ERROR ASSESSMENT FOR EMERGING TRAFFIC DATA COLLECTION DEVICES

FINAL PROJECT REPORT

by

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16. Abstract

Providing accurate and reliable travel time information to roadway users is a critical part of Advanced Traffic Management Systems (ATMS) and Advanced Travelers Information Systems (ATIS). Access to travel time information can significantly influence the decision making on both the supply side (i.e. efficient management of network capacity, saving travel time, reducing congestion etc.) and the demand side (i.e. mode choice, route choice etc.) of transportation. In this context, the need for accurate and reliable travel time information sources is becoming increasingly apparent.

Identifying the sensors best suited to providing travel time data for a given corridor is an important step in the process of providing travel time data. Currently, there are very few studies available that evaluate the effectiveness of various travel time data collection technologies side-by-side, thus it is often unclear which approach should be used for a given application. Therefore, a comprehensive overview of existing technologies as well as a side-by-side evaluation will provide more insight into selecting the appropriate technology for a given application. This evaluation is intended to provide decision support for transportation agencies selecting travel time systems based on the accuracy, reliability and cost of each system.

Ultimately, each system in the analysis has different strengths and weaknesses that should be considered in addition to their accuracy and sample rates. Some systems can provide additional data; others trade accuracy and coverage for cost or portability. Ultimately, engineers will need to weigh their requirements for accuracy and sample rates against the other engineering constraints imposed on their system. For example, the BlueTOAD units installed on SR 522 and I-90 are solar powered and use cellular data networks, reducing infrastructure and deployment costs. The BlipTrack units have higher sampling rates and marginal accuracy superiority in exchange for power requirements. The Inrix data does not require any DOT infrastructure and has wide availability. ALPR units have high accuracy and a comparatively high installation cost. The Sensys system has perhaps the most complicated set of tradeoffs. Sensys magnetometers can be used as replacements for loop detectors in intersection operations, making the marginal costs of adding Sensys re-identification lower at some intersections than others.

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Glossary

ALPR	Automated License Plate Reader
ANPR	Automated Number Plate Reader
APVD	Aggregated Probe Vehicle Data
ATIS	Advanced Travelers Information Systems
ATMS	Advanced Traffic Management Systems
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
CCD	Charge-Coupled Devices
CFD	Cumulative Frequency Distributions
DRG	Dynamic Route Guidance
EDI	Eberle Design Inc
FHWA	Federal Highway Administration
ITS	Intelligent Transportation Systems
GPS	Global Positioning System
LAN	Local Area Network
LCD	Liquid-Crystal Display
LED	Light-Emitting-Diode
MAC	Media Access Control
MAD	Mean Absolute Deviation
MAPE	Mean Absolute Percent Error
MPE	Mean Percent Error
PC	Personal Computer
PDA	Personal Digital Assistant
RMSE	Root Mean Squared Error
SDPE	Standard Deviation Of Percentage Error
SR	State Route
TCI	TrafficCast International
VDPU	Video Detection Processor Unit
VIL	Virtual Induction Loop
VIP	Video Image Processor

Executive Summary

Providing accurate and reliable travel time information to roadway users is a critical part of Advanced Traffic Management Systems (ATMS) and Advanced Travelers Information Systems (ATIS). Access to travel time information can significantly influence the decision making on both the supply side (i.e. efficient management of network capacity, saving travel time, reducing congestion etc.) and the demand side (i.e. mode choice, route choice etc.) of transportation. In this context, the need for accurate and reliable travel time information sources is becoming increasingly apparent.

Identifying the sensors best suited to providing travel time data for a given corridor is an important step in the process of providing travel time data. Currently, there are very few studies available that evaluate the effectiveness of various travel time data collection technologies side-by-side, thus it is often unclear which approach should be used for a given application. Therefore, a comprehensive overview of existing technologies as well as a side-by-side evaluation will provide more insight into selecting the appropriate technology for a given application. This evaluation is intended to provide decision support for transportation agencies selecting travel time systems based on the accuracy, reliability and cost of each system.

The choice of a sensor system and its corresponding accuracy could play a significant role on the benefits of the information provided for the users (i.e. utility) according to a FHWA report by Toppen and Wunderlich (2003). The relationship between accuracy of the information obtained by ATIS and the benefits for the users was determined for a case study in Los Angeles (seeFigure 1.1). The researchers found that when accuracy drops below a critical point, users are better off not using the data provided by the ATIS and relying instead on experience with historical traffic patterns.

A good approach to judging sensor accuracy is to look at the MAD to judge the expected magnitude of error. Then examine the MPE to determine whether there are systematic biases to the data. Note that for travel time it is reasonable to expect errors to be skewed toward longer travel times in most cases, since travel time underestimation is bounded on the lower end by zero. This is particularly true for SR 522 where individual segment free flow travel times are on the order of a minute and the whole corridor can be traversed in five minutes. The MAPE is useful to find the relative magnitude of the error. Finally, the RMSE is useful in determining whether a few large errors or many smaller errors are occurring. Between the four measures of error, a user can determine the magnitude of error, its biases, the relative impact of that error and the magnitude of the typical error.

This study focuses on two test corridors. The first test corridor is SR 522 between the NE 153rd Street and 83rd Place NE intersections. This section of SR 522 is an urban arterial with frequent intersections. This corridor experiences heavy daily commuting traffic and has frequent incidents that can make travel times unpredictable. An automated license plate reader system has been in place on the SR 522 corridor for a number of years with three westbound segments in the study area, from 83rd Pl. NE to 68th Ave. NE, 68th Ave. NE to SR 104 and SR 104 to NE 153rd St. For this analysis, even though the ALPR system has different segments on eastbound SR 522, the analysis used the same segments for eastbound because every other system used the same segments eastbound and westbound.

The second test corridor is on I-90 from milepost 109 (Ellensburg, WA) to milepost 32 (North Bend, WA). This section of I-90 is a rural freeway from western Washington to eastern Washington over the Snoqualmie Pass whose summit is at milepost 52. There were no pre-existing travel time measurement systems on I-90 before this study. Segments on I-90 are described by mileposts 32, 52, 70 and 109.

The sensor systems deployed on SR 522 include the pre-existing ALPR system, a Sensys emplacement on westbound SR 522, the TrafficCast BlueTOAD system, Blip Systems BlipTrack sensors and a 3rd party feed from Inrix. The I-90 corridor was instrumented with the BlueTOAD system in addition to using the Inrix data feed. The ALPR system reads the license plates of vehicles passing the sensors and holds the license plate number in memory until the vehicle passes the next sensor location. The Bluetooth and WiFi sensors built into the BlueTOAD and BlipTrack systems function similarly by reading the MAC address of wireless electronic devices from location to location. The Sensys system reads the magnetic signature of passing vehicles and attempts to match vehicles based on signature and platoon organization. The Inrix data is based on cellphone and GPS data from its users.

Collecting the data for this project has been a significant expenditure of effort. Collecting data from the Washington State Department of Transportation (WSDOT), Inrix, Sensys, TrafficCast, and Blip Systems has required the research team to visit multiple websites and databases. Collating and organizing data with different temporal resolutions, included data and segments required the research team to find common intervals and expend significant effort just to make the different data sets comparable.

There are two important factors to consider in analyzing the sensor results. The first is the accuracy of the reported travel time. To address this, each sensors' data is compared against the ALPR system on westbound SR 522. The ALPR system has been previously evaluated and deemed accurate enough to serve as the ground truth for this study. The lack of ALPR data or other similarly dependable travel time data source limits the research team's ability to analyze eastbound SR 522 and the I-90 corridor. A number of accuracy measures have chosen for this analysis to give readers more insight into the frequency, severity and directionality of errors.
The westbound SR 522 analysis found that the accuracy of the systems varied by segment with every system reporting their least accurate travel times on the 83rd Pl. NE to 68th Ave.NE segment. The daily analysis revealed that the systems experienced error spikes during the morning peak period on all segments. With the exception of the Inrix data, all systems generally reported satisfactory results, with the Bluetooth and WiFi based systems staying below the 25% error threshold except during overnight hours and some spikes in the peak periods. It should be noted that the Sensys travel time used was the 90th percentile travel time, where the other systems reported mean or median values, yet still the Sensys system posted acceptable accuracy in most cases. The Sensys travel time error may be reduced by selecting another one of the ten provided travel time values.

The systems did have some notable accuracy limitations. Specifically, the BlueTOAD system can be less reliable overnight when sampling is low. The Inrix system was generally the least responsive to traffic changes and tended to have systematically high or low travel times, probably the results of conservative free flow travel time estimation.

The I-90 and eastbound SR 522 analysis of travel time focused on more qualitative aspects of system performance. For I-90, the research team was looking for reasonable travel times and daily traffic patterns as well as response to known road closure events. The eastbound SR 522 results met expectations based on the westbound analysis, with most patterns repeating, including the systematic over or underestimation of travel time by Inrix. The I-90 analysis noted that both systems were able to respond to daily patterns; however, Inrix and BlueTOAD reported significantly different results on some segments. When the road closure time periods were examined, both systems had their flaws. The BlueTOAD system continued to report a travel time for 30 minutes after the road closure and the Inrix data either failed to react significantly to the closure or reported impossible travel times. Both systems include specific data that can be used to identify when such event occur.

The collection of sensors assembled for this study is impressive. By setting up so many sensors on the same corridor and having reliable ground truth data in the form of an established ALPR system, the WSDOT has made it possible to perform an in-depth analysis of the different systems. This work shows that sensors of different types and complexities can accomplish the goal of measuring travel time.

Ultimately, each system in the analysis has different strengths and weaknesses that should be considered in addition to their accuracy and sample rates. Some systems can provide additional data; others trade accuracy and coverage for cost or portability. Ultimately, engineers will need to weigh their requirements for accuracy and sample rates against the other engineering constraints imposed on their system. For example, the BlueTOAD units installed on SR 522 and I-90 are solar powered and use cellular data networks, reducing infrastructure and deployment costs. The BlipTrack units have higher sampling rates and marginal accuracy superiority in exchange for power requirements. The Inrix data does not require any DOT infrastructure and has wide availability. ALPR units have high accuracy and a comparatively high installation cost. The Sensys system has perhaps the most complicated set of tradeoffs. Sensys magnetometers can be used as replacements for loop detectors in intersection operations, making the marginal costs of adding Sensys re-identification lower at some intersections than others.

Note that high level conclusions are presented here. For detailed observations see the relevant chapters. Readers are specifically encouraged to review Figure 1.1, Figure 4.1, Figure 4.9, Figure 4.10 and Figure 4.24.

Chapter 1 Introduction

1.1 Background

Providing accurate and reliable travel time information plays a critical role in Advanced Traffic Management Systems (ATMS) and also Advanced Travelers Information Systems (ATIS). Access to travel time information can significantly influence the decision making on both the supply side (i.e. efficient management of network capacity, saving travel time, reducing congestion etc.) and the demand side (i.e. mode choice, route choice etc.) of transportation. In this context, the need for accurate and reliable travel time information sources is becoming increasingly apparent.

A wide range of travel time data collection technologies have been introduced over the last decade. While increased focus has been granted to the technological advances in collecting travel time information, it remains critical to monitor and identify technologies that present the lowest life cycle cost for obtaining reliable and accurate volume and speed information.

There are very few studies available that evaluate the effectiveness of various travel time data collection technologies side-by-side, thus it is often unclear which approach should be used for a given application. Therefore, a comprehensive overview of existing technologies as well as a side-by-side evaluation will provide more insight into selecting the appropriate technology for a given application. This evaluation is intended to provide decision support for transportation agencies selecting travel time systems based on the accuracy, reliability and cost of each system.

The choice of a system and its corresponding accuracy could play a significant role on the benefits of the information provided for the users (i.e. utility) according to a FHWA report by Toppen and Wunderlich (2003). The relationship between accuracy of the information obtained by ATIS and the benefits for the users was determined for a case study in Los Angeles (see Figure 1.1). The researchers found that when accuracy drops below a critical point, users are better off not using the data provided by the ATIS and relying instead on experience with historical traffic patterns. In Figure 1.1, there are four utility curves representing the utility realized during morning peak trips, evening peak trips, off peak and all trips. For evening peak trips, represented by the green line on top, the per trip utility realized on 25 minute trip for perfect and near perfect data was two dollars.

The point at which the ATIS data became worthless to users was at approximately 21% accuracy, where using the ATIS data produce negative utility values. Beyond a certain point, below 5% error for example, it makes little sense to invest in improving accuracy as users realize little to no increased benefit. In this case, funds for ATIS improvements would be better spent in areas besides improving accuracy, such as expanding coverage to other roadways (Toppen and Wunderlich, 2003). Therefore, a trade-off needs to be made based on the required accuracy and the costs of implementing ATIS technologies. Figure 1.1 shows that as travel time error approaches 20% users realize no value from ATIS data. Innamaa (2009) stated that the net benefit from an advanced traveler information service was positive in earlier studies only if the error in service reporting was below the range of 10–25%, but the cost-efficiency of the service was likely to suffer if error levels below 5% were being pursued. In this study, based on earlier studies by Innamma (2009), Toppen and Wunderlich (2003), and Jung et al. (2003) the ATIS error band is defined as 10-25%. Acceptable error is defined as 25% error for this research.

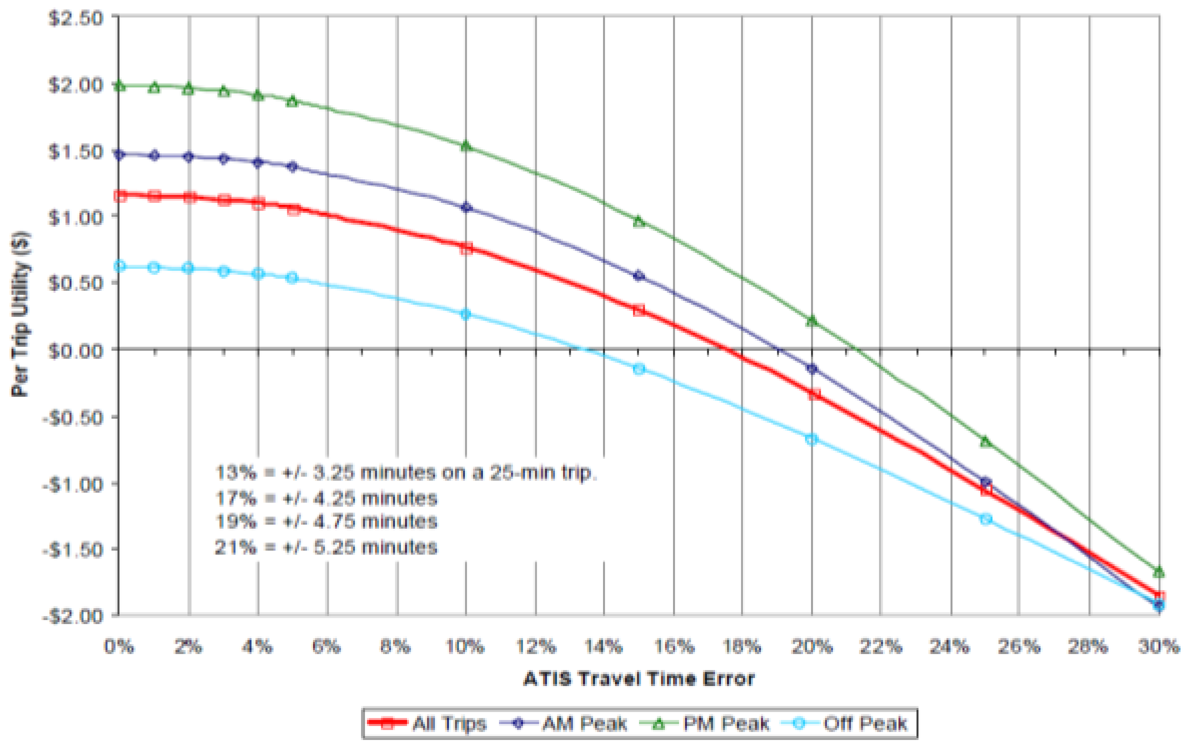


Figure 1.1 Benefit-Accuracy relationship for case study in Los Angeles (Source: Toppen and Wunderlich, 2003)

Since each technology captures data at different resolutions and accuracy, it is important to know what resolution/match rate/density of data points are necessary to predict reliable travel times at a stated level of confidence. Hence, conducting a side-by-side comparative study of the various technologies on a common corridor is intended to provide ITS planners the data required to make cost effective decisions regarding deployment of surveillance technologies to support ATIS solutions.

In this study, two corridors were selected for side-by-side comparisons of the various available travel time data collection technologies. The first evaluation corridor is State Route 522, (SR 522), which is an urban commuting corridor to and from Seattle, Washington (see Figure 3.1). The second evaluation corridor is a rural section of Interstate 90 (I-90) east of Seattle, Washington, (see Figure 3.2). The main research objectives can be summarized as follows:

- Evaluate multiple travel time, volume and speed data collection technologies side-by-side;

- Determine the relative accuracy and performance (Error Matrix) of the evaluated technologies;
- Determine the relative reliability (Reliability Matrix) of the evaluated technologies.
- Define appropriate technologies for common data collection scenarios and needs.

Chapter 2 Travel Time Data Collection Methodology

Several data collection techniques can be used to measure or collect travel time. Many of the technologies being evaluated in this study use different methodologies to generate travel time information. These various techniques can be classified into a few generalized methodologies, such as those using: probe vehicles, vehicle re-identification, and volume and speed estimation methods (also referred to as flow estimation techniques). Note that the flow estimation technique is presented for completeness. These techniques are designed to collect travel times and average speeds on designated roadway segments or links. A general overview of the various techniques is provided in the following paragraphs.

2.1 Probe Vehicle Method

The probe vehicle method utilizes instrumented vehicles in the traffic stream and remote sensing devices to collect travel times (Travel Time Data Collection Handbook, 1998). An ITS probe vehicle can be a personal, public transit, or commercial vehicle. Generally, methods of travel time estimation via probe vehicles currently in use rely on GPS systems to gather data regarding position and speed. These GPS systems may be integrated into the vehicle, such as for fleet vehicle operations or portable systems such as smart phones. Other systems in use include transponder and radio-based systems. The goal of the probe vehicle based methodologies is to estimate travel times for all vehicles in the traffic stream based upon high quality travel time data from a subset of vehicles in traffic.

2.1.1 *ITS Probe Vehicle Data Collection Systems*

Probe vehicles may be equipped with several different types of electronic transponders or receivers, from passive transponders to live GPS transmissions.

2.1.1.1 **Signpost-Based Automatic Vehicle Location (AVL)**

This technique has mostly been used by transit agencies. With an AVL system, probe vehicles communicate at intervals with a transmitter and receiver infrastructure. Note that these systems may be active, with vehicles frequently broadcasting data, or passive, where transponders only broadcast when queried by the transmitter infrastructure. Depending on the frequency and quality of data transmitted, AVL systems may operate like probe vehicles, or more as a vehicle re-identification system, discussed later.

2.1.1.2 **Radio Navigation**

Radio navigation systems use triangulation techniques to locate radio transponders on vehicles, and are used in route guidance and communication systems. Data are collected by communication between probe vehicles and a radio tower infrastructure (Mathew, 2013). Typically, this type of system is used for fleet dispatch, such as for transit, commercial or government vehicle dispatch.

2.1.1.3 **GPS Position and Speed**

GPS based systems are increasingly found at the personal level with dedicated GPS navigation systems and smart phones being the most common implementations. Some of these systems broadcast data back to service providers for use in providing real-time traffic data.

2.1.2 *General Advantages and Disadvantages*

The advantages and disadvantages of this method can be summarized as (Travel Time Data Collection Handbook, 1998):

Advantages

- Low cost per unit of data
- Continuous data collection
- Automated data collection
- Data are in electronic format
- No disruption of traffic

Disadvantages

- High implementation cost (depending on system used)
- Fixed infrastructure constraints - Coverage area, including locations of antenna

- Requires skilled software
- Not recommended for small scale data collection efforts

2.2 Vehicle Re-identification Method

Re-identification relies on recording unique characteristics (i.e. a signature) of the target vehicle to be used to identify the target vehicle at subsequent sensor locations. Vehicle re-identification is the process collecting vehicle identification data (i.e. signature) and the timestamp of vehicles passing a road side reader device and matching against data from another reader passed by the target vehicle to determine the travel time between reader locations.

2.2.1 *Vehicle Re-identification Data Collection Systems*

Probe vehicles may be equipped with several different types of electronic transponders or receivers.

2.2.1.1 **Vehicle Signature Matching**

Estimates travel time by matching (or correlating) unique vehicle signatures between sequential observation points. These methods can utilize a number of point detectors. Travel time is then the differences in the times that each (matched) vehicle arrives at the upstream and downstream sensor stations. One characteristic of signature matching systems is a time delay built into data collection related to the time it takes for vehicles to travel from one detector to the next.

Examples of signature matching include license plate readers, inductive loop detector signature re-identification, magnetometer signature re-identification and Bluetooth/WiFi Media Access Control address (MAC) re-identification. The unique signature differentiating vehicles in each case is different, but the methodology is the same. As previously discussed, transponder based systems with low frequency data collection may operate more like signature based re-identification systems than probe vehicle based systems.

2.2.1.2 **Platoon Matching**

Platoon matching is a special case of vehicle re-identification that relies on the fact that vehicles tend to travel in platoons. This method estimates average travel time by matching unique features of vehicle platoons such as the position and/or distribution of vehicle gaps or unique vehicles. Platoon matching assumes that vehicles in a platoon will travel at approximately the same speed and retain approximately the same order between sensor locations. Because of these assumptions, platoon matching generally requires closely spaced detection points to prevent platoons from changing too drastically for the algorithms to re-identify between sensors.

