technologies which provide “experienced travel time”, this technology has the potential to provide travel time estimates with less lag (more closely matching predicted travel times for users entering the corridor). Additionally, this technology does not unnecessarily attract the drivers' attention and is generally easier to setup and move to alternative locations. Whereas Bluetooth® and GPS-based monitoring is a function of device penetration rates in the fleet, this technology is completely independent of the monitored fleet. The technology works very well when traffic conditions are light. The iCone® technology has the capability to update its estimated travel time at 1-minute intervals via the webpage (Figure 32). Furthermore, the iCone® technology maps the location of the deployed iCone® units, spot speed information, and estimated travel time information on the webpage and its webpage is very easily accessible to users.

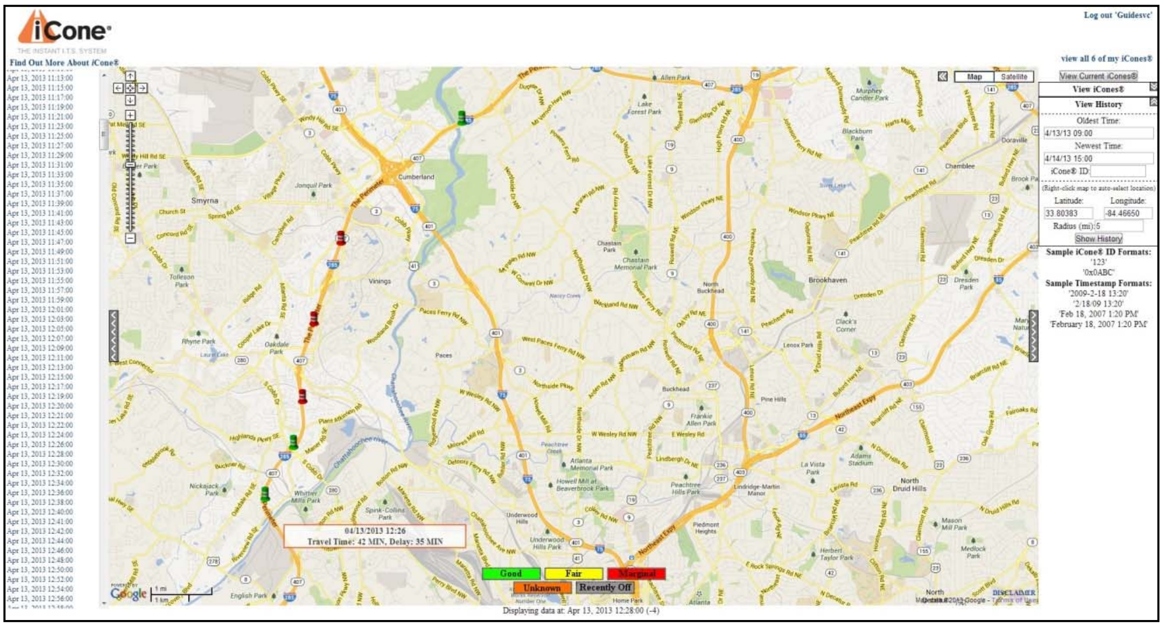

Figure 32: iCone® Live Travel Time Report

7 Conclusions and Recommendations

Due to the difficulty of evaluating the performance of travel time data collection technologies, this study focused on the accuracy of the travel time and the timeliness of data provided by the selected technologies.

ELSAG ALPR and BlueMAC® Bluetooth® were compared with the travel times collected by manual license plate matching. In this process, the ability to predict travel times by each selected technology was not analyzed. The underlying assumption is that the capability to collect more accurate "experienced travel times" leads to presentation of more reliable predictive travel times. The difference between the manually-collected travel times and estimated iCone® travel times were also compared.