2.2.2 *General Advantages and Disadvantages*

The advantages and disadvantages of this method can be summarized as (Travel Time Data Collection Handbook, 1998):

Advantages

- Travel times from a large sample of motorists
- Simple Technique
- Automated data collection
- Data are in electronic format
- Provides a continuum of travel times during the data collection period
- No disruption of traffic

Disadvantages

- Travel time data limited to locations where readers can be positioned;
- Limited geographic coverage
- Requires skilled software
- Inherent personal privacy risk

2.3 Point Based Volume and Speed Estimation Method

Volume and speed estimation technologies rely on the classical steady-state traffic flow relationship between the traffic stream flow rate (q), the traffic stream density (k), and the traffic stream space-mean-speed ($\bar{u}_s$) derived by Lighthill and Witham (1955) as follows:

$$q = k.\bar{u}_s \tag{2.1}$$

Traffic stream speeds are typically measured in the field using a variety of spot speed measurement technologies. These approaches try to extrapolate local point data into corridor level information. The average traffic stream speed can be computed in two different ways: a time-mean speed and a space-mean speed. The difference in speed computations is attributed to inherent difference in definitions of time-mean speed and a space-mean speed. The space-mean speed reflects the average speed over a spatial section of roadway, while the time-mean speed reflects the average speed of the traffic stream passing a specific stationary point (Rakha and Zhang, 2005).

2.3.1 *Point Based Volume and Speed Estimation Data Collection Systems*

2.3.1.1 **Inductive Loop Detectors (ILD)**

The most common of these spot speed measurement technologies is an inductive loop detector set to report presence or occupancy (the percentage of time an ILD detects the presence of a vehicle). The loop coil of an ILD is embedded in a roadway, generally in a square or circle that generates a magnetic field. When a vehicle enters the detection zone, the sensor is activated and remains activated until the vehicle leaves detection zone. ILDs can thus identify the presence and passage of vehicles over a short segment of roadway (typically 5 to 20 meters long) (Rakha and Zhang, 2005). These surveillance detectors measure the traffic stream flow rate (number of actuations per unit time), traffic stream speed (in the case of dual loop detectors), and percentage of time that the detector is occupied. The traditional practice for estimating speeds from single loop detectors is based on the assumption of a constant average effective vehicle length and constant speed.

2.3.1.2 **Video Detection**

Video detection systems works based on virtual loop detectors (VIL). AVIL is a virtual detector created by processing the input of another sensor type into that of a standard induction loop. VILs are designed to play the same role as a legacy ILD to interface with existing equipment. In this way, a VIL service gathers real time information of the vehicles traversing this virtual detector (Gramaglia et. al, 2013). In general, VILs try to mimic the data obtained by inductive loops and collect the data about vehicle passage, presence, count, and occupancy. Because of this close emulation VILs share many of the same strengths and weaknesses of traditional ILDs.

2.3.1.3 **Magnetometers**

This method relies on matching vehicle signatures from wireless sensors. The sensors provide a noisy magnetic signature of a vehicle and the precise time when it crosses the sensors. A match (re-identification) of signatures at two locations gives the corresponding travel time of the vehicle.

2.3.2 *General Advantages and Disadvantages*

Advantages

- Travel times from a large sample of motorists
- Simple technique
- Provides a continuum of travel times during the data collection period
- Performs well in both high and low volume traffic and in different weather conditions (Sreedevi, 2005).

Disadvantages

- Expensive deployment and maintenance costs (Particularly for invasive ILDs)
- Trouble measuring low-speed vehicles (Some VILs may be better or worse)
- Only provide point values to estimate link travel times
- Limited spatial coverage

- Issues with reliability and sensitivity, primarily from improper connections and installation
- Inability to directly measure speed. If speed is required, then a two-loop speed trap is employed or an algorithm involving loop length, average vehicle length, time over the detector, and number of vehicles counted is used with a single loop detector (Sreedevi, 2005) (Some VILs may be able to measure speed directly).

Chapter 3 Experiment Design and Data Collection

Two test sites are considered for this study; State Route 522 (SR 522) northwest of Seattle and I-90 across Snoqualmie Pass east of Seattle. Both corridors are located in Washington State. The main reason to use these test sites was that the WSDOT has already instrumented sections of SR 522 and I-90 with substantial sensing capabilities. Moreover, running tests on both sites with different functional classifications, the SR 522 test corridor is an urban arterial and the I-90 corridor is a rural freeway, allows the systems to be examined under different conditions. The different link lengths also provide an opportunity to evaluate the errors related to short corridors versus long corridors. Each site is detailed in the following sections.

3.1 <u>State Route 522 in Seattle, Washington</u>

A section of SR 522 between NE 153rd Street and 83rd Place NE in Seattle, Washington was selected as one of the test sites to conduct the side-by-side comparison. This site consists of 3 links between the following four intersections:

- Point 1: SR 522 and NE 153rd Street
- Point 2: SR 522 and State Route 104 (SR 104)
- Point 3: SR 522 and 68th Avenue NE
- Point 4: SR 522 and 83rd Place NE

Four intersections break the SR 522 corridor into 3 segments. The westbound segments are SR 522 and 83rd Place NE to SR 522 and 68th Avenue NE, SR 522 and 68th Avenue NE to SR 522 and SR 104 Junction and SR 522 and SR 104 Junction to SR 522 and NE 153rd Street. For brevity's sake these names will be shortened in the text to 83rd Pl. NE to 68th Ave. NE, 68th Ave. NE to SR 104, and SR 104 to NE 153rd St. Where space is constrained the following abbreviations will be used (with Excel chart abbreviations in parentheses): 83rd → 68th (83rd > 68th), 68th → SR 104 (68th > SR 104) and SR 104 → 153rd (SR 104 > 153rd). Likewise, the eastbound segments are SR 522 and NE 153rd Street to SR 522 and SR 104 Junction, SR 522 and SR 104 Junction to SR 522 and 68th Avenue NE, and SR 522 and 68th Avenue NE to SR 522 and

83rd Place NE. The eastbound segment short names are NE 153rd St. to SR 104, SR 104 to 68th Ave. NE, and 68th Ave. NE to 83rd Pl. NE. Finally, the eastbound abbreviations (and Excel abbreviations) are: 153rd → SR 104 (SR 104 > 153rd), SR 104 → 68th (SR 104 > 68th), and 68th → 83rd (68th > 83rd).

WSDOT has instrumented the SR 522 corridor with substantial sensing capabilities. Currently, the SR 522 corridor is equipped with Pips Technology license plate readers, EDI and Reno inductive loops, TrafficCast BlueTOAD Bluetooth sensors, Blip Systems combination Bluetooth and WiFi sensors, Traficon video detection units, Sensys Networks magnetometers and a 3rd party data feed from Inrix. Note that similar technologies have been grouped in the figure for clarity. Specifically, the various loop detectors and the video detection units (which are emulating loop detectors) are grouped together and the BlueTOAD and Blip Ssytems Bluetooth sesnors have been grouped. In the case of loop detectors (ILD or VIL), one system is implemented at each intersection, providing comparable data. For the Bluetooth systems, each system is implemented at each test site.

3.1.1 *Data availability on SR 522*

The data availability by link for the East-bound and West-bound directions on SR 522 are shown in Figure 3.1. The arrows represent the direction of the traffic where there is available data. The list of technologies implemented at each intersection is summarized in Table 3.1 and Table 3.2.

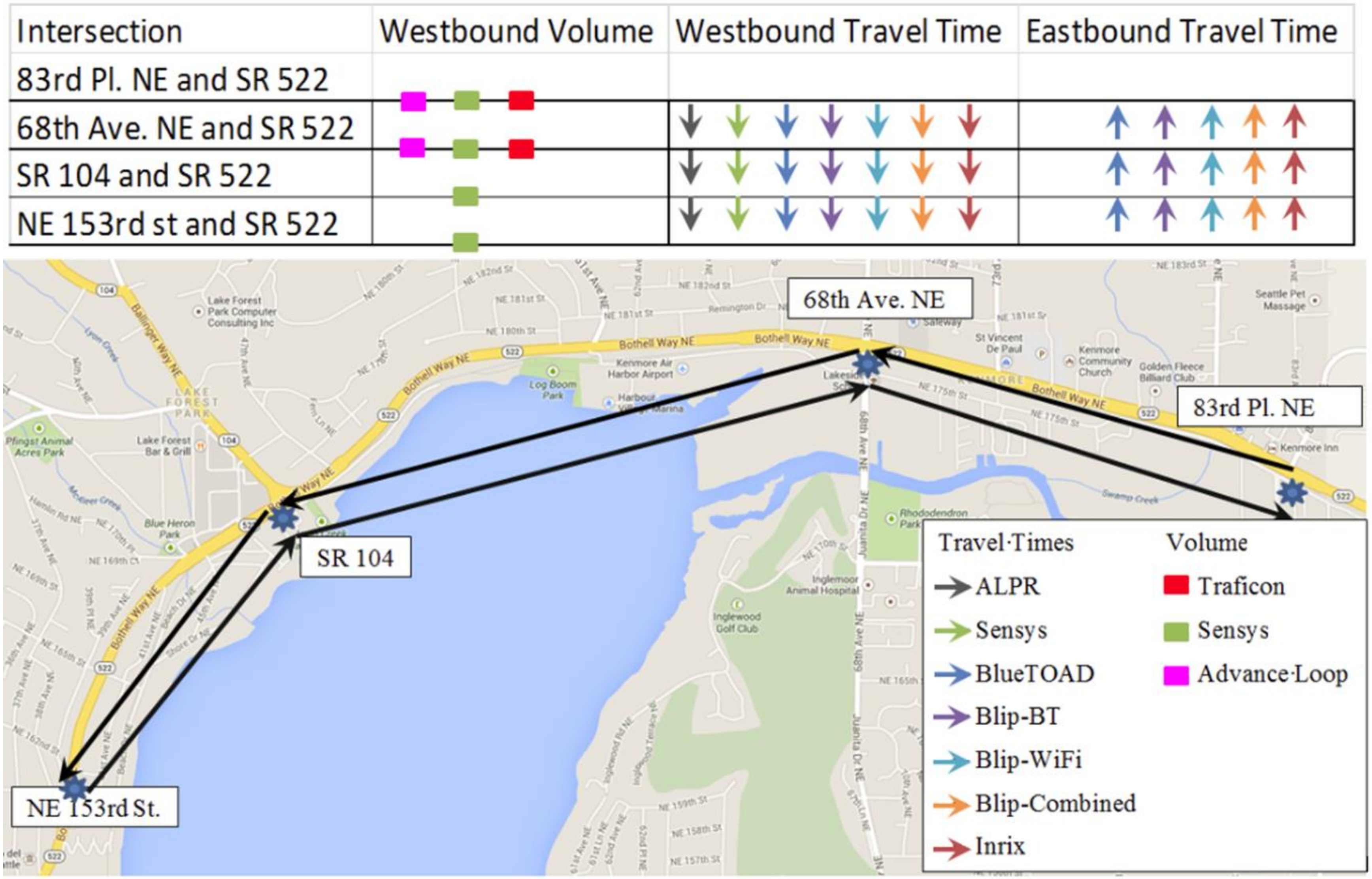


Figure 3.1 Sensor locations and segments along the SR 522 corridor

Table 3.1 List of technologies implemented along SR 522

Sensor	Manufacture	Model	Website
Loop	EDI	Oracle 2	http://www.editraffic.com/home.html
Loop	Reno A&E	1100-SS	http://www.renoae.com/traffic/
VDPU	Traficon	VIP3D.2	http://www.kargor.com/traficon_master.html
ALPR	Pips Technology	P372 model	http://pipstechnology.com/home_us/
BlueTOAD	TrafficCast	BT-Cell-50W	http://trafficcast.com/
BlipTrack	Blip Systems	BlipTrack-BT	http://www.bliptrack.com
BlipTrack	Blip Systems	BlipTrack-WiFi	http://www.bliptrack.com
Magnetometer-Access point	Sensys	AP240-EC-Ver	http://www.sensysnetworks.com/
Magnetometer-Repeater	Sensys	RP240-B	http://www.sensysnetworks.com/
Magnetometer-Sensor	Sensys	VSN540-F	http://www.sensysnetworks.com/
APVD	Inrix	N/A	http://www.inrix.com/

Note: (VDPU): Video Detection Processor Unit; (ALPR): Automated License Plate Reader; (APVD) Aggregated Probe Vehicle Data

Table 3.2 List of sensors mounted at SR 522 intersections

Technology	Intersection			
	NE 153rd St./SR 522	SR 104/SR522	68th Place NE/SR 522	83rd Place NE/SR 522
Loop	EDI-Oracle 2	EDI-Oracle 2	EDI-Oracle 2	EDI-Oracle 2
VDPU	-	Traficon- VIP3D.2	-	Traficon- VIP3D.2
ALPR	P372 model	P372 model	P372 model	P372 model
Bluetooth	BlueTOAD-BT-Cell-50W	BlueTOAD-BT-Cell-50W	BlueTOAD-BT-Cell-50W	BlueTOAD-BT-Cell-50W
	BlipTrack™-BT	BlipTrack™-BT	BlipTrack™-BT	BlipTrack™-BT
	BlipTrack™-WiFi	BlipTrack™-WiFi	BlipTrack™-WiFi	BlipTrack™-WiFi
Magnetometer	Access point AP240-EC-Ver	Access point AP240-EC-Ver	Access point AP240-EC-Ver	Access point AP240-EC-Ver
	Repeater- RP240-B	Repeater- RP240-B	Repeater- RP240-B	Repeater- RP240-B
	Sensor- VSN540-F	Sensor- VSN540-F	Sensor- VSN540-F	Sensor- VSN540-F

Note: Inrix data is not associated with individual intersections and is not presented here

3.2 I-90 Freeway Test At Snoqualmie Pass, Washington

A section of I-90 between North Bend, Washington and Ellensburg, Washington was selected as the other test site in order to conduct the side-by-side comparison for longer rural corridors. Given the longer links inherent to this test corridor and that there are no traffic signals between data collection sites, the research team expect there to be fewer confounding factors in the data at this site. Conversely, there are fewer sensor types installed along I-90, so there is less opportunity for comparing results between sensor types. This site consisted of 3 links between following mileposts:

- Point 1: I-90 at milepost 32
- Point 2: I-90 at milepost 52
- Point 3: I-90 at milepost 70
- Point 4: I-90 at milepost 109

The segment names for I-90 are much simpler with segments being named in the form of milepost X to milepost Y and the abbreviation MP being used for milepost. The westbound routes then become milepost 109 to milepost 70, milepost 70 to milepost 52, and milepost 52 to milepost 32. Eastbound segments are milepost 32 to milepost 52, milepost 52 to milepost 70 and milepost 70 to milepost 109. These names are shortened to the abbreviations MP 109 → MP 70 (MP 109 > MP 70), MP 70 → MP 52 (MP 70 > MP 52), and MP 52 → MP 32 (MP 52 > MP 32) for westbound and similarly for eastbound.

3.2.1 *Data availability on I-90*

The I-90 Snoqualmie Pass corridor is equipped with BlueTOAD Bluetooth sensors and makes use of the overlapping 3rd Party data feed from Inrix. I-90 segments are indicated in Figure 3.2. The list of technologies available on each intersection is summarized in Table 3.3 and Table 3.4.

Figure 3.2 Sensor locations and segments along the I-90 Snoqualmie Pass corridor

Table 3.3 List of technologies implemented on I-90

Sensor	Manufacture	Model	Website
BlueTOAD	Trafficast	BT-Cell-50W	http://trafficcast.com/
APVD	Inrix	N/A	http://www.inrix.com/

Table 3.4 List of sensors mounted on I-90

Technology	Milepost			
	I-90 Milepost 32	I-90 Milepost 52	I-90 Milepost 70	I-90 Milepost 109
Bluetooth	BlueTOAD-BT-Cell-50W	BlueTOAD-BT-Cell-50W	BlueTOAD-BT-Cell-50W	BlueTOAD-BT-Cell-50W
APVD	Inrix	Inrix	Inrix	Inrix

3.3 Traffic Data Collection Techniques

In the following sections various technologies implemented in this study are demonstrated. Three categories of travel time data collection technologies are used in this study which could be classified as follows:

- Volume and speed estimation technologies
  - Inductive Loop Detectors (ILD)
    - EDI: Oracle 2
    - Reno A&E: 1100SS
  - Video Detection Processor Unit (VDPU)
    - Traficon: VIP3D.2
  - Magnetometer
    - Sensys: VSN540-F

- Vehicle re-identification technologies
  - Automated License Plate Reader (ALPR)
    - Pips Technology: P372 model
  - Bluetooth/WiFi MAC address Matching
    - Trafficast: BlueTOAD-BT-Cell-50W
    - BlipSystems: BlipTrack^{TM}-BT
    - BlipSystems: BlipTrack^{TM}-WiFi
  - Magnetic Signature Matching
    - Sensys: VSN540-F
- Probe vehicles technologies
    - 3rd Party Inrix

3.3.1 *Volume and Speed Estimation Technologies*

There are multiple techniques that make use of point sensor data to create travel time estimates. In this study area, two types of inductive loop detectors are used (providing advance loop volumes). Additionally, a VDPU system from Traficon (i.e. Traficon- VIP3D.2) is used which emulates traditional double or single loop detectors. Their locations are shown in Figure 3.1.

3.3.1.1 **Inductive Loop Detectors**

The operating principles and design factors for the two types of inductive loop detectors namely EDI Oracle 2 and Reno A&E: 1100SS used in this study are explained in next sections.

EDI Oracle 2 Series Inductive Loop Detectors

The EDI Oracle2 is an inductive loop detector from Eberle Design Inc (EDI). The ORACLE 2E (2EC) Enhanced Loop Monitor™ series is a full featured two channel inductive loop vehicle detector. The ORACLE "ENHANCED" detectors not only indicate vehicle presence, but also incorporate a complete built-in loop analyzer for optimum detector set-up and loop diagnostic purposes. Each channel incorporates a loop inductance meter which assists in determining optimum sensitivity setting by displaying the magnitude of change in inductance caused by traffic moving over the roadway loop (Eberle Design, Inc. Product Overview, 2013).

Figure 3.3 EDI Oracle 2E series Inductive Loop Detector

The system architecture used to collect and convey ILD data to the WSDOT is shown in Figure 3.4. Loop detector cards such as the EDI Oracle 2E are connected to loop coils embedded in the roadway. These detector cards then process the inductance readings read form the loop coils to determine whether a vehicle is present or not. The signal control cabinet's controller polls the loop detector cards to determine whether a given loop is currently occupied many times each second. At regular intervals, 20 seconds for the WSDOT, the controller reports the number of vehicles detected and the number of scanning intervals during which the ILD was occupied. This information is then carried along the corridor's communications backbone to the WSDOT network where data can be processed, aggregated and stored in a database. Note that this loop detector architecture that applies to ILDs in general.

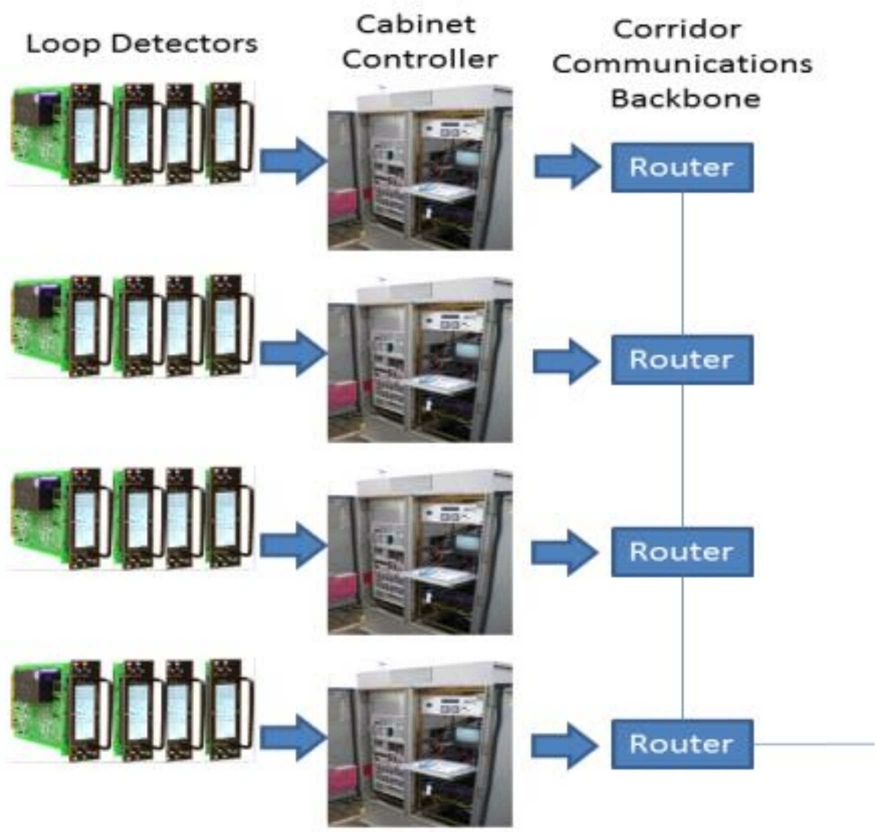


Figure 3.4 Loop Detector System Architecture

Reno A&E 1100 Series Inductive Loop Detectors

The C-1100-ss is an ILD from standard model C by Reno A&E. The Reno A&E model C-1100 series is a scanning detector. The C-1100 series is a two channel, loop detector with individual channel detect and loop fail indications provided via two high intensity red light-emitting-diode (LED)s and an easy to read Liquid-crystal display (LCD) screen. The C-1100-ss offers advanced features providing built-in diagnostic capabilities all of which are viewable by means of the LCD screen. These include: 1.) real-time loop frequency, 2.) loop inductance and -ΔL/L% (*L* = Inductance, henrys), 3.) a bar-graph indication of relative inductance change (which assist in proper selection of sensitivity level), 4.) a record of accumulated loop failures, and 5.) a timer countdown of programmed timing functions. See Figure 3.4 for system architecture (RENO A&E Product Overview, 2013).

Figure 3.5 Reno A&E Model C-1100 Series Inductive Loop Detectors

3.3.1.2 **Video Detection Processor Unit**

The video detection technique involves setting up a series of virtual detection loops in each approach lane at a specified distance from the stop line. These virtual loops provide the same speed, volume and density information as in pavement loops. VIP3D can emulate traditional double or single loop detectors. A VDPU unit from Traficon is implemented in this study. Its operating principle and design factors are briefly explained in the following section.

Traficon Video Detection

The key factor in a Traficon detection system is the Video Image Processor (VIP). In addition to the traffic data, it provides pulses similar to those provided by inductive loops. The VIP 3D.2 provides 4 data detection zones per camera and collects count, speed, classification, occupancy, density, headway and gap time. It also provides double and single loop data simulation. Queue length measurements and directional counts on the intersection can also be conducted (Traficon Product Overview, 2013). The system architecture for VDPUs is very similar to the system architecture for ILDs shown in Figure 3.4. The architecture differs from the ILD one only in the use of cameras in place of loop coils as shown in Figure 3.7.

Cabinet

VIP 3D2 unit

Figure 3.6 Traficon VIP3D.2 sensor

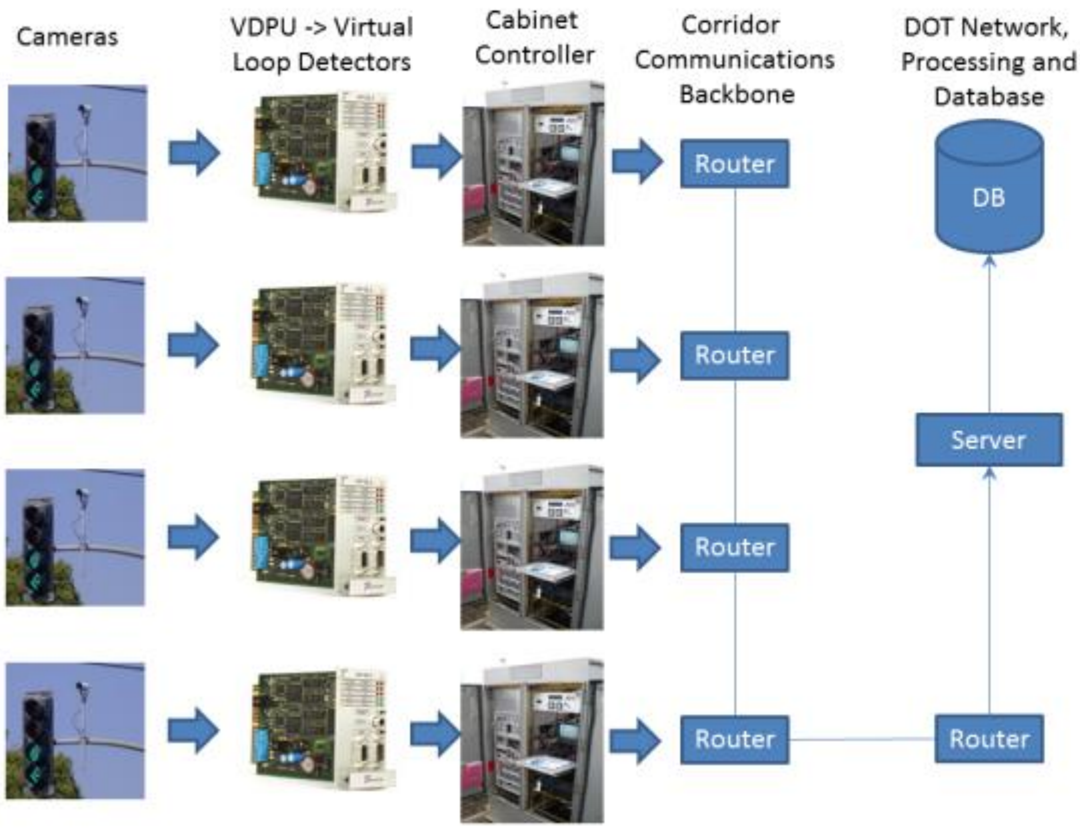


Figure 3.7 VDPU System Architecture

3.3.1.3 **Magnetometer**

Magnetometers operate by detecting changes in the Earth's magnetic field caused by the metal objects traveling over them. Sensys magnetometer pucks are battery operated units placed in the roadway which communicate via radio with receivers that communicate that data to controllers for processing. Sensys pucks are discussed in greater detail under reidentification in Section 3.3.2.3.

3.3.2 *Vehicle Re-identification Technologies*

A wide range of vehicle re-identification technologies are now in use. In this study, six different vehicle re-identification technologies are used, which can be classified into three categories: automated license plate recognition, Bluetooth / WiFi MAC address matching and magnetic signature matching. Their operating principles and design factors are discussed in the following sections.

3.3.2.1 **Automated License Plate Reader**

One traditional method of vehicle re-identification is license plate matching. License plate matching techniques consist of collecting vehicle license plate characters (i.e. unique ID or signature) and arrival times at various checkpoints. The license plate characters are then matched between consecutive checkpoints and travel times computed from the difference between arrival times (Travel Time Data Collection Handbook, 1998). In this study, the ALPR system manufactured by Pips Technology is used.

Pips Technology ALPR Sensor

The P372 Spike (a trademark of PIPS Technology, a subsidiary of Federal Signal Company and Motorola, Inc.) is a compact, rugged, fully integrated license plate reading camera incorporating the camera, illuminator and the ALPR processor within a single sealed enclosure. The unit is comprised of a monochrome CCD camera with a built-in infra-red (IR) LED illuminator. The Spike will output ALPR data comprised of a vehicle license plate reading, time, date, location (sensor ID), plate patch image or full IR image, overview image (if camera fitted), and read confidence. There is an option for wireless LAN connectivity, which may save on installation and cabling costs. Setup and monitoring of the unit is by web-browser interface from a PC or PDA (Pips Technology Product Overview, 2013).

Figure 3.8 Pips P327 Spike ALPR sensor

3.3.2.2 **MAC Address Matching Technology**

Bluetooth-based travel time measurement is one of the emerging methods of vehicle re-identification. This method involves identifying and matching the unique Media Access Control or Media Access Control (MAC) address of Bluetooth-enabled devices carried by motorists as they pass a detector location. As with ALPRs, the difference in time between the two observations yields the travel time. This approach relies on having a device with an active Bluetooth or Wi-Fi adapter in the sensor's detection range. In this Bluetooth technology from two different manufacturers are evaluated.

BlueTOAD Bluetooth Sensors

BlueTOAD (a trademark of TrafficCast) is a Bluetooth MAC address detection system developed by TrafficCast International (TCI). The BlueTOAD device consists of the MAC address reader, a power source, and a communication source. The BlueTOAD devices are capable of Ethernet or cellular communication. The options for power are hard wire or solar power. The BlueTOAD cellular solar power option requires a service provider in order to communicate with the TCI servers. The Ethernet option allows for a direct connection to a hard wired network. The hard wire option can be connected to any power source capable of supporting 110V of AC power (TrafficCast Product Overview, 2013). The BlueTOAD cellular Solar Power 50W is used in this research, shown in Figure 3.9.

The device reads the MAC address broadcast from any active Bluetooth device and sends the time of the read and MAC information to the TrafficCast central processing server to calculate travel times. TrafficCast then filters the data to remove outliers and provides the information to clients via a web interface. The TrafficCast secure cyber-center processes the data collected by BlueTOAD devices. Data can be viewed in real-time or analyzed historically through a BlueTOAD web interface, which provides travel times, road speeds, and MAC address detection counts.

Figure 3.9 BlueTOAD sensor design and components

BlipTrack Bluetooth Sensors

BlipTrack (a trademark of Blip Systems) is a Bluetooth sensor developed by Blip Systems. The BlipTrack Traffic sensor has 3 Bluetooth antennae including 2 directional antennae and 1 omnidirectional. The size of the detection zone varies from 70-200m on either side of the sensor along the road. When using 3 Bluetooth radios, BlipTrack has a 3 times greater chance of detecting a Bluetooth device and also covers an area more than 3 times as large as a single radio solution. BlipTrack also has built-in 3G and LAN connectivity for easy upload and a GPS sensor for auto positioning. The BlipTrack Bluetooth Traffic sensor uses 220V power with a battery backup (Blip Systems A/S Product Overview, 2013). The sensor configuration and components are shown in Figure 3.10.

BlipTrack works by detecting Bluetooth devices in proximity to a BlipTrack Access Point. The sensors relay each detection event to a central server using their 3G connection. Each detection event is comprised of the MAC address of the detected device and the detection timestamp. Blip Systems then filters the data to remove outliers and provides the information to clients via a web interface. BlipTrack has a graphical interface with Google Maps integration, widgets and a wide range of real-time and historical analytical tools, which provides travel times, road speeds, and MAC address detection counts.

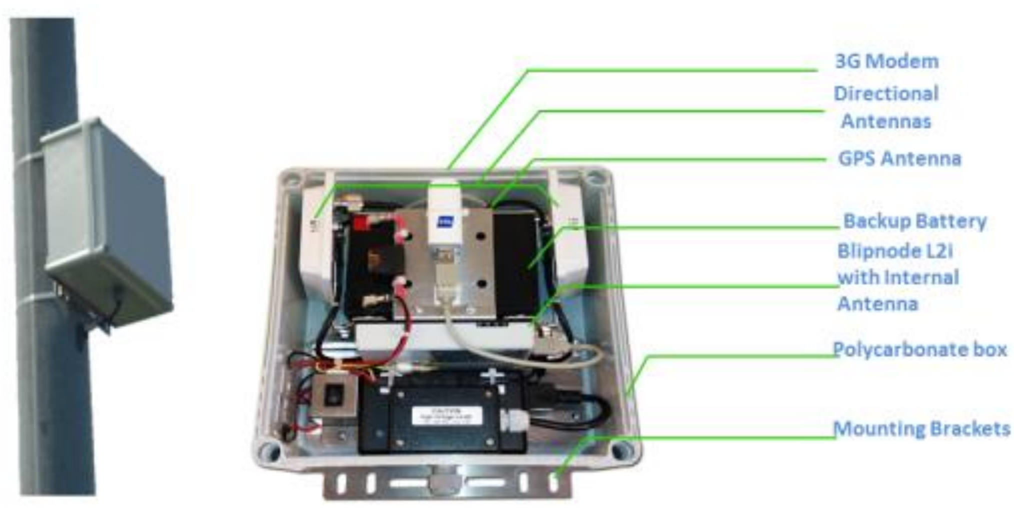


Figure 3.10 BlipTrack sensor design and components

The new model of BlipTrack sensor incorporates a WiFi processor into the design. In this design an external WiFi unit can be connected to the Bluetooth unit. The joint WiFi/Bluetooth unit has the capability of detecting the MAC addresses transmitted by both WiFi and Bluetooth-enabled devices (Blip Systems A/S Product Overview, 2013). The architecture of BlipTrack solution is shown in Figure 3.12.

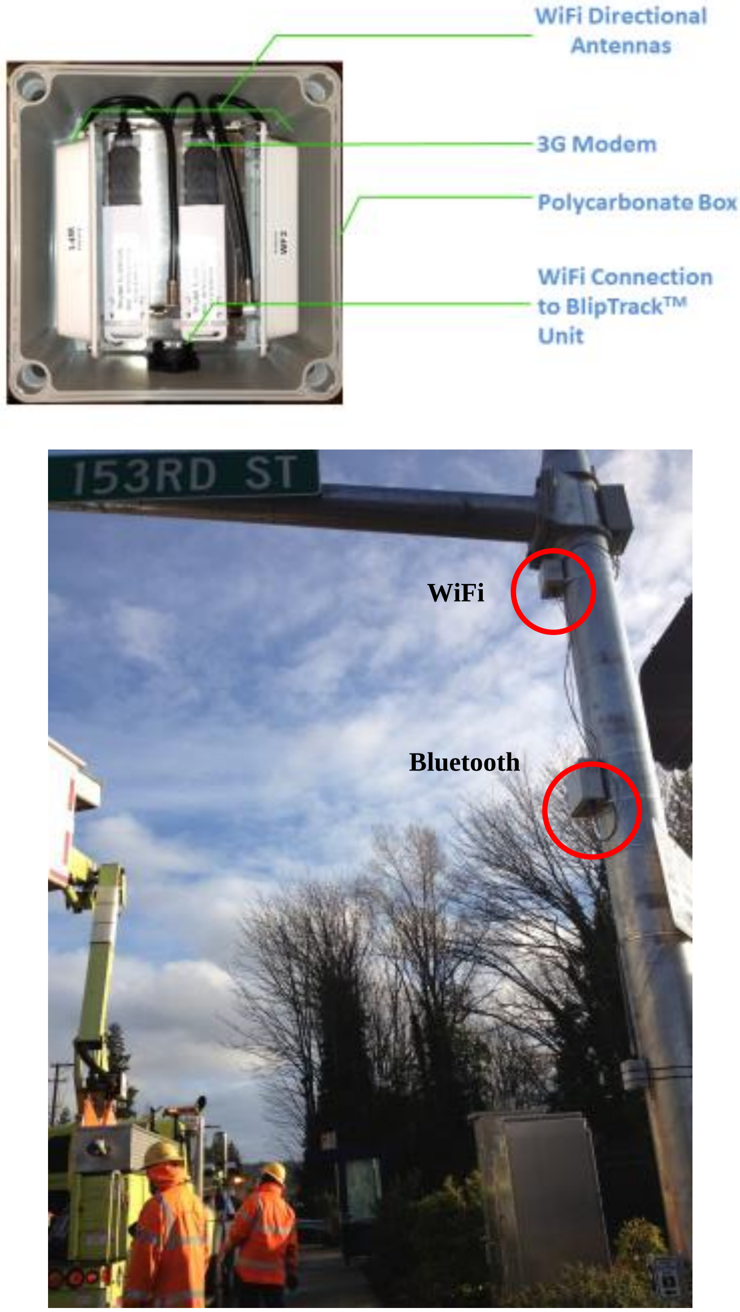


Figure 3.11 BlipTrack WiFi sensor design and components

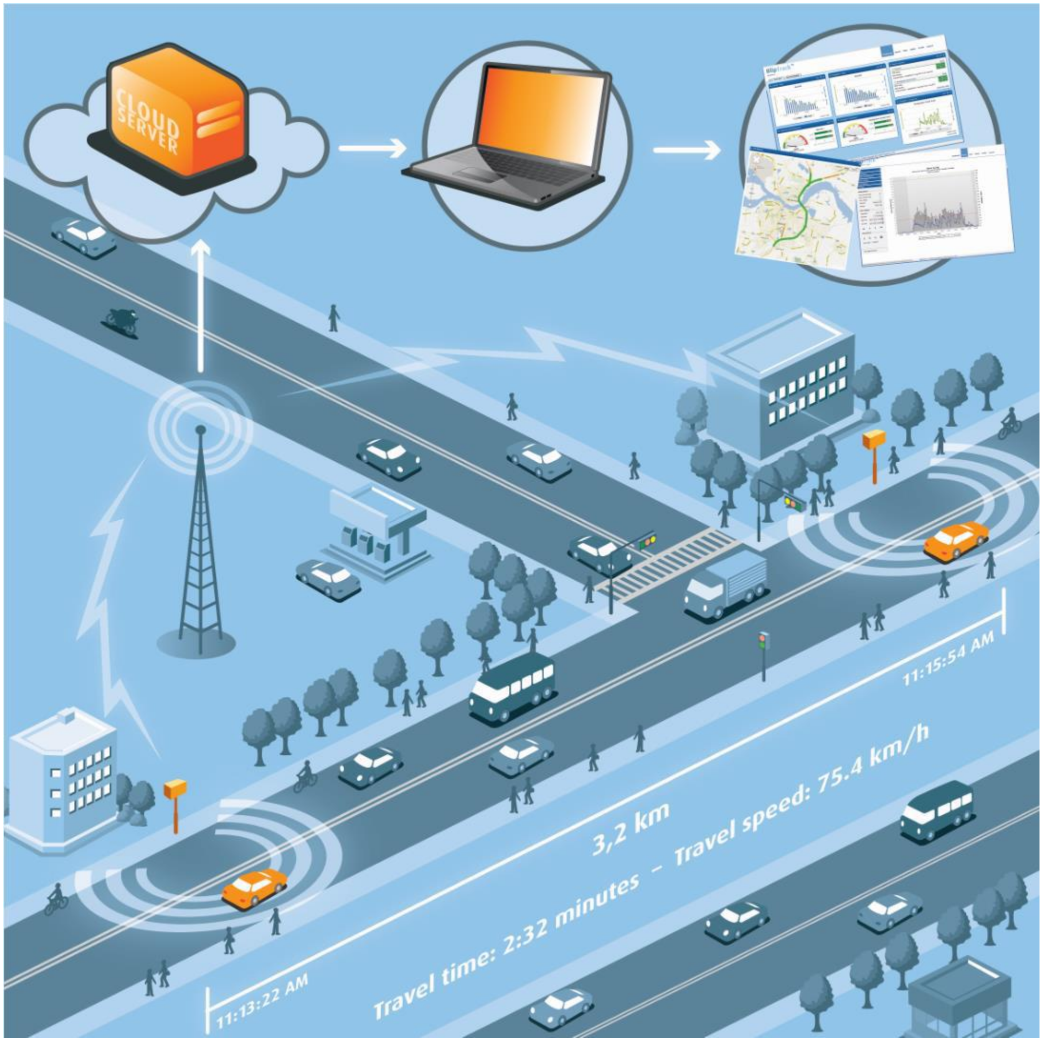


Figure 3.12 Architecture of BlipTrack solution

3.3.2.3 **Magnetic Signature Matching**

This method relies on matching vehicle signatures from wireless sensors. The sensors provide a noisy magnetic signature of a vehicle and the precise time when it crosses the sensors. A match (re-identification) of signatures at two locations gives the corresponding travel time of the vehicle.

Sensys Wireless Vehicle Detection System

The Sensys (a trademark of Sensys Networks, Inc.) wireless vehicle detection system uses pavement-mounted magnetic sensors to detect the presence and movement of vehicles. The magneto-resistive sensors are wireless, transmitting their detection data in real-time via low-power radio technology to a nearby Sensys access point that then relays the data to one or more local or remote traffic management controllers and systems.

The Sensys VSN240-F is an in-pavement wireless vehicle sensor designed for permanent deployment in all traffic conditions from freeways to intersections to parking lots to gates. The VSN240-F detects vehicular traffic and reports it back to an AP240 access point. Each sensor node contains a 3 axis magnetometer, microprocessor, memory, low power radio and batteries within a watertight case. After a vehicle passes over the sensor array, each sensor transmits its unique magnetic signature information to a wireless access point located within 150 feet of the array. If the sensor array is located outside this range, a battery operated repeater can retransmit the information up to 1,000 feet away. The access point collects the data from each sensor or repeater and retransmits the information to a data archiving server. Once the information is collected by the data archive server, it is used by the re-identification engine for travel time analysis. A Sensys access point (AP240-EC) is an intelligent device operating under the Linux operating system that maintains two-way wireless links to an installation's sensors and repeaters, establishes overall time synchronization, transmits configuration commands and message acknowledgements, and receives and processes data from the sensors. The Sensys access point then uses either wired or wireless network connections (or both) to relay the sensor detection data to a roadside traffic controller or remote server, traffic management system, or other vehicle detection application. A Sensys repeater (RP240-B) extends the range and coverage of an installation's access point. The three devices may be seen Figure 3.13 (Sensys Networks Product Overview, 2013). Architecture of Sensys magnetometers are presented in Appendix I.

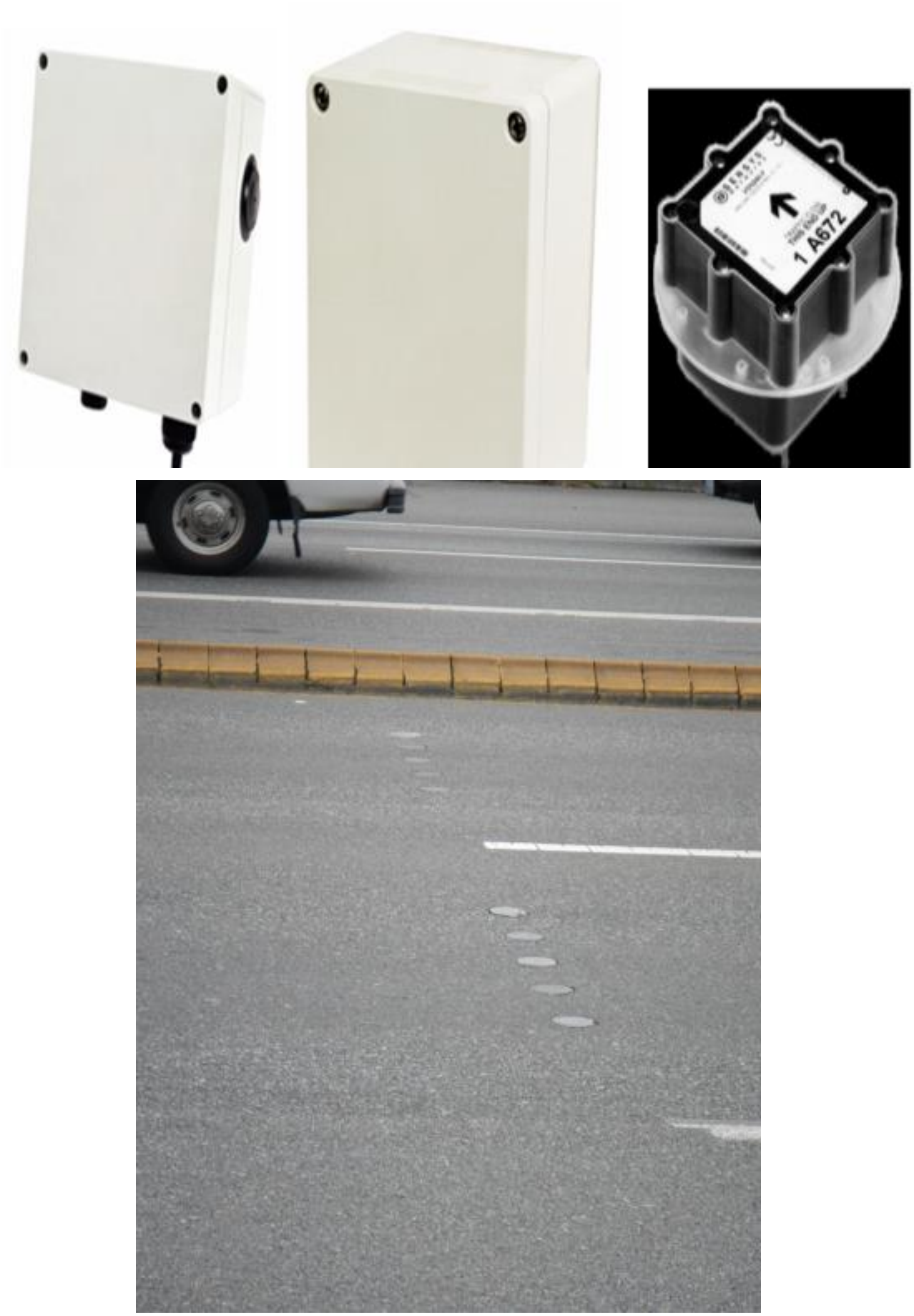


Figure 3.13 Sensys wireless vehicle detection system

3.3.3 *3rd Party Inrix Data*

Inrix aggregates traffic-related information from millions of GPS-enabled vehicles and mobile devices, traditional road sensors and hundreds of other sources. The result is a real-time, historical and predictive traffic services on freeways, highways, and secondary roadways, including arterials and side streets (Inrix, 2013). For this research historical Inrix data was acquired through the WSDOT contract with Inrix.