The results indicated that the ELSAG ALPR and BlueMAC® Bluetooth® had the capability to provide reasonable "experienced travel times," although the travel times were biased toward slower moving vehicles in the field deployments. Hence, it is important to set up equipment to capture representative traffic conditions when multiple lanes are involved and the speeds vary across lanes. The research team found that the BlueMAC® Bluetooth® data tend to have less bias compared to the ELSAG ALPR data. However, the ELSAG ALPR provided a significantly larger sample size of travel time data under typical deployment conditions. The iCone® system was also able to provide reasonable travel time data, although the travel times exhibited larger variations over time, especially under congested conditions. This result was expected, because the iCone® travel time estimations assume that spot speed data at two measurement points are representative of traffic condition between the two points. When congestion waves are forming or dissipating within the zone, predicted travel time variability can be quite large. Hence, the choice of location for deploying the iCone® system and the number of units deployed is more critical than the choice of location for deploying the direct travel time measurement based systems.

The timeliness of data provided by the selected technologies was evaluated as well. ELSAG ALPR and BlueMAC® Bluetooth® systems were expected to have time lags, since they only report on the experienced travel times as vehicles reach the end of the monitored corridor. These systems are not designed to predict future travel times when conditions are changing within the monitored corridor. The analysis was intended to evaluate the time lag between the "experienced travel times" from ELSAG ALPR and BlueMAC® Bluetooth®, the "estimated travel times" from iCone®, and "actual travel time" which drivers experience at the time they enter the monitored roadway segment. The analyses confirmed the weakness of ELSAG ALPR and BlueMAC® Bluetooth® in providing "predictive travel time data". For these technologies, travel times are computed as vehicles complete their trips between the two detection points, and the inherent latency in travel time reporting is directly proportional to the trip duration between the data collection sites. Also, the iCone® travel times had some level of latency in providing "predictive travel time data". This lag is believed to be correlated with the travel times. Therefore, the level of lag is expected to vary depending on the traffic conditions.

In iCone® deployments, contractors need to ensure that a sufficient number of iCone® units are deployed to properly represent the data under conditions of congestion wave formation and dissipation. The software employed by iCone® may also need to be modified to better address high variations in low speed observations across consecutive measurements.

A major finding of the study is that significant travel time differentials exist across freeway work zone travel lanes, which means that placement of the various technologies may bias collected speeds towards the specific freeway lanes that are monitored, or from which more data are collected due to the nature of the technology. Hence, the speed differential across lanes introduces significant bias into monitored travel time results that becomes even more pronounced under fluctuating congestion conditions (especially when congestion is actively increasing within the work zone).

7.1 Deployment Configurations

The lane bias analysis results (significant travel time differentials do exist across freeway work zone travel lanes) indicates that the physical placement of detection technologies can yield detection biases towards specific freeway lanes. This, in turn, introduces significant bias into monitored or predicted travel time results. These biases become more pronounced under changing congestion conditions. For example, the Bluetooth® technology experienced problems when deployed under a bridge (near large obstacles that block signal reception). ALPR needs to be fairly close to the roadway for optimal performance. ALPR works better with fewer working lanes and medium to low congestion; whereas, Bluetooth® does not suffer as severe performance degradation when these conditions are not met. The iCone® deployments may have issues with data representativeness, depending upon iCone® separation distance and traffic conditions. Road geometries, including curvatures, merge/diverge points, etc., also need to be taken into consideration. From a deployment perspective, the iCone® and Bluetooth® equipment are deployment ready, while ALPR equipment was not yet ready for widespread deployment (as the software requires modification for data streaming and real-time analysis). The ELASAG equipment also lacked the software back-end to automatically generate travel times. However, given that the research team was able to make the basic software enhancements, we expect that professional development would be readily managed by the manufacturer.

7.2 Technology Field Experience and Lessons Learned

In terms of technology field experience, the research team experienced a number of issues that will need to be taken into account when deploying these systems:

7.2.1 iCone®

The iCone® units did experience power and communication failures. For example, one of the units deployed during the work zone experiment was not fully charged and failed to communicate data. The unit had to be replaced right away with another charged unit. The equipment provider was very experienced in the use of these systems; so this failure is not an event arising out of unfamiliarity with equipment and similar problems can be expected in work zone deployments. Monitoring staff need to be aware of this limitation and plan to have spare equipment available in the event of hardware failure. The research team recommends that work zone staff maintain an inventory of 10-15% spare equipment for field deployments.