Chapter 4 Evaluation Frame Work

Considering the extensive sensing capabilities installed along SR 522 and I-90, performing a systematic comparison of the available technologies is a matter of selecting the appropriate metrics, pulling the data from the various sources and then performing an error analysis. In this study, a framework has been designed and implemented to evaluate the accuracy and reliability of the various technologies.

4.1 <u>Error and Reliability Matrix</u>

In order to evaluate the accuracy and reliability of travel time estimates obtained by various ATIS technologies, three types of analysis are conducted.

- First, the distributions of the travel time data and sample rates relative to the ground truth and other ATIS technologies are compared.
- Second, a number of accuracy measures are used to provide a numerical evaluation of the error associated with each of the technologies for travel time estimation.

In order to use a consistent data format, the comparisons are made based on 5 minutes aggregated travel time and capture rates. The two datasets that were not available on a five minute basis were BlueTOAD capture rates and Inrix capture rates. BlueTOAD capture rates were available at 15 minute intervals and divided by 3 to match up to the other systems as closely as possible. The Inrix data does not include a capture rate. In this study the ALPR data are used as the ground truth the accuracy analysis and baseline for vehicle sampling counts.

4.1.1 *Data Distribution*

Distributions of the data around the ground truth are compared using time plots. This enables readers to get an overview of the distributions of the data relative to the ground truth.

4.1.2 *Travel Time Accuracy and Error*

A number of accuracy metrics are used to represent the error. In these metrics, error is the difference between the observations and the ground truth travel time. These accuracy measures are:

1. Mean Absolute Deviation (MAD) (also known as the mean absolute error) – the average of errors.

$$\mathrm{MAD} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}\left|\hat{\mathrm{T}} - \mathrm{T_i}\right| \tag{4.1}$$

$\boldsymbol{N}$: The number of observations

$\boldsymbol{T_i}$: The corresponding ground truth travel time, i

$\boldsymbol{\hat{T}}$: The ATIS estimated travel time

2. Mean Percent Error (MPE) – the average percentage difference between the estimate and ground truth.

$$\mathrm{MPE} = 100.\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}\frac{\left(\hat{\mathrm{T}} - \mathrm{T_i}\right)}{\mathrm{T_i}} \tag{4.2}$$

3. Mean Absolute Percent Error (MAPE) – the average absolute percentage difference between the estimate and ground truth.

$$\mathrm{MAPE} = 100.\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}\frac{\left|\hat{\mathrm{T}} - \mathrm{T_i}\right|}{\mathrm{T_i}} \tag{4.3}$$

4. Root Mean Squared Error (RMSE) – the square root of the average of the squared errors.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\hat{T} - T_i\right)^2} \qquad \textbf{(4.4)}$$

There are reasons to use each error measurement methodology. The MAD is a good indication of how much error should be expected from an average reading, but does not indicate whether the results are consistently high or low. The MPE will indicate if there is systematic bias to the error, i.e. if readings are consistently high or low, but will allow positive and negative errors to cancel each other out. The MAPE is a combination of MAD and MPE, indicating average magnitude of error. The RMSE gives a good indication of whether there are many small errors or a few larger errors.

A good approach to judging sensor accuracy is to look at the MAD to judge the expected magnitude of error. Then examine the MPE to determine whether there are systematic biases to the data. Note that for travel time it is reasonable to expect errors to be skewed toward longer travel times in most cases, since travel time underestimation is bounded on the lower end by zero. This is particularly true for SR 522 where individual segment free flow travel times are on the order of a minute and the whole corridor can be traversed in five minutes. The MAPE is useful to find the relative magnitude of the error. Finally, the RMSE is useful in determining whether a few large errors or many smaller errors are occurring. Between the four measures of error, a user can determine the magnitude of error, its biases, the relative impact of that error and the magnitude of the typical error.

4.1.3 *Data Analysis Resolutions*

Since the reporting intervals of the data available vary among different technologies, analyses are conducted for three different levels of resolutions. The three levels of resolution considered for evaluation are: hourly, daily, and monthly basis. It is important to consider the various temporal resolutions of data analysis while evaluating the various sensors. When looking at weekly data, the consistency of the travel times across multiple days provides a good measure of the highs and lows that should be expected for travel times between the two intersections. Monthly data can be used to analyze whether the travel times between the two intersections are consistent and cyclical. By analyzing monthly data, it is also possible to indicate some days that recorded significantly longer travel times than others. This may be indicative of incidents blocking traffic. Further examinations would need to be undertaken to establish causal factors.

4.2 Data Availability

Data collection on SR 522 started on December 2012 and continued until June 2013. Table 4.1 and Table 4.2 display the time intervals when data were collected for both westbound and eastbound respectively. As can be seen, ALPR and Sensys data were only available on westbound, hence this direction will be used as the basis of travel time accuracy analysis. The gaps shown on the tables represent time periods that a technology was not either installed or was not working.

In the time span between April 5th, 2013 through June 8th 2013 all systems collected data side-by-side. The most data overlap between various systems occurred during this time period which provided a sufficiently large dataset for analysis. Therefore, this time period allows comparing the accuracy of data collected by all different systems in terms of travel time and capture rate (with the partial exception of BlueTOAD data which only reports match rates at 15 minute intervals). The 5 minute aggregated travel time and sample counts were used as the basis of analysis. Due to the difference of traffic pattern on weekends and working days, this study uses traffic data collected on weekdays for conducting error analyses.

Due to the differences between sensor availability and type of data collected by these sensors, the type of analyses conducted for eastbound and westbound varies. Sensor availability and types of data analysis for westbound and eastbound on SR 522 are summarized in Table 4.1 and Table 4.2, respectively. ALPR data are used as ground truth both for travel time analysis and sample count comparison. Inrix data does not include sample counts, so that system is excluded from sample count analysis.

When it comes to eastbound SR 522, there is no ALPR data that lines up with the other systems in the eastbound direction. This prevents an analysis based on using the ALPR system for ground truth. Also, there is no Sensys system on eastbound SR 522 to compare with the other sensors. Due to these limitations, travel time data obtained by BlueTOAD, Inrix, and BlipTrack are compared to each other and westbound results to explore whether there is a similar pattern between data distributions on eastbound and westbound. Observation of such pattern could provide a better understanding of the sensors function.

The analysis of sensors placed on I-90 differs from the analysis of sensors installed on SR 522 in that there is not a system comparable to the ALPR system on SR 522 to use as a ground truth travel time measurement. This restricts the analysis of I-90 data to be more qualitative than the SR 522 analysis. Specifically, the evaluation of I-90 data looks at data availability, daily pattern variation, and reaction to traffic events such as construction delays and mountain pass closures due to snow removal. Data availability for the BlueTOAD and Inrix data may be found in Table 4.3. One interruption of note is that the BlueTOAD device at the summit (MP 52) experienced extended communications failures, interrupting data collection for segments between milepost 32 and milepost 70.

Table 4.1 Data Availability on SR-522 Westbound

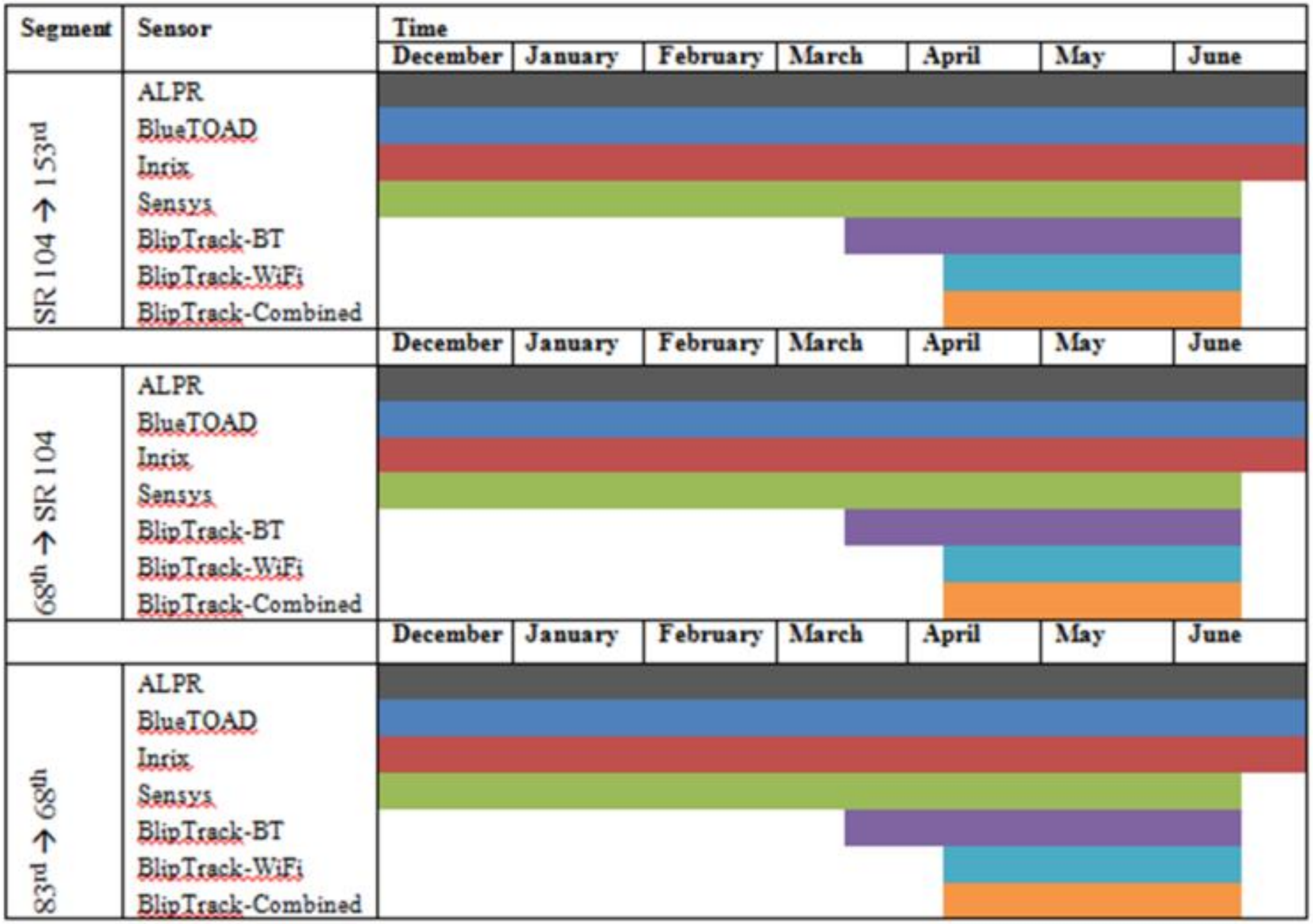


Table 4.2 Data Availability on SR-522 Eastbound

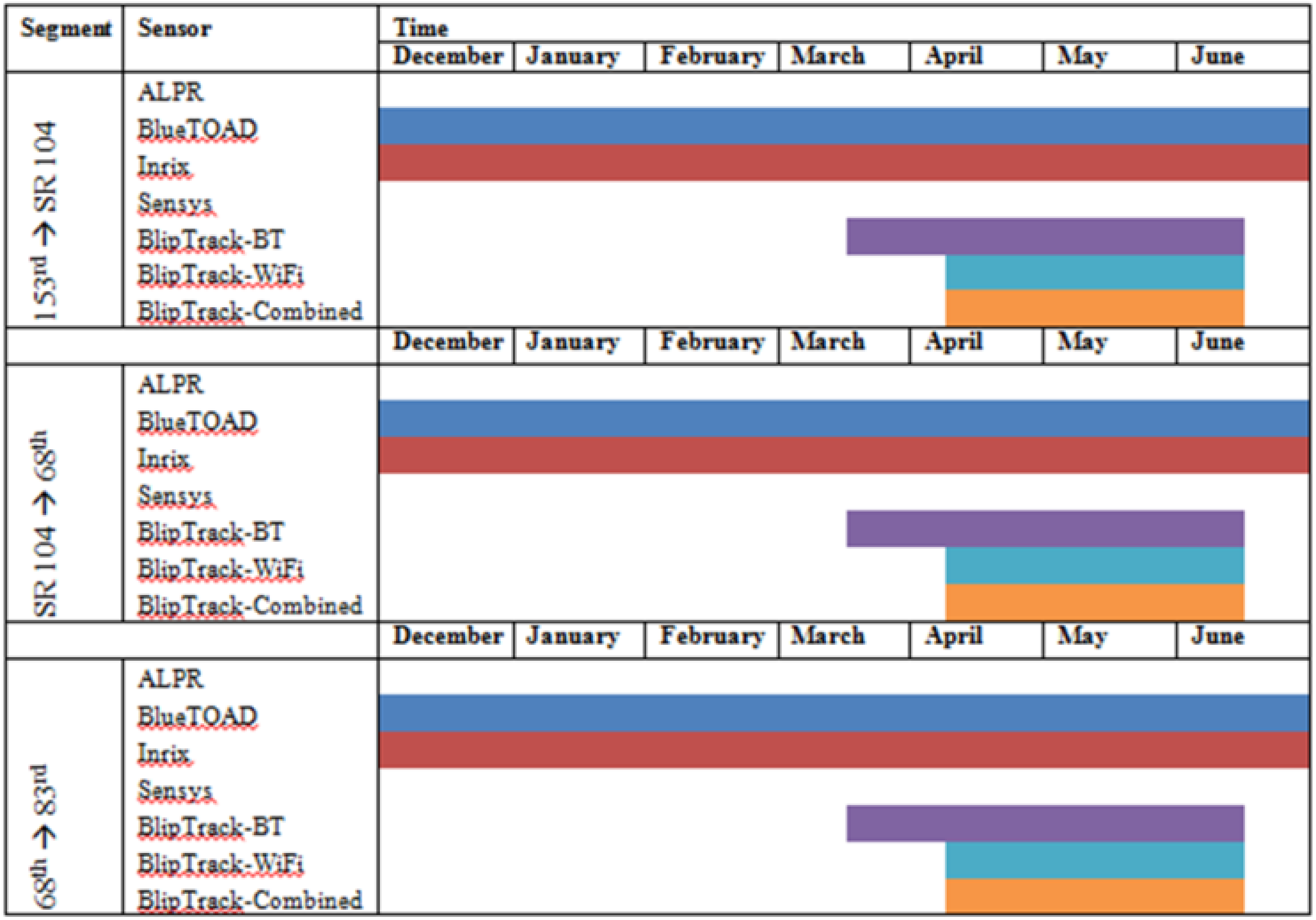


Table 4.3 Data availability by month and system for I-90

Direction	Segment	Sensor	Time					
			January	February	March	April	May	June
Eastbound	MP 32 → MP 52	BlueTOAD						
		Inrix						
	MP 52 → MP 70	BlueTOAD						
		Inrix						
	MP 52 → MP 32	BlueTOAD						
		Inrix						
Westbound	MP 109 → MP 70	BlueTOAD						
		Inrix						
	MP 70 → MP 52	BlueTOAD						
		Inrix						
	MP 52 → MP 32	BlueTOAD						
		Inrix						

4.2.1 *Types of Data*

Due to the differences between sensor availability and type of data collected by these sensors, the type of analysis conducted for eastbound and westbound varies. Sensor availability and types of data analysis for eastbound and westbound on SR 522 are summarized in Table 4.4. ALPR data are used as ground truth both for travel time analysis and sample count comparison.

Table 4.4 Data availability and type of analysis on westbound and eastbound SR 522

Direction	Sensor	Sensor Availability	Data Collected	
			Travel Time	Sample Count
Eastbound	BlueTOAD	✓	✓	✓
	Sensys	x	x	x
	Inrix	✓	✓	x
	Blip-BT	✓	✓	✓
	Blip-WiFi	✓	✓	✓
	Blip-Combined	✓	✓	✓
	ANPR	x	x	x
Westbound	BlueTOAD	✓	✓	✓
	Sensys	✓	✓	✓
	Inrix	✓	✓	x
	Blip-BT	✓	✓	✓
	Blip-WiFi	✓	✓	✓
	Blip-Combined	✓	✓	✓
	ANPR	✓	✓	✓

Data available on I-90 is shown in Table 4.5. Due to the lack of ground truth data on this corridor travel time analyses are restricted to qualitative rather than quantitative analysis.

Table 4.5 Data availability and type of analysis on westbound and eastbound I-90

Direction	Sensor	Sensor Availability	Data Collected	
			Travel Time	Sample Count
Eastbound	BlueTOAD	✓	✓	✓
	Inrix	✓	✓	x
Westbound	BlueTOAD	✓	✓	✓
	Inrix	✓	✓	x

4.3 Data analysis and discussions for SR 522

Evaluations of various technologies are conducted in terms of sample count and accuracy of travel time estimation. The following sections present the results of data analysis based on visual and numerical methods.

4.3.1 *Sample Count*

Sample counts and the corresponding penetration rate are two important factors for evaluating various travel time technologies. These represent the proportion of the actual traffic flow being captured by the sensors. The results of the sample count analysis for westbound and eastbound are presented in the following sections.

4.3.1.1 **Westbound sample count**

The results of sample count on westbound for the period between April 5th, 2013 through June 8th, 2013 are summarized in Table 4.6. As stated in section 4.1, the ALPR sample counts are used as the baseline. In this context, penetration rates are computed by dividing sample counts of various systems by the corresponding ALPR value.

$$Penetration\ rate_{Sensor\ (i)} = \frac{Sample\_Counts_{Sensor(i)}}{Sample\_Counts_{ALPR}} \quad \textbf{(4.5)}$$

According to Table 4.6, on average, the penetration rate of Sensys is identical (103%) to the sample captured by ALPR. This is followed by Blip-Combined with more than 28% of the ALPR captures, Blip-WiFi with 17% and Blip-BT with 12% of ALPR capture rates. This also indicates that by combining Bluetooth and WiFi technologies, it is possible to capture twice as many samples compared to the use of a single technology. The BlueTOAD capture rate is 6%.

Figure 4.1 shows the average penetration rate over the analysis period (April 5th, 2013 through June 8th, 2013) for various sensors on the westbound links. In order to give an overview of the sample counts variations over the weekdays, Figure 4.2, Figure 4.3, and Figure 4.4 display the capture rates of the various systems on SR 522 westbound links for a one week period May 1st, 2013 through May 8th, 2013. Comparing the penetration rates of the various sensors on the three links shows that despite the differences in traffic flow on the various links, the ratios are similar which indicates the reliability of the sensor detection results.

Although Blip-BT, Blip-WiFi and Blip-Combined, and BlueTOAD have a significantly lower penetration rates compared to ALPR and Sensys, they still demonstrate responsiveness to the variations in traffic volumes during the day. BlueTOAD data in Figure 4.2, Figure 4.3, and Figure 4.4 is blockier in profile due to being aggregated in 15-minute intervals instead of the 5-minute interval used by other sensor systems. In order to represent the BlueTOAD data on the same scales as the other systems, the BlueTOAD capture data was divided by 3, which may cause its capture rate to be underrepresented in low volume conditions due to rounding.

Table 4.6 Sample counts on westbound SR 522 during April 5th, 2013 through June 8th 2013

83rd Pl. NE to 68th Ave. NE			
Sensor	**Sample Count**	**Capture Rate (%)**	**# Intervals**
BlueTOAD	25207	5	11659
Sensys	478421	99	11161
Inrix	Not Available	Not Applicable	13232
Blip-BT	51539	11	13248
Blip-WiFi	80285	17	13238
Blip-Combined	131823	27	13238
ALPR	483984	100	-
68th Ave. NE to SR 104			
Sensor	**Sample Count**	**Capture Rate (%)**	**# Intervals**
BlueTOAD	37980	7	12112
Sensys	639211	110	11162
Inrix	Not Available	Not Applicable	13232
Blip-BT	76493	13	13248
Blip-WiFi	108063	19	13247
Blip-Combined	184556	32	13247
ALPR	580379	100	-
SR 104 to NE 153rd St.			
Sensor	**Sample Counts**	**Capture Rate (%)**	**# Intervals**
BlueTOAD	31149	6	11933
Sensys	424688	82	11164
Inrix	Not Available	Not Applicable	13232
Blip-BT	65112	13	13248
Blip-WiFi	71211	14	13247
Blip-Combined	136323	26	13247
ALPR	517657	100	-

Note: ALPR capture rate is defined as 100% with all other sensors judged relative to ALPR

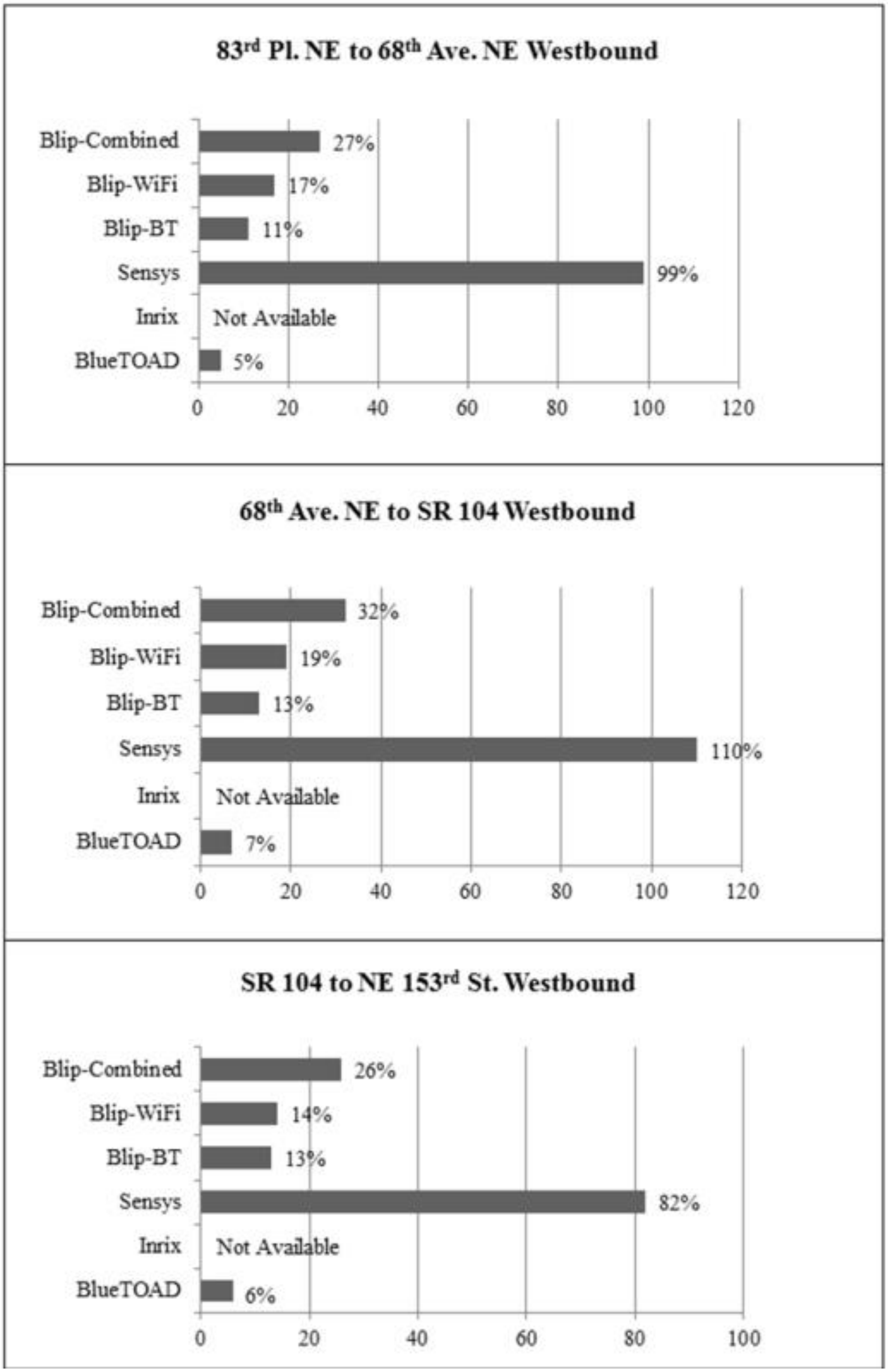


Figure 4.1 Capture rate comparison on westbound SR 522 between April 5th, 2013 through June 8th 2013

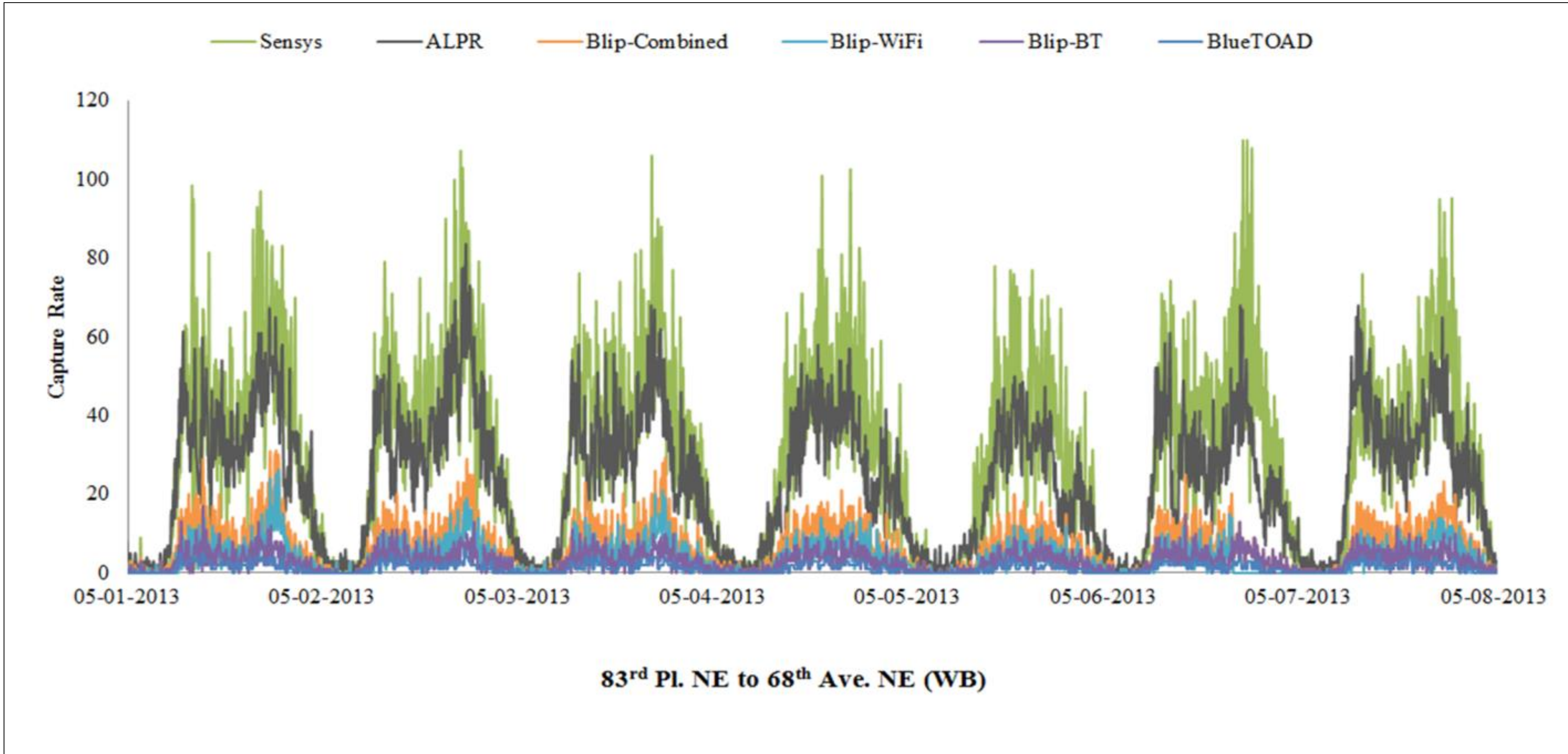


Figure 4.2 Comparing capture rate of different systems from 83rd Pl. NE to 68th Ave. NE (WB) for May 1st, 2013 through May 8th, 2013

Figure 4.2 shows the overlaid profiles of capture rate for various sensors on 83rd Pl. NE to 68th Ave. NE (WB) for May 1st, 2013 through May 8th, 2013. It clearly shows that Sensys and ALPR have higher capture rates, followed by Blip-Combined, Blip-WiFi and Blip-BT, and BlueTOAD. Figure 4.2 shows that regardless of the variations in capture rates for different systems; all of the systems were capable of registering the flow variation for peak and off-peak over the course of weekdays and weekends.

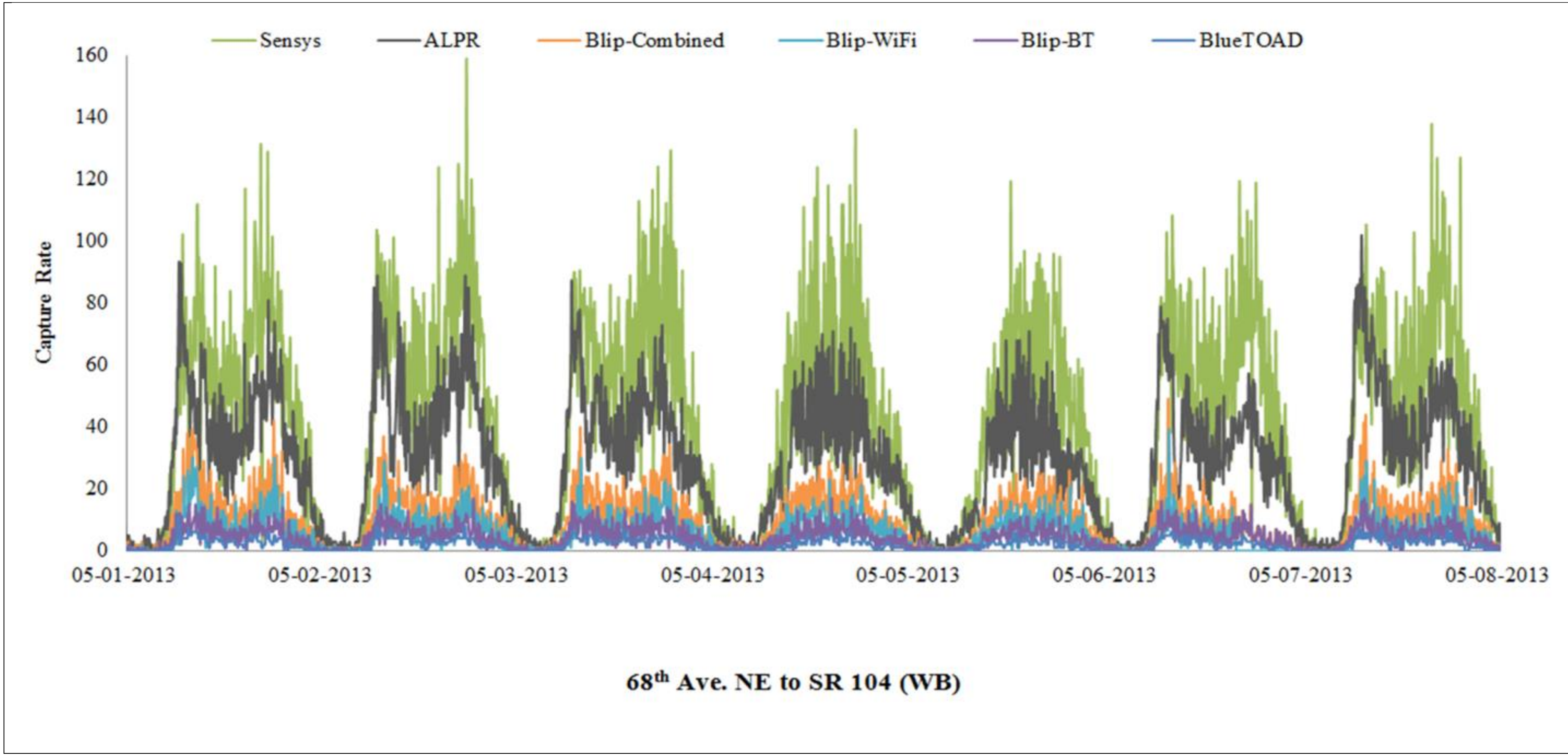


Figure 4.3 Comparing capture rate of different systems from 68th Ave. NE to SR 104 (WB) for May 1st, 2013 through May 8th, 2013

Figure 4.3 shows the overlaid profiles of capture rate for various sensors on 68th Ave. NE to SR 104 (WB) for May 1st, 2013 through May 8th, 2013. It clearly shows that Sensys and ALPR have the higher capture rate which followed by Blip-Combined, Blip-WiFi and Blip-BT, andBlueTOAD. Figure 4.3 shows that all of the systems were capable of registering the flow variation for peak and off-peak over the course of weekdays and weekends.

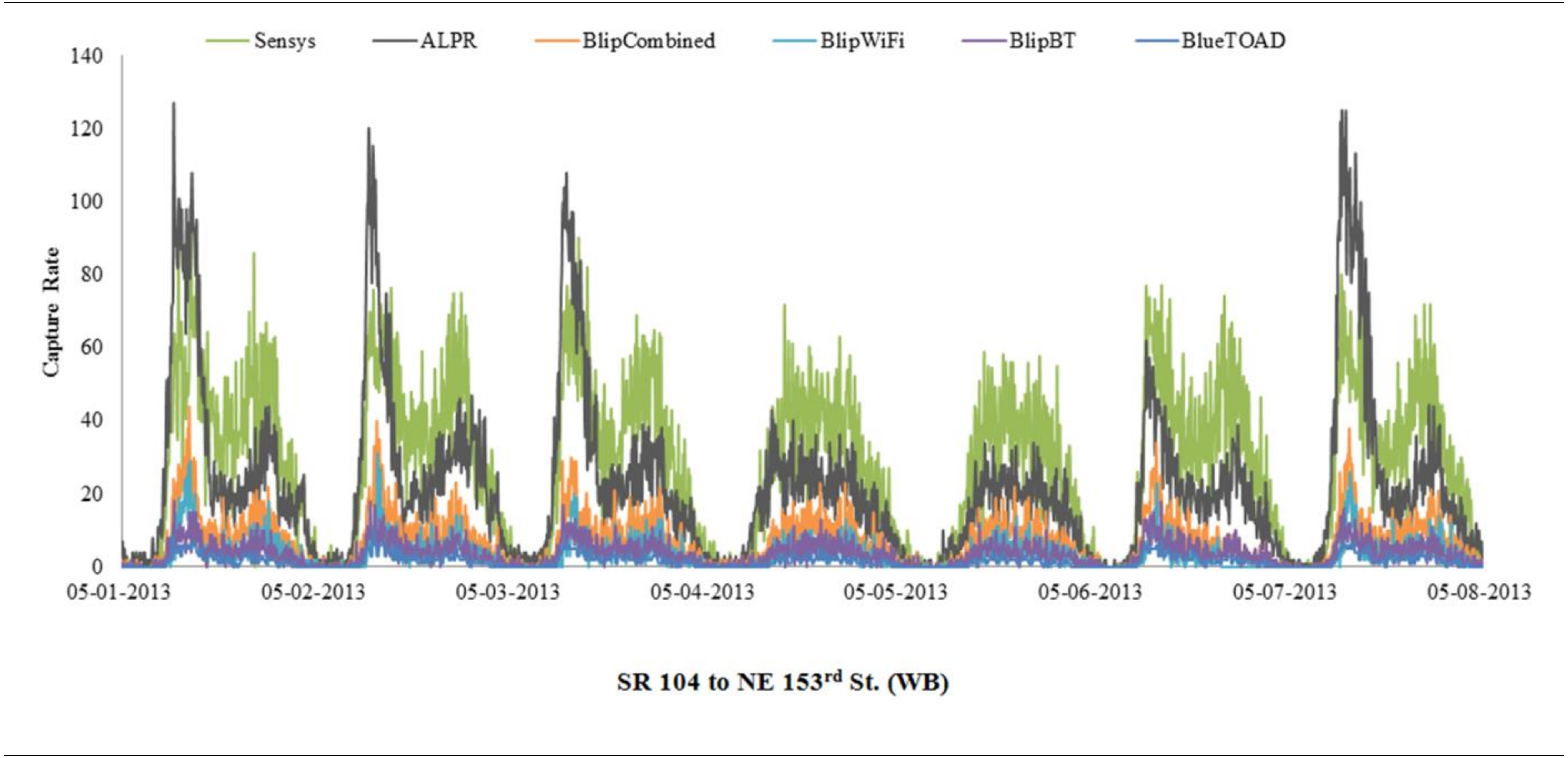


Figure 4.4 Comparing capture rate of different systems from SR 104 to NE 153rd St. (WB) for May 1st, 2013 through May 8th, 2013

Figure 4.4 shows the overlaid profiles of capture rate for various sensors from SR 104 to NE 153rd St. (WB) for May 1st, 2013 through May 8th, 2013. It clearly shows that Sensys and ALPR have the higher capture rate which followed by Blip-Combined, Blip-WiFi and Blip-BT, and BlueTOAD. Figure 4.4 shows that all of the systems were capable of registering the flow variation for peak and off-peak over the course of weekdays and weekends.

When examining the various technologies, it is important to understand how well each technology performs in relative and absolute terms. While the ALPR system was chosen as a ground truth reference for travel time, the ALPR system was not designed as a volume measurement system. In the following figures volumes from each system that provides a volume measurement and the match rates for each system are shown. For comparison purposes, the advance loop detectors are shown as well as the Traficon system volumes at the 83rd Pl. NE and 68th Ave. NE intersections.

The placement of each system will have some implications to be taken into account when examining this data. Specifically, the advance loop detectors are upstream of the signal on the through movement lanes, while the ALPR, Sensys and Traficon systems are placed on the downstream side of the intersection. Traficon and Sensys counts generally agree, though they are not identical and Sensys does report marginally lower volumes.

The ALPR volumes follow the trends seen in the other three volume data sets, but are generally the lowest reported volumes. This is unsurprising since the ALPR system was not designed for volume data collection. A number of factors such as vehicle height, spacing, and license plate cleanliness can affect the ALPR's ability to read a license plate. Loop detectors, magnetometers and VIP units are not trying to read a small target, like a license plate, and have generally more robust detection.

The placement of the advance loop detectors is likely to affect volume counts. The placement of the loop detectors means that only entering through vehicles are counted, left and right turning vehicles from the cross street are not counted. Additionally, the advance loop detectors may be subject to queuing and intersection signal timing impacts. With all of these factors it is unsurprising that the advance detectors consistently report the second lowest volumes.

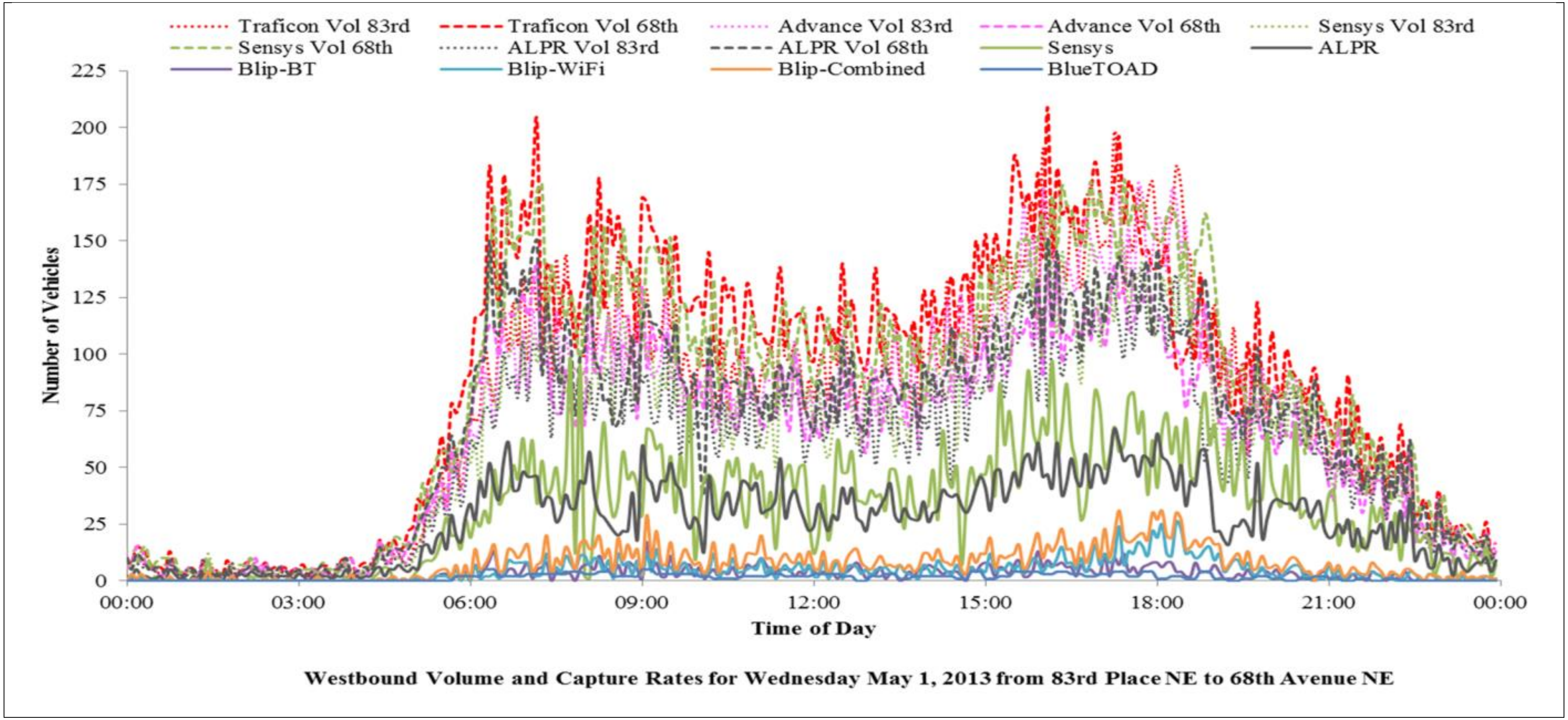


Figure 4.5 Westbound Volume and Capture Rates for Wednesday May 1, 2013 from 83rd Place NE to 68th Avenue NE

In Figure 4.5 the number of matches reported by each system are represented by solid lines. Dotted lines are used to represent the volumes reported at the upstream intersection and dashed lines are used to represent the volume at the downstream intersection. Sensys volumes and match rates are shown in green. ALPR volumes and match rates are shown in dark gray. The BlueTOAD match rate is shown in dark blue. The Blip Bluetooth, WiFi and Combined match rates are shown in purple, light blue and orange, respectively. The 83rd Place NE intersection includes Traficon and advance loop detectors upstream of the intersection included here for volume counts, shown by red and magenta dotted lines, respectively. The 68th Avenue NE intersection also includes Traficon and advance loop detectors on the upstream side of the intersection included here for volume counts, shown by red and magenta dashed lines, respectively. Readers should note that the Sensys and ALPR systems report significantly higher match rates than the other systems. Also of interest is that the two Bluetooth systems perform comparably with regards to match rates. The additional matches reported by Blip-Combined are largely a result of the added WiFi sensors.