In another case, one of the units was deployed beneath a wide overpass (Paces Ferry Road) without a clear view of at least part of the sky. The unit failed to communicate its position and was not recognized in the iCone® map, preventing travel time estimates from being provided. In general for these portable equipment which typically depends on GPS for location updates and mobile data connections for data communications, care should be taken to deploy the units away from obstructions and avoid deployments under overpasses or trees.

7.2.2 Bluetooth®

The Bluetooth® units deployed often experienced initial connectivity problems and GPS lock issues that created problems with map location and initial delays in streaming real time data.

- During the initial stages of testing of the equipment, some data communication delays were observed, as seen in the data reported on the website. The issue was satisfactorily resolved by the vendor before the final deployment.

- During the early stages of the project, some communication failures resulted from poor connectivity between the USB cellular dongle and the Bluetooth® computer. The problem resulted from operator error on the part of field deployment staff, but similar problems could be experienced in future deployments given that the error is difficult to detect.

- The units typically took several minutes to recognize a physical move and update the position on the map. The best workaround was to power-cycle the unit whenever it was moved and power-up at the new location. For example, in one instance a unit was deployed underneath tall trees, possibly obscuring the view of satellites, and unit showed up with a website map location that was approximately 40 miles away from the actual deployment location.

Low detection rates are also experienced with Bluetooth® systems:

- Based upon some of the deployments, there is reason to believe that line of sight affects Bluetooth® detection rates. For example, in one particular deployment of the unit near an overpass, the number of vehicle detections was very low. Another unit deployed a couple hundred yards downstream produced a much higher number of vehicle detections.

- One specific Bluetooth® monitoring unit had a lower detection rate. After further testing and communication with the vendor, the vendor confirmed that the unit's software was not updated. The software update was performed wirelessly and took approximately 30 minutes to complete. After the update, the unit no longer exhibited a lower detection rate.

Even though the Bluetooth® detection units are fairly portable, it is advisable to deploy the units:

- About 7-10 feet above the ground.
- Away from physical obstructions to the line of sight to the vehicles (the Bluetooth® units are located inside the vehicles).

- Such that the unit has a clear view of at least part of the sky (and hence the GPS satellites) so that the GPS unit is able to locate itself accurately.

During deployment it would be useful to carry a portable device with internet connectivity and web page viewing capability to confirm that the unit has located itself accurately and is generating a steady stream of detections.

7.2.3 ALPR

The ALPR units need a fair amount of fine tuning for each field deployment to ensure they are obtaining the optimal view required for license plate recognition. In this regard, while it might make sense for GDOT to own and operate Bluetooth® and iCone® systems themselves, ALPR deployments might be better implemented via contract deployment, with the contractor performing the construction/maintenance having specific expertise in calibrating ALPR equipment in the field.

On some occasions, it was difficult to get the ALPR units functioning properly in the field due to failure of the cameras to register on the computer. Usually, shutting down the system, disconnecting the wiring, re-connecting the wiring, and restarting the system resolved the connection issue. The ALPR units were not nearly as plug-and-play ready as the Bluetooth® and iCone® equipment. ALPR units required some fine-tuning of the camera field of view to generate a steady stream of data.

7.3 Latency in Travel Time Data Reporting

To be useful to travelers, travel time and vehicle speed data need to be reported with a maximum 5-minute communication latency. Work zone travel time data from direct measurement systems have inherent latencies equal to the travel time between sensor locations. This latency can be reduced by decreasing the gap between consecutive detection stations. For example, to ensure a 5-minute maximum trip time across a seveerly congested segment (10 mph), the distance between readings should be less than 0.83 miles. For the iCone® system, a detectors should be placed both upsteam and downstream of any potential bottleneck to ensure speeds from both traffic flow regimes are sampled. Both iCone® and Bluetooth® technologies supported real-time XML data streameing. XML data streams enable easy integration with other systems such as GDOT’s NaviGAtor system.

8 References

[1] Zwahlen, H. T. 2001. Evaluation of a Real-Time Travel Time Prediction System in a Freeway Construction Work Zone. Ohio Department of Transportation.

[2] USDOT. 2010. Real-Time Traveler Information Market Assessment White Paper.

[3] FHWA. 2001. TRAFFIC MONITORING GUIDE.