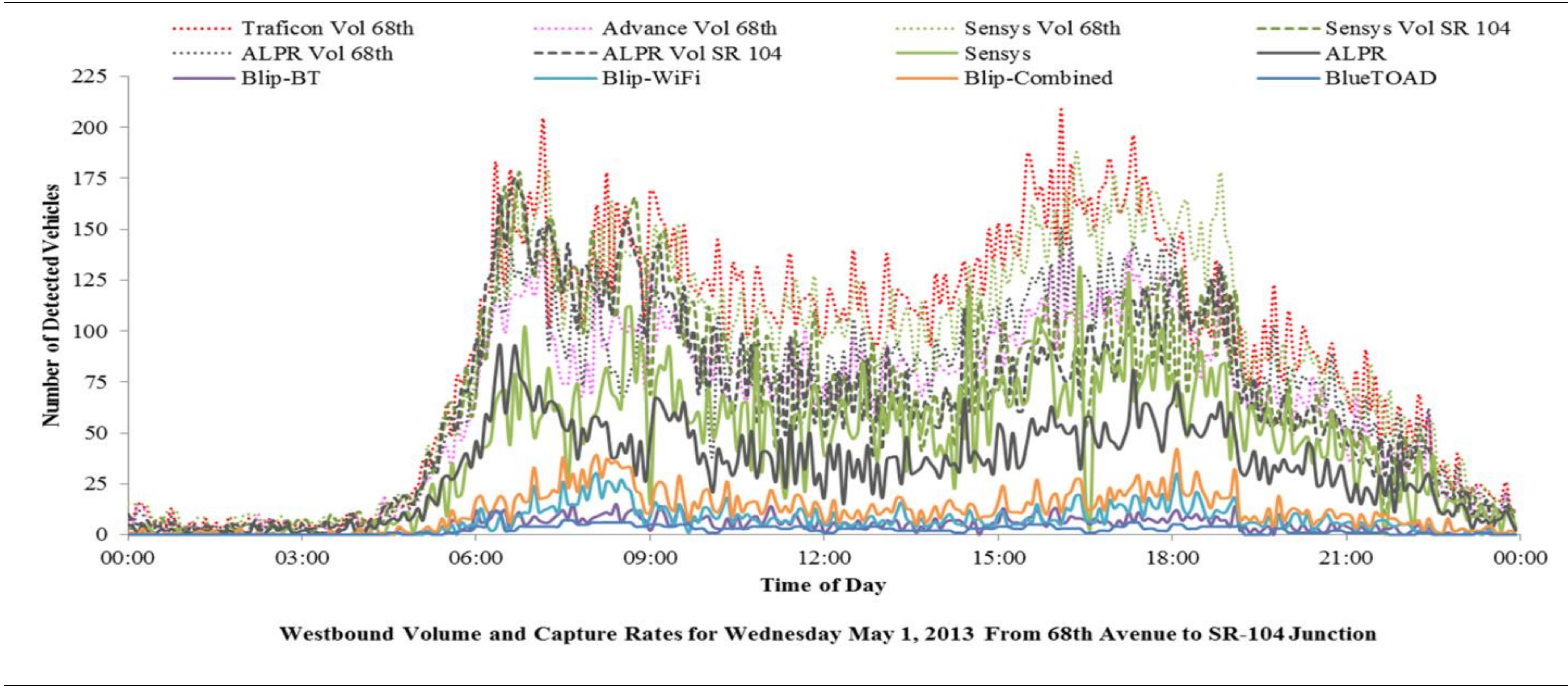


Figure 4.6 Westbound Volume and Capture Rates for Wednesday May 1, 2013 From 68th Avenue to SR-104 Junction

In Figure 4.6 the number of matches reported by each system are represented by solid lines. Dotted lines are used to represent the volumes reported at the upstream intersection and dashed lines are used to represent the volume at the downstream intersection. Sensys volumes and match rate are shown in green. ALPR volumes and match rate are shown in dark gray. The BlueTOAD match rate is shown in dark blue. The Blip Bluetooth, WiFi and Combined match rates are shown in purple, light blue and orange, respectively. The 68th Avenue NE intersection includes Traficon and advance loop detectors upstream of the intersection included here for volume counts, shown in by red and magenta dashed lines, respectively. Readers should note that the Sensys and ALPR systems report significantly higher match rates than the other systems. The ALPR system appears to be more effective during the morning peak. Also of interest is that the two Bluetooth systems perform comparably with regards to match rates. The additional matches reported by Blip-Combined are a result of the added WiFi sensors. The WiFi sensors also appear to have stronger morning and evening peaks than Bluetooth.

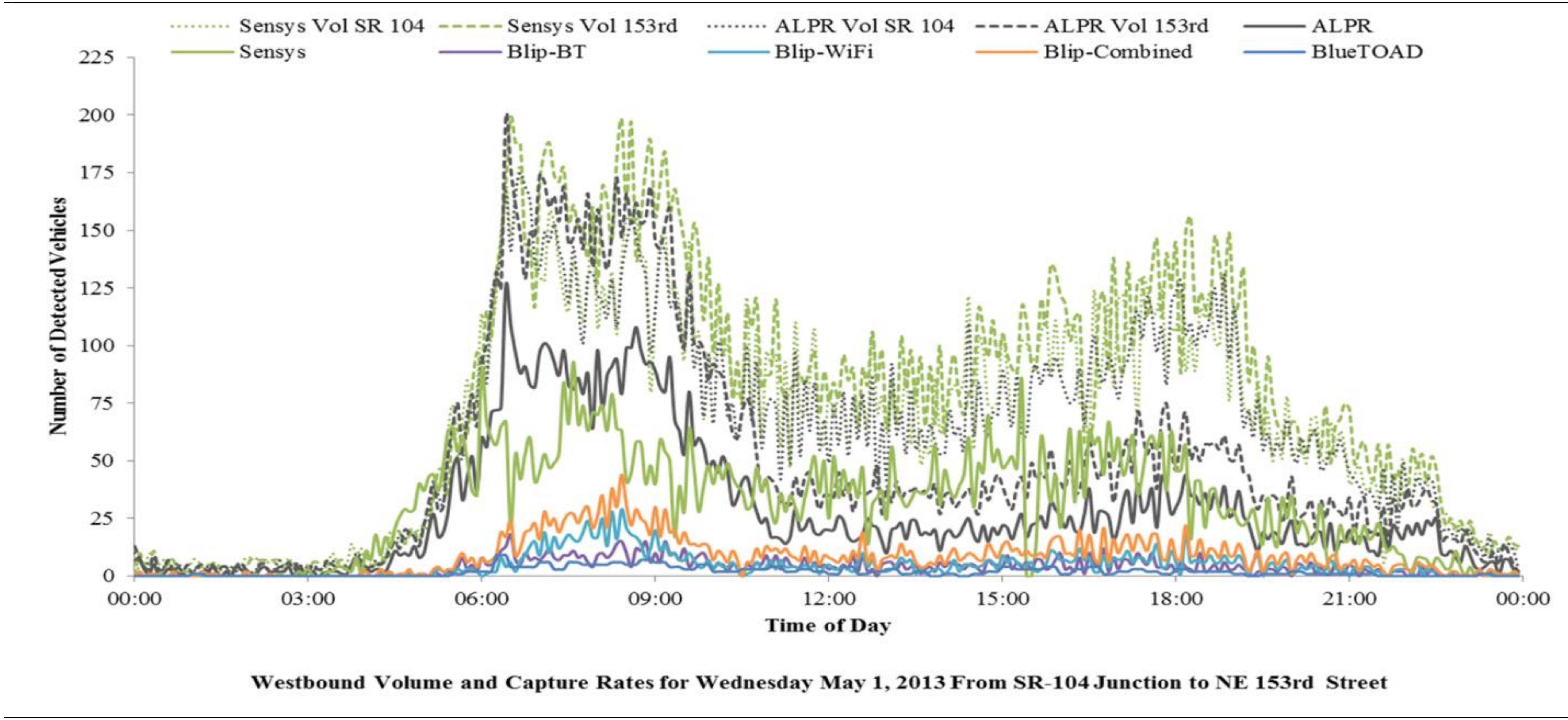


Figure 4.7 Westbound Volume and Capture Rates for Wednesday May 1, 2013 From SR-104 Junction to NE 153rd Street

In Figure 4.7 the number of matches reported by each system are represented by solid lines. Dotted lines are used to represent the volumes reported at the upstream intersection and dashed lines are used to represent the volume at the downstream intersection.Readers should note that the Sensys and ALPR systems report significantly higher match rates than the other systems. Also of interest is that the two Bluetooth systems perform comparably with regards to match rates. The additional matches reported by Blip-Combined are a result of the added WiFi sensors. The WiFi sensors also appear to have stronger morning and evening peaks than Bluetooth.

4.3.1.2 **Eastbound Sample Count**

The sample count results for eastbound for the period of April 5th, 2013 through June 8th, 2013 are summarized in Table 4.7. One notable point is that similar to the westbound sample counts, the Blip-Combined capture rate is about two times higher than the capture rates of the Blip-BT and Blip-WiFi. There are more Blip-WiFi matches than Blip-BT matches. Results show that overall there are 20% more devices seen by the WiFi sensor than Bluetooth. The WiFi devices detected are primarily iPhones, Android and Windows Phone 8 devices. These devices are not detected by the Bluetooth sensor, due to specific implementation of the Bluetooth software in these phones. So the WiFi detections could well complement the Bluetooth data.

Table 4.7 Sample counts on eastbound SR 522 over period of April 5th, 2013 through June 8th, 2013

Sensor	Sample Counts		
	68th → 83rd	SR 104 → 68th	153rd → SR 104
BlueTOAD	18260	388239	36886
Sensys	Not Available	Not Available	Not Available
Inrix	Not Available	Not Available	Not Available
Blip-BT	52130	76701	68657
Blip-WiFi	62225	97644	62717
Blip-Combined	118324	174344	131373
ALPR	Not Available	Not Available	Not Available

Figure 4.8, Figure 4.9, and Figure 4.10 display the capture rate of various systems on SR 522 eastbound links for the period of one week (May 1st, 2013 through May 8th, 2013). As seen for westbound, even though Blip-BT, Blip-WiFi and Blip-Combined have significantly lower capture rates but they are capable of representing the variations of traffic flow during the day. This could be seen by peaks during morning and afternoon on weekdays and likewise peaks on around noon on the weekends. However, due to lack of ground truth for this direction it is not possible to verify the travel time results.

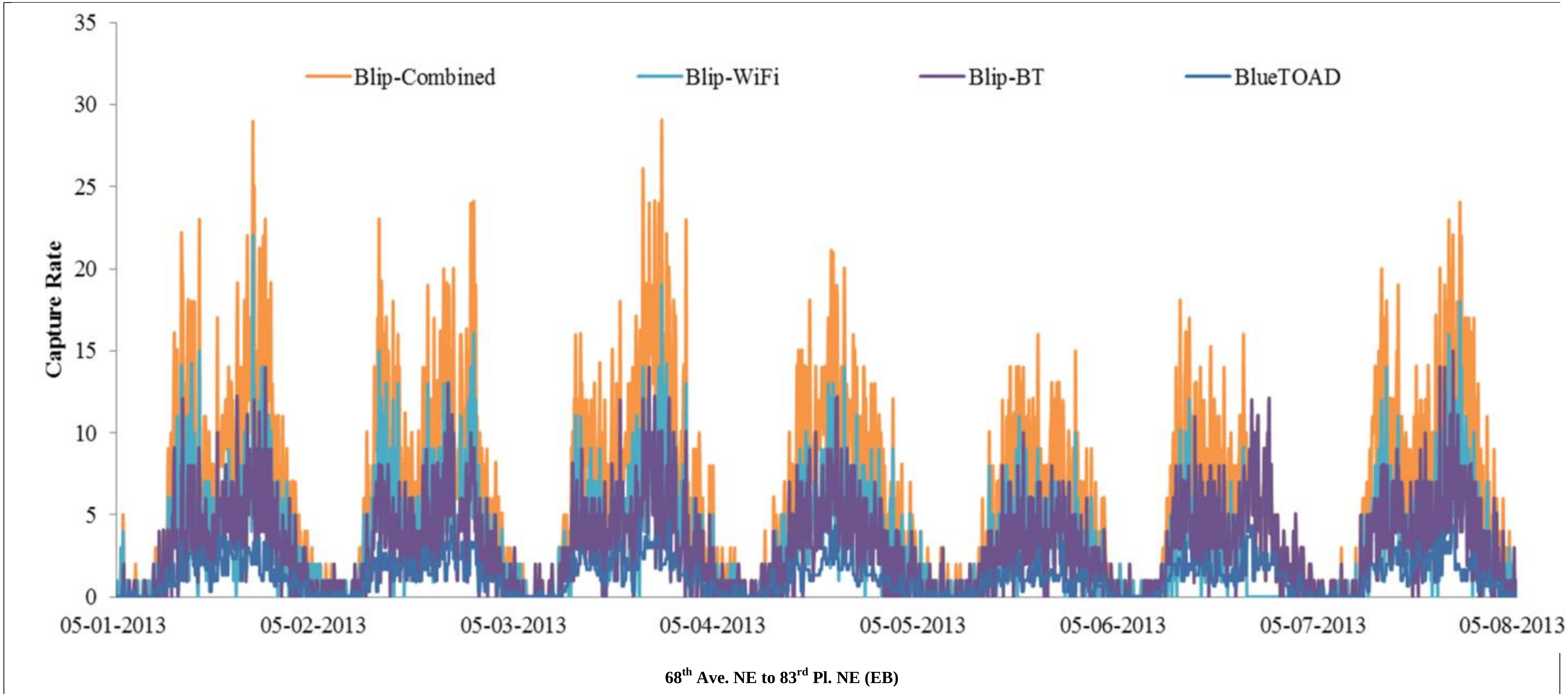


Figure 4.8 Comparing capture rate of different systems from 68th Ave. NE to 83rd Pl. NE (EB) for May 1st, 2013 through May 8th, 2013

Figure 4.8 shows capture rate for Blip-Combined, Blip-WiFi, Blip-BT, and BlueTOAD on 68th Ave. NE to 83rd Pl. NE (EB) segment for May 1st, 2013 through May 8th, 2013. Figure 4.8 demonstrates that regardless of the variations in capture rates for different systems; all systems were capable of detecting the cyclical pattern of traffic flow for peak and off-peak hours over the course of weekdays and weekends.

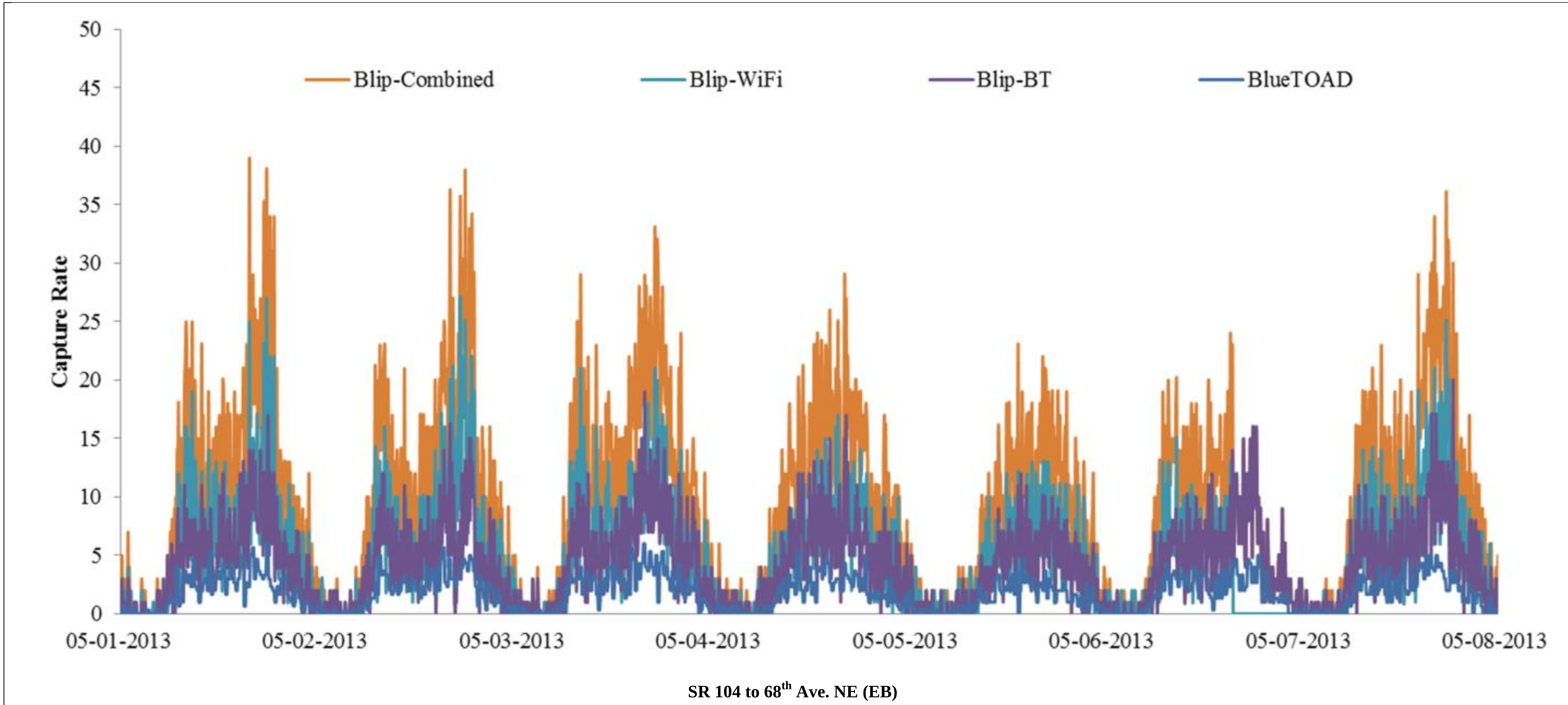


Figure 4.9 Comparing capture rate of different systems from SR 104 to 68th Ave. NE (EB) for May 1st, 2013 through May 8th, 2013

Figure 4.9 shows capture rate for Blip-Combined, Blip-WiFi, Blip-BT, and BlueTOAD on SR 104 to 68th Ave. NE (EB) segment for May 1st, 2013 through May 8th, 2013. Figure 4.9 shows that regardless of the variations in capture rates for different systems; all systems were capable of detecting the cyclical pattern of traffic flow for peak and off-peak hours over the course of weekdays and weekends.

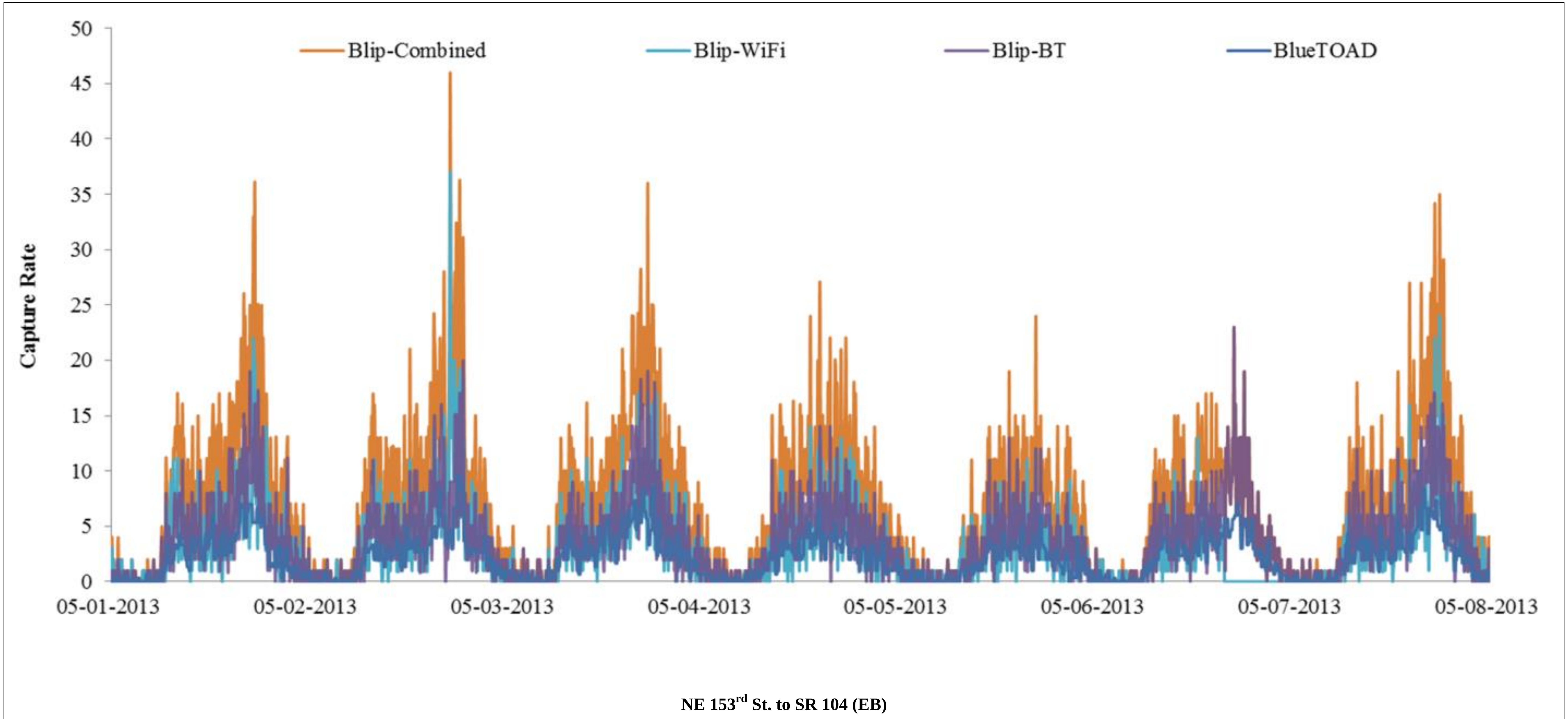


Figure 4.10 Comparing capture rate of different systems from NE 153rd St. to SR 104 (EB) for May 1st, 2013 through May 8th, 2013

Figure 4.10 shows capture rate for Blip-Combined, Blip-WiFi, Blip-BT, and BlueTOAD on NE 153rd St. to SR 104 (EB) segment for May 1st, 2013 through May 8th, 2013. Figure 4.10 indicates that regardless of the variations in capture rates for different systems; all systems were capable of detecting the cyclical pattern of traffic flow for peak and off-peak hours over the course of weekdays and weekends.

4.4 Travel Time

The accuracy and reliability of the travel time estimations are critical parameters for evaluating various sensor technologies. Due to the difference in data availability for westbound and eastbound directions, the results of the travel time analyses are presented separately by direction. On westbound, in order to provide a better foundation for comparing accuracy of different systems, analyses are conducted for different time resolutions. The accuracy analysis looks at the overall accuracy for April 5^{th}, 2013 through June 8^{th}, 2013, and also on a 24 hour daily resolution for all Wednesdays in this period (refer to Figure 4.14, Figure 4.15, and Figure 4.16). However, on eastbound due to the lack of ALPR data to act as ground truth data during the analysis period, analysis of the eastbound data is limited to descriptive statistics.

4.4.1 *Westbound Travel Time*

Travel time plots for the three segments on SR 522 westbound are shown in Figure 4.11, Figure 4.12, and Figure 4.13 for the analysis period of May 1^{st}, 2013 through May 8^{th}, 2013. The consistency of the travel times across the week provides a good measure of the highs and lows that should be expected for travel times on the three segments. The weekly data demonstrates that the travel times on all three corridors are consistent and cyclical. May 6^{th} is a Saturday and May 7^{th} is a Sunday. Saturday and Sunday have reduced peaks centered at midday. The regular workdays have earlier and longer peaks that have a minor peak in the morning and a major one in the evening for the 83^{rd} Pl. NE to 68^{th} Ave. NE segment and narrow major peaks in morning and wider evening peaks for the other two segments. These results are in accordance with expectations based on local traffic and commuter patterns.

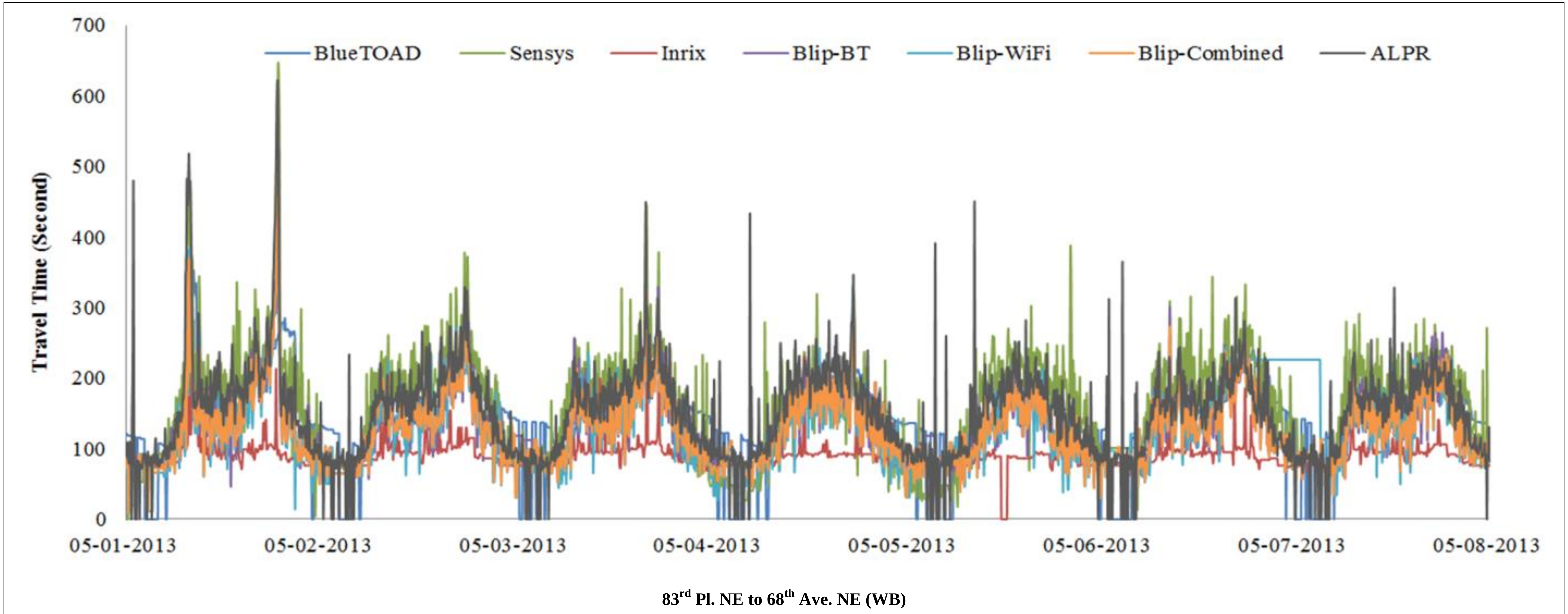


Figure 4.11 Travel time plot for 83rd Pl. NE to 68th Ave. NE (WB) for May 1st, 2013 through May 8th, 2013

Figure 4.11 shows the overlaid travel times for all the sensors from 83rd Pl. NE to 68th Ave. NE (WB) over the course of a week from May 1st, 2013 through May 8th, 2013. It is clear that all the sensors are capable of responding to the cyclical pattern of travel time over weekdays and weekends and also for the morning and afternoon peaks. Over the peak and off-peak hours all sensors follow the ALPR pattern and thus have a strong overlap with the ground truth. However, Inrix data tend to significantly underestimate the travel time. A number of gaps or low travel times were reported for all methods (except Inrix) over the mid night hours.

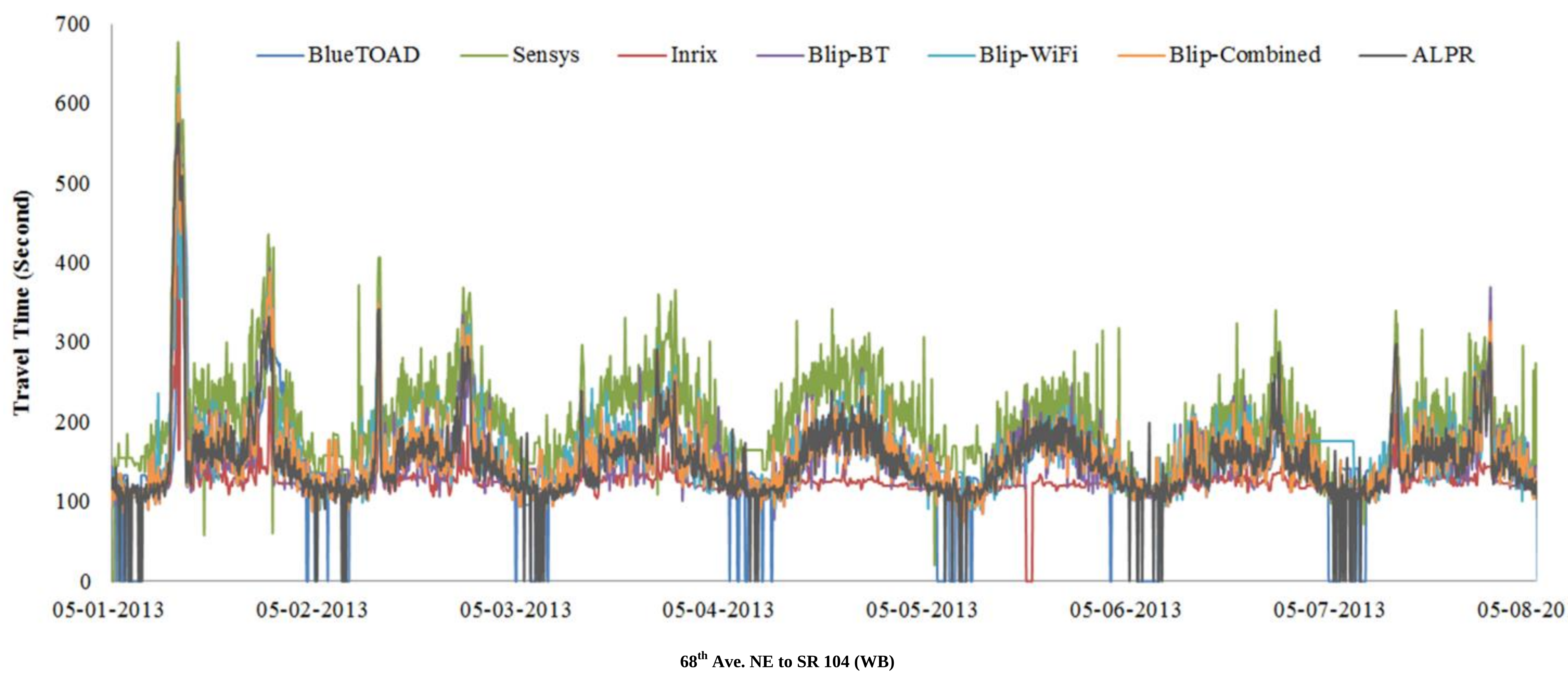


Figure 4.12 Travel time plot for 68th Ave. NE to SR 104 (WB) for May 1st, 2013 through May 8th, 2013

Figure 4.12 shows the overlaid profiles of travel time for all the sensors from 68th Ave. NE to SR 104 (WB) over the course of a week from May 1st, 2013 through May 8th, 2013. It is clear that all the sensors are capable of responding to the cyclical pattern of travel time over weekdays and weekends and also for the morning and afternoon peaks. Over the peak and off-peak hours all sensors follow the ALPR pattern and therefore have a strong overlap with the ground truth. However, Inrix data tend to significantly underestimate the travel times. A number of gaps or low travel times were reported for all methods (except Inrix) over the mid night hours.

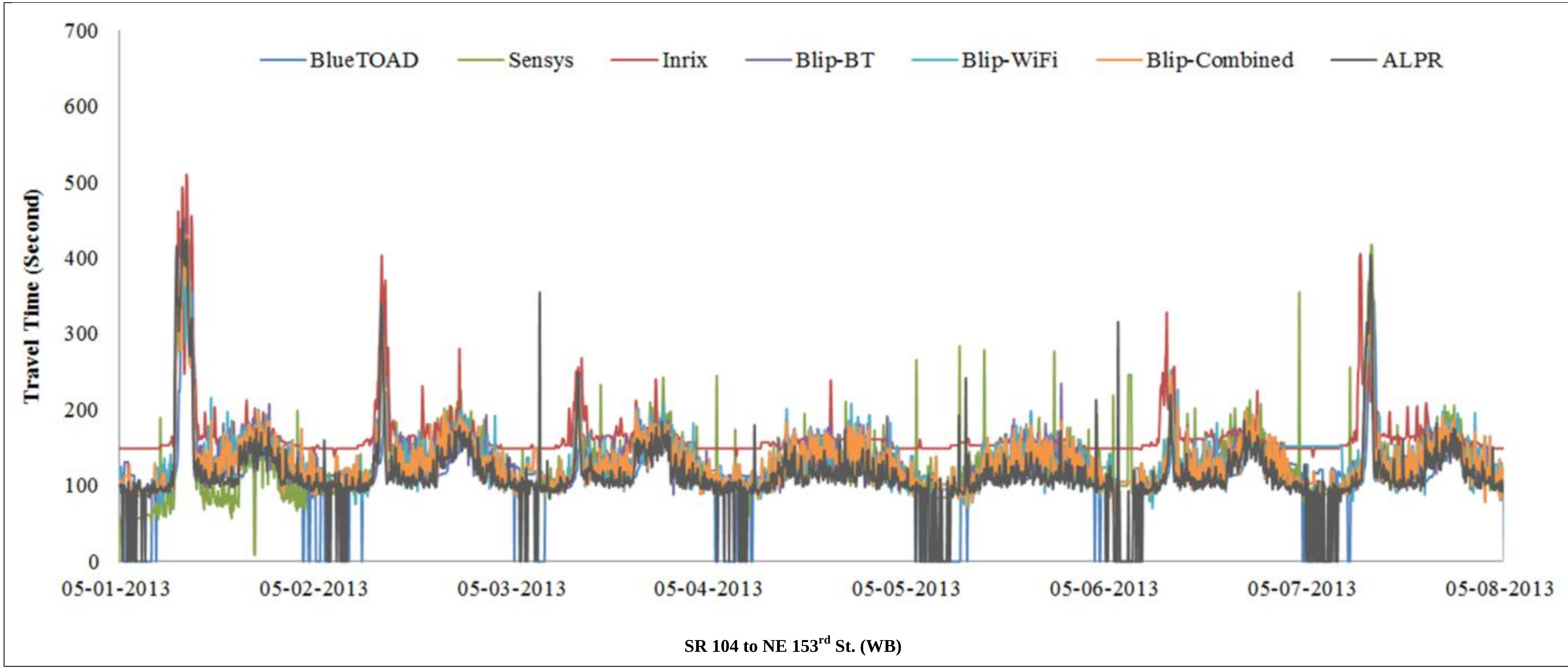


Figure 4.13 Travel time plot from SR 104 to NE 153rd St. (WB) for May 1st, 2013 through May 8th, 2013

Figure 4.13 shows the overlaid profiles of travel time for all the sensors from SR 104 to NE 153rd St. (WB) over the course of a week from May 1st, 2013 through May 8th, 2013. It is clear that all the sensors are capable of responding to the cyclical pattern of travel time over weekdays and weekend and also for the morning and afternoon peaks. Over the peak and off-peak hours all sensors follow the ALPR pattern and have a strong overlap with the ground truth. However, Inrix data tend to significantly overestimate the travel time during off-peak intervals. A number of gaps or low travel times have also been reported for all methods (except Inrix) over the mid night hours.

4.4.1.1 **Travel Time Accuracy Analysis for Westbound**

In order to provide a daily overview of the accuracy of the travel time estimated by various technologies, the MAPE for all westbound segments are calculated for Wednesdays over the of two month period from April 5, 2013 to June 8, 2013. The results of the MAPE analysis are shown in Figure 4.14, Figure 4.15, and Figure 4.16. The patterns observed for the three segments are different; however, it can be seen that, in general, during the peak hours estimations tend to be more biased and the percentage of errors increase. For all three segments, during the peak hours Inrix tends to be more biased and less accurate than the Sensys and Blip-BT, Blip-WiFi and Blip-Combined. For the SR 104 to NE 153rd St. segment BlueTOAD also shows significant bias for the morning peak. BlueTOAD also show significant bias in the overnight hours for the 83rd Pl. NE to 68th Ave. NE segment.

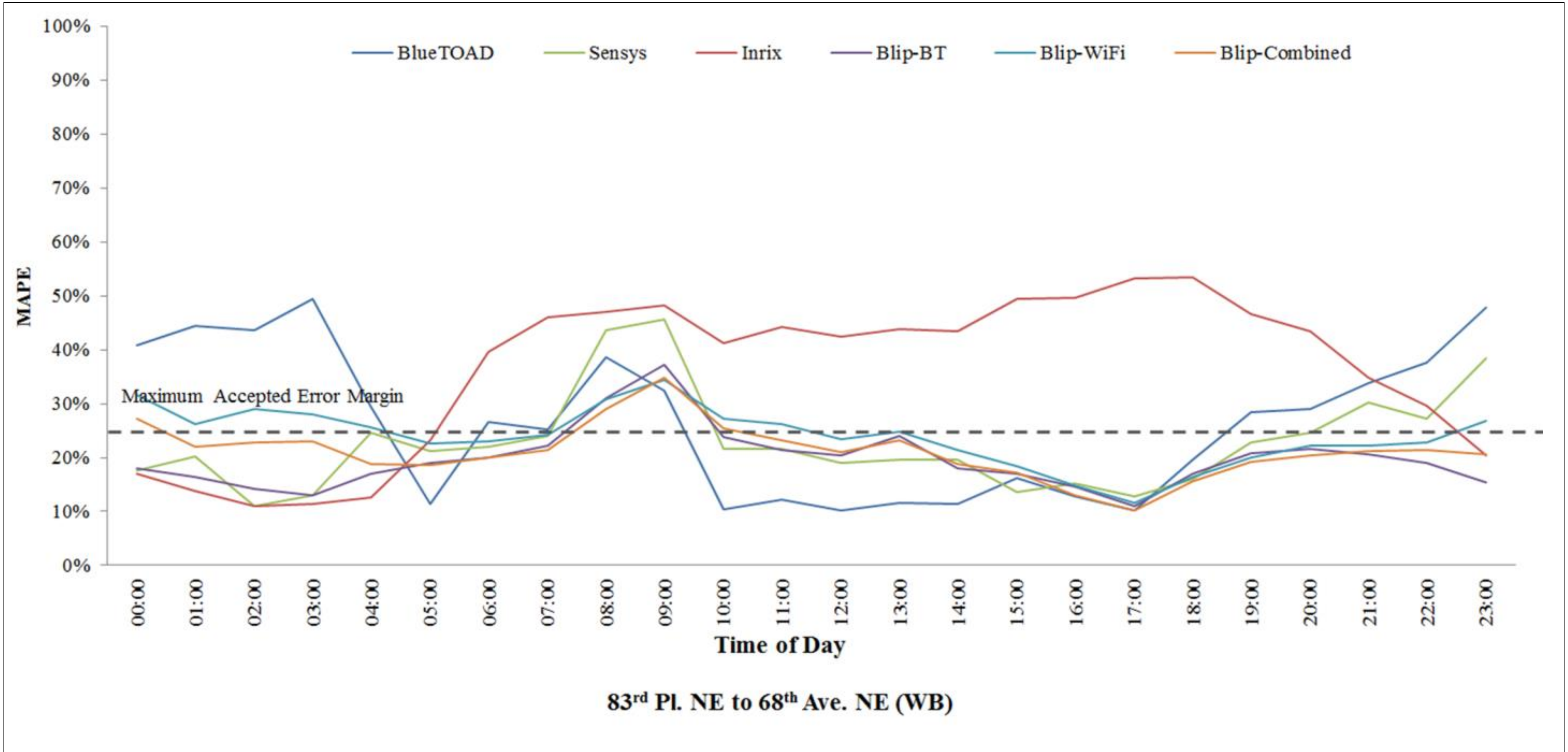


Figure 4.14 The MAPE variation for 83rd Pl. NE to 68th Ave. NE (WB) over 24 hours on Wednesdays over the period of April 5th, 2013 through June 8th, 2013

Figure 4.14 presents the variation of MAPE over 24 hours for Wednesdays over the period of April 5th, 2013 through June 8th, 2013 at for 83rd Pl. NE to 68th Ave. NE (WB). It is clear that the accuracy of the various systems' estimated travel times varies between peak and off-peak hours. This is especially true of the morning peak from 8am to 9am. As shown, BlueTOAD has a lower MAPE over the course of the day followed by Blip-Combined, Blip-BT, Blip-WiFi, Sensys and Inrix. Compared to other systems, Inrix has significantly lower accuracy during the day and BlueTOAD shows significantly lower accuracy during the night.