[4] FHWA. 2008. Comparative Analysis Report: The Benefits of Using Intelligent Transportation Systems in Work Zones.

[5] Agent, K. R. 1999. Evaluation of The ADAPTIR System For Work Zone Traffic Control. Federal Highway Administration.

[6] Gregorski, T. 2002. Upgrading Work-Zone Safety: Real-Time Traffic Information Helps Notify Motorists Of Upcoming Work Zones. Transportation Management and Engineering. 6 (6): p. 28-29.

[7] Tudor, L. H., A. Meadors and R. Plant II. 2003. Deployment of Smart Work Zone Technology in Arkansas. Transportation Research Record. 1824: p. 3-14.

[8] Wasson, J., R. Haseman, and D. Bullock. 2010. Real-Time Measurement of Work Zone Travel Time Delay and Evaluation Metrics Using Bluetooth® Probe Tracking, in Transportation Research Board 89th Annual Meeting.

[9] Fontaine, M. D. 2007. Assessing the Benefits of Smart Work Zone Systems, in Transportation Research Board 86th Annual Meeting.

[10] Horowitz, A. J. 2006. Criteria for Portable ATIS in Work Zones, in 2006 ITE Annual Meeting and Exhibit.

[11] Maze, T. H., G. Burchett and J. Hochstein. 2005. Synthesis of Procedures to Forecast and Monitor Work Zone Safety and Mobility Impacts. Federal Highway Administration.

[12] McCoy, P. T., and G. Pesti. 2001. Smart Work Zone Technology Evaluations: Speed Monitoring Displays and Condition-Responsive, Real-Time Travel Information Systems, in ITE 2001 Annual Meeting and Exhibit.

[13] Turner, S. M., W. L. Eisele, R. J. Benz, and D. J. Holdener. 1998. TRAVEL TIME DATA COLLECTION HANDBOOK. Federal Highway Administration.

[14] Knapick, R. J. 2007. TRAVEL TIME DATA COLLECTION ASSESSMENT. Genesee Transportation Council.

[15] Puckett, D., and M. Vickich. 2010. Bluetooth®-Based Travel Time/Speed Measuring Systems Development. Texas Transportation Institute.

[16] Porter, J. D., D. S. Kim, and M. E. Magaña. 2011. Wireless Data Collection System for Real-Time Arterial Travel Time Estimates. Oregon Department of Transportation.

[17] Box, S., Arterial Travel Time Data Collection Using Bluetooth® Technology. 2011. Georgia Institute of Technology.

[18] BlueMAC®. 2013. Available from: http://www.digiwest.com/BlueMAC®.html

[19] ELSAG North America. 2013. "ALPR Products and Solutions". Available from: http://www.elsag.com/alpr_applications.htm.

[20] iCone®. 2013. Available from: http://www.iCone®products.com/

[21] Sheckler, Ross D. 2010. "Prototyping and Testing of a Fully Autonomous Road Construction Beacon, The iCone®," The New York State Department of Transportation. Available from: https://www.dot.ny.gov/divisions/engineering/technical-services/trans-r-and-d-repository/C-05-05%20iCone®_Final%20Report_April%202010.pdf

[22] Chandler, B., K. Beasley, and J. Rephio. 2010. National Evaluation of the Safe Trip-21 Initiative: I-95 Corridor Coalition Test Bed, Final Evaluation Report: North Carolina Deployment of Portable Traffic Moniotring Device.

[23] Colberg, Kathryn. (2013). "Investigating the Ability of Automated License Plate Recognition Camera systems to Measure Travel Times in Work Zones." Master's Thesis, Georgia Institute of Technology.

[24] Toth, C., W. Suh, V. Elango, R. Sadana, A. Guin, M. Hunter, and R. Guensler (2013). "Tablet-Based Traffic Counting Application Designed to Minimize Human Error." Transportation Research Record. Number 2339. pp. 39-46. National Academy of Sciences. Washington, DC. 2013.

[25] Colberg, K., W. Suh, J. Anderson, S. Zinner, A. Guin, M. Hunter, and R. Guensler. Lane Bias Issues in Work Zone Travel Time Measurement and Reporting. Transportation Research Record: Journal of the Transportation Research Board, No. 2458, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 78-87.