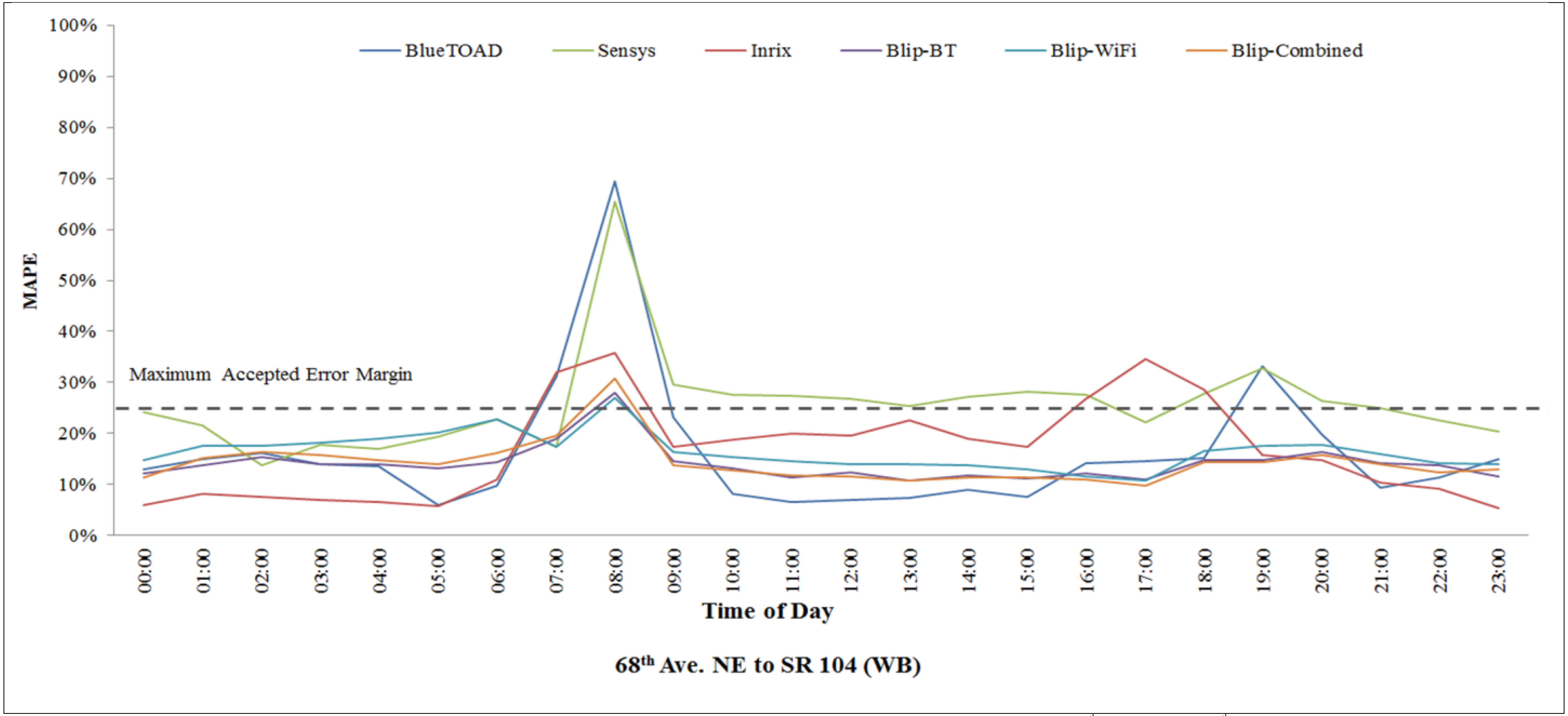


Figure 4.15 The MAPE variation from68th Ave. NE to SR 104 (WB) over 24 hours on Wednesdays over the period of April 5th, 2013 through June 8th, 2013

Figure 4.15 presents the variation of MAPE over 24 hours for Wednesdays over the period of April 5th, 2013 through June 8th, 2013 at 68th Ave. NE to SR 104 (WB). The accuracy of the estimated travel times varies over the day, though not as significantly as on the 83rd Pl. NE to 68th Ave. NE segment. As shown Blip-BT, Blip-WiFi, and Blip-Combined estimate travel time with approximately 15% error over the course of the day. Although, accuracy of travel time estimated by BlueTOAD fluctuates between peak and off-peak hours, in off-peaks it can estimate travel time with less than 15% error which rises to 70% error during peak. In this segment, Sensys performance on this segment is acceptable overnight, with an error spike in the peak hour and just over the acceptable error threshold over the day. For this segment, Inrix has a modest accuracy, generally competitive with the other systems.

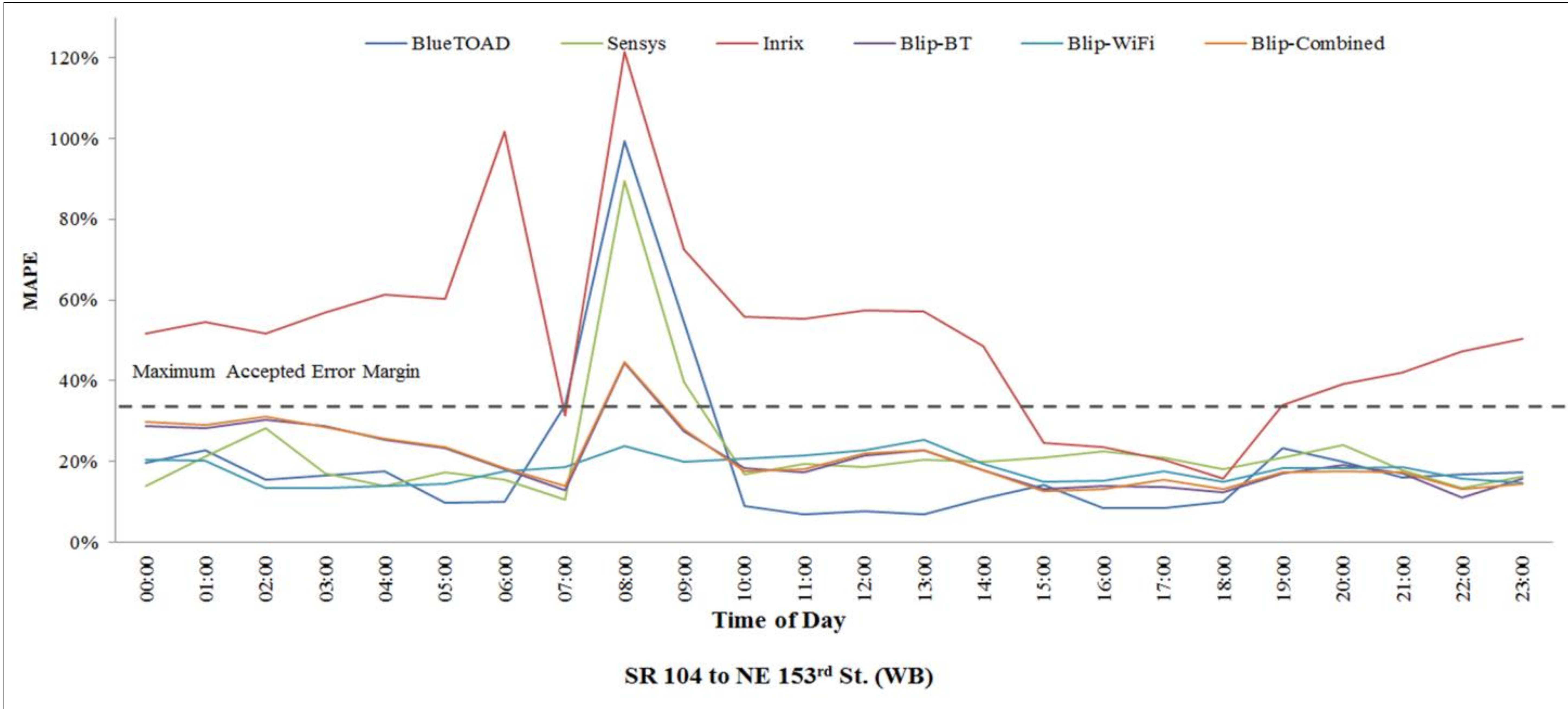


Figure 4.16 The MAPE variation from SR 104 to NE 153rd St. (WB) over 24 hours on Wednesdays over the period of April 5th, 2013 through June 8th, 2013

Figure 4.16 presents the variation of MAPE over 24 hours for Wednesdays over the period of April 5th, 2013 through June 8th, 2013 from SR 104 to NE 153rd St. (WB). It is clear that the accuracy of the estimated travel time by various systems varies between peak and off-peak hours. As shown Sensys and BlueTOAD have lower accuracy during the morning peak followed by Blip-Combined and Blip-BT with Blip-WiFi being the most accurate. During the morning peak there is a significant rise in the BlueTOAD and Sensys error rates which leveled out for the rest of the day. Inrix data for this segment was subject to significant error.

In order to further explore this pattern, data collected between 9am-10am (off-peak) on Wednesdays during two months (April 5th, 2013 through June 8th, 2013) are analyzed. Table 4.8 presents descriptive statistics of the collected data. As seen in Table 4.8, the average ALPR travel time is closely estimated by all sensors. Table 4.8 presents the travel time samples recorded by each system grouped by segment as well as the sample penetration rate compared to the ALPR system. The travel time standard deviation in seconds, minimum travel time, 1st quartile, median, mean, 3rd quartile and maximum are also presented.

To evaluate the accuracy of the sensors on an hourly basis, the MAPE for each sensor on each segment of the corridor is calculated for 9am-10am (off-peak) on Wednesdays during two months (April 5th, 2013 through June 8th, 2013), as seen in Table 4.9 .As presented, in general the Blip-BT, Blip-WiFi, Blip-Combined, Sensys and BlueTOAD provide comparable results. On the opposite end of the spectrum, Inrix results are less representative. Since the accuracy varies between the three segments, it is wise to be cautious in drawing conclusions based on the limited number of segments analyzed.

Table 4.8 Hourly descriptive statistics for westbound over the period of April 5th, 2013 through June 8th, 2013

	Sensor	Sample Count	Penetration Rate (%)	Std. Dev.	Min	1st Qtr	Median	Mean	3rd Qtr	Max
83rd Pl. NE to 68th Ave. NE	BlueTOAD	309	7	14.4	144.9	163.0	168.5	170.2	173.9	243.4
	Sensys	4464	108	32.5	134.0	178.8	198.0	200.4	220.3	342.0
	Inrix	NA	NA	19.3	67.0	94.0	101.0	103.8	110.3	169.0
	Blip-BT	551	13	27.1	70.0	130.8	144.0	147.6	163.3	224.0
	Blip-WiFi	725	18	29.7	60.0	126.0	142.0	145.2	161.0	262.0
	Blip-Combined	1276	31	26.9	61.0	128.5	143.0	145.5	162.5	243.0
	ALPR	4126	100	33.5	15.0	157.8	169.0	169.0	183.0	320.0
68th Ave. NE to SR 104)	Sensor	Sample Count	Penetration Rate	Std. Dev.	Min	1st Qtr	Median	Mean	3rd Qtr	Max
	BlueTOAD	456	8	45.0	128.0	141.6	145.3	158.7	156.8	415.3
	Sensys	6459	112	35.3	120.0	160.0	181.0	187.0	211.3	283.0
	Inrix	NA	NA	21.7	108.0	120.8	127.5	131.4	134.0	261.0
	Blip-BT	798	14	28.4	112.0	134.8	148.5	154.3	167.0	234.0
	Blip-WiFi	986	17	28.2	108.0	136.0	162.5	161.0	182.3	234.0
	Blip-Combined	1784	31	27.4	119.0	135.8	149.5	156.3	170.3	233.0
	ALPR	5784	100	25.0	103.0	128.0	143.0	149.3	168.3	217.0
SR 104 to NE 153rd St.	Sensor	Sample Count	Penetration Rate	Std. Dev.	Min	1st Qtr	Median	Mean	3rd Qtr	Max
	BlueTOAD	459	7	70.7	112.6	118.9	141.1	169.5	196.1	392.6
	Sensys	4939	80	60.9	88.0	119.0	129.5	146.1	147.0	399.0
	Inrix	NA	NA	56,3	140	165	170,5	190,0741	193	464
	Blip-BT	833	13	46.2	102.0	114.0	124.0	136.8	142.3	365.0
	Blip-WiFi	759	12	21.5	92.0	117.0	130.5	131.9	142.5	233.0
	Blip-Combined	1592	26	45.4	102.0	118.0	128.0	139.2	140.3	365.0
	ALPR	6175	100	15.9	67.0	106.0	112.5	114.1	119.0	189.0

MAPE results for various sensors are compared for all three SR 522 segments in Table 4.9. As can be seen, all sensors are more accurate from 68th Ave. NE to SR 104 (WB). However, accuracy varies between the different segments and sensors, which might be attributed to the corridor length and the number of busy intersections as well as sensor ranges and operating principles.

Table 4.9 Results of the MAPE for hourly analysis over the period of April 5th, 2013 through June 8th, 2013

Sensor	MAPE		
	83rd Pl. NE to 68th Ave. NE	68th Ave. NE to SR 104	SR 104 to NE 153rd St.
BlueTOAD	32.30%	23.20%	54.40%
Sensys	45.60%	29.60%	39.60%
Inrix	48.20%	17.30%	72.50%
Blip-BT	37.20%	14.60%	27.60%
Blip-WiFi	34.40%	16.40%	20.00%
Blip-Combined	34.90%	13.70%	28.10%

Note: The Maximum accepted level of accuracy is set as 25%. The MAPE is colored green below 15%, transitioning through yellow at 20% to red at or above 25%.

Error! Reference source not found. Table 4.9 summarizes the MAPE results for all the sensors on SR 522 westbound segments for 9-10 am on Wednesdays over the period of April 5th, 2013 through June 8th, 2013. Confirming the results shown in Figure 4.14, Figure 4.15, and Figure 4.16, all the sensors tend to have a better performance on the 68th Ave. NE to SR 104 segment.

To look at more aspects of sensor accuracy, accuracy measures for a period of two months (from April 5th, 2013 through June 8th, 2013) are calculated. This is intended to clarify the influence of traffic variation on accuracy of the estimated travel time. The results of the accuracy analysis are summarized in Table 4.10. For the hourly analysis, Sensys, Blip-BT, Blip-WiFi, Blip-Combined and BlueTOAD provide more accurate travel time estimates than Inrix. Second, sensors are generally less accurate on 83rd Pl. NE to 68th Ave. NE than other segments, though Inrix and BlueTOAD are least accurate on SR 104 to 68th Ave. NE.

Comparing the MPE values in Table 4.10 shows that the sensors tend to overestimate travel time on the 83rd Pl. NE to 68th Ave. NE and SR 104 to NE 153rd St. and underestimate travel time on the 68th Ave. NE to SR 104 (WB) segments. For 83rd Pl. NE to 68th Ave. NE, Blip-BT, Blip-WiFi and Blip-Combined underestimate the travel time. For the 68th Ave. NE to SR 104 segment all sensors are more accurate, except the Sensys sensors. On this segment all sensors report MAPE rates below the 25% error threshold. For the SR 104 to NE 153rd St. segment all sensors overestimate travel times relative to the ALPR system.

The MAPE and MAD also correlate to the results of the RMSE on all three corridors. The consistency of the three different accuracy measures on three corridors increases confidence in the evaluation results. It can be concluded that Blip-BT, Blip-Combined, Blip-WiFi and BlueTOAD achieve the most overall reliable travel times followed by Sensys and Inrix.

Table 4.10 Travel time accuracy analysis for westbound SR 522 for the period of April 5th, 2013 through June 8th, 2013

83rd Pl. NE to 68th Ave. NE				
Sensor	**RMSE (Second)**	**MAD (Second)**	**MPE (%)**	**MAPE (%)**
BlueTOAD	141.81	33.99	5.51	20.76
Sensys	146.63	35.87	13.18	21.54
Inrix	149.24	65.21	-35.33	35.93
Blip-BT	134.25	33.46	-12.22	18.47
Blip-WiFi	136.19	38.63	-16.10	23.01
Blip-Combined	134.52	34.56	-15.18	19.68
68th Ave. NE to SR 104				
Sensor	**RMSE (Second)**	**MAD (Second)**	**MPE (%)**	**MAPE (%)**
BlueTOAD	38.94	23.10	3.94	13.33
Sensys	51.43	37.20	19.01	23.37
Inrix	45.32	29.63	-12.37	15.41
Blip-BT	36.17	23.03	2.31	13.36
Blip-WiFi	37.59	26.16	8.99	16.00
Blip-Combined	35.57	22.63	4.79	13.33
SR 104 to NE 153rd St.				
Sensor	**RMSE (Second)**	**MAD (Second)**	**MPE (%)**	**MAPE (%)**
BlueTOAD	40.33	22.63	7.88	15.85
Sensys	41.37	25.69	13.88	18.86
Inrix	69.33	57.24	46.11	47.84
Blip-BT	34.85	22.08	10.21	16.12
Blip-WiFi	35.44	24.01	11.53	17.38
Blip-Combined	34.83	22.29	11.26	16.35

Note: The maximum accepted level of accuracy error is set as 25% for percent based error measures. The MAPE and MPE are colored green below 15%, transitioning through yellow at 20% to red at or above 25%.

4.4.2 *Eastbound Travel Time*

Travel time plots for three segments on eastbound SR 522 are shown in Figure 4.17, Figure 4.18 through Figure 4.19 for the analysis period of May 1^{st}, 2013 through May 8^{th}, 2013. The weekly data demonstrates that the travel times on all three segments are consistent and cyclical. The difference between weekdays and weekends is distinguishable. These results are in accordance with expectations based on westbound performance.

The descriptive statistics for the two month period (April 5^{th}, 2013 through June 8^{th}, 2013) are summarized in Table 4.11. Due to the lack of ground truth on the eastbound segments it is not possible to evaluate the sensors' accuracy; however, it is clear the Inrix data indicates a significantly higher or lower and more highly smoothed travel time over the off-peak hours compared to the others. For the 68^{th} Ave. NE to 83^{rd} Pl. NE segment, the Inrix results are significantly lower and less responsive than the other systems. For SR 104 to 68^{th} Ave. NE Inrix reports a lower travel time, but with less separation than the other two segments and more responsiveness to traffic conditions. For the NE 153^{rd} St. to SR 104 segment Inrix data is generally higher and somewhat responsive to traffic conditions. Overnight, BlueTOAD was observed to have a number of gaps in its data. This is not necessarily a problem, as it is likely an effect of low traffic volumes, when travel time data is least likely to be needed, but the lack of data should be noted.

In order to have an overall view of the accuracy of travel time estimation on eastbound, data collected between 9 am and 10 am (an off-peak period) on Wednesdays across two months (April 5^{th}, 2013 through June 8^{th}, 2013) are analyzed for all sensors. Table 4.11 presents descriptive statistics of the collected data. As seen in Table 4.11 the average travel times are closely estimated by all sensors. Inrix has the highest difference with the other sensors. The matches recorded by Blip-BT, Blip-WiFi, Blip-Combined and BlueTOAD shown in Table 4.11 are proportional to those shown in Table 4.8. This indicates that the penetration rate of each individual system on both time scales and directions is consistent.

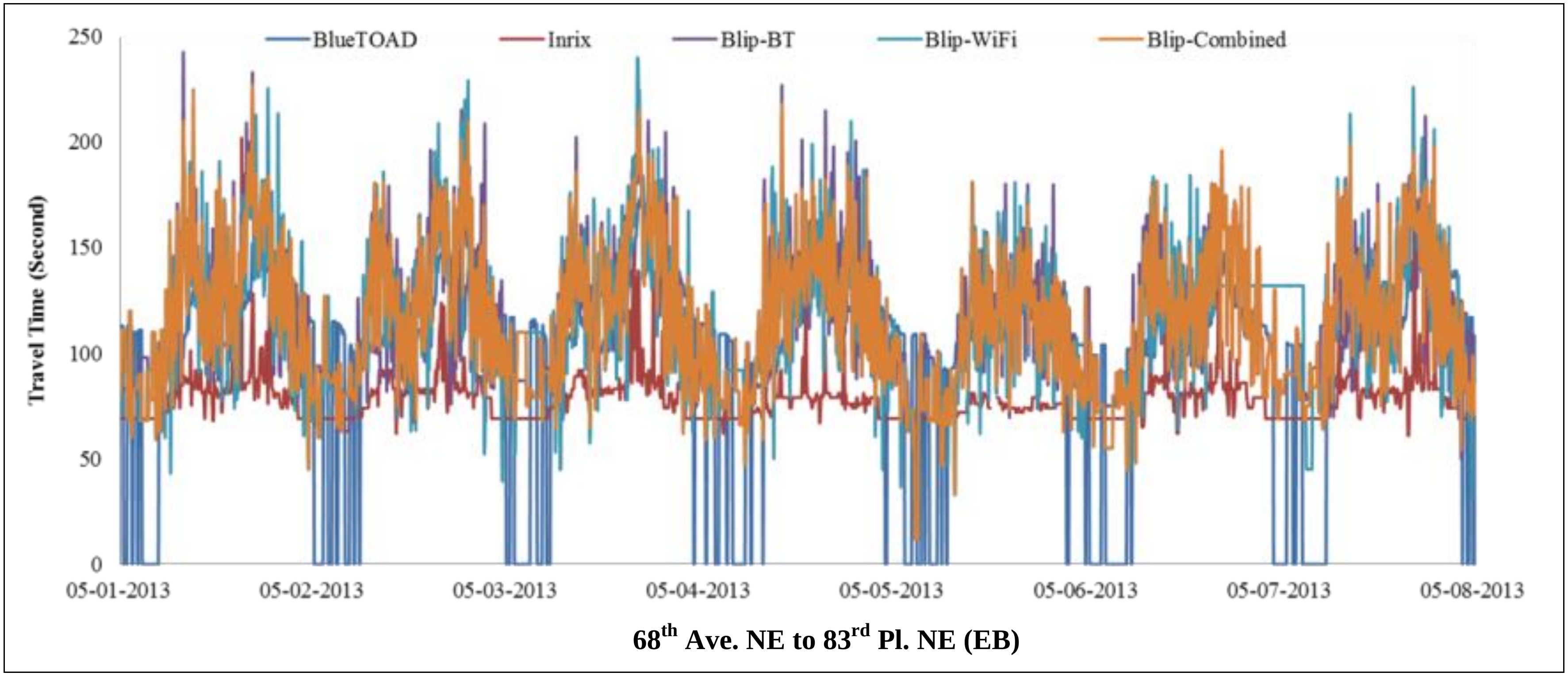


Figure 4.17 Travel time plot from 68th Ave. NE to 83rd Pl. NE (EB) for May 1st, 2013 through May 8th, 2013

Figure 4.17 shows the overlaid profiles of travel time for all the sensors on 68th Ave. NE to 83rd Pl. NE (EB) over the course of a week from May 1st, 2013 through May 8th, 2013. It is clear that all the sensors are capable of detecting the cyclical pattern of travel time over weekdays and weekend and also for the morning and afternoon peaks. However, it is clear the Inrix reports a significantly lower and highly smoothed travel time on this segment compared to others. Overnight, BlueTOAD was observed to have a number of gaps in its data.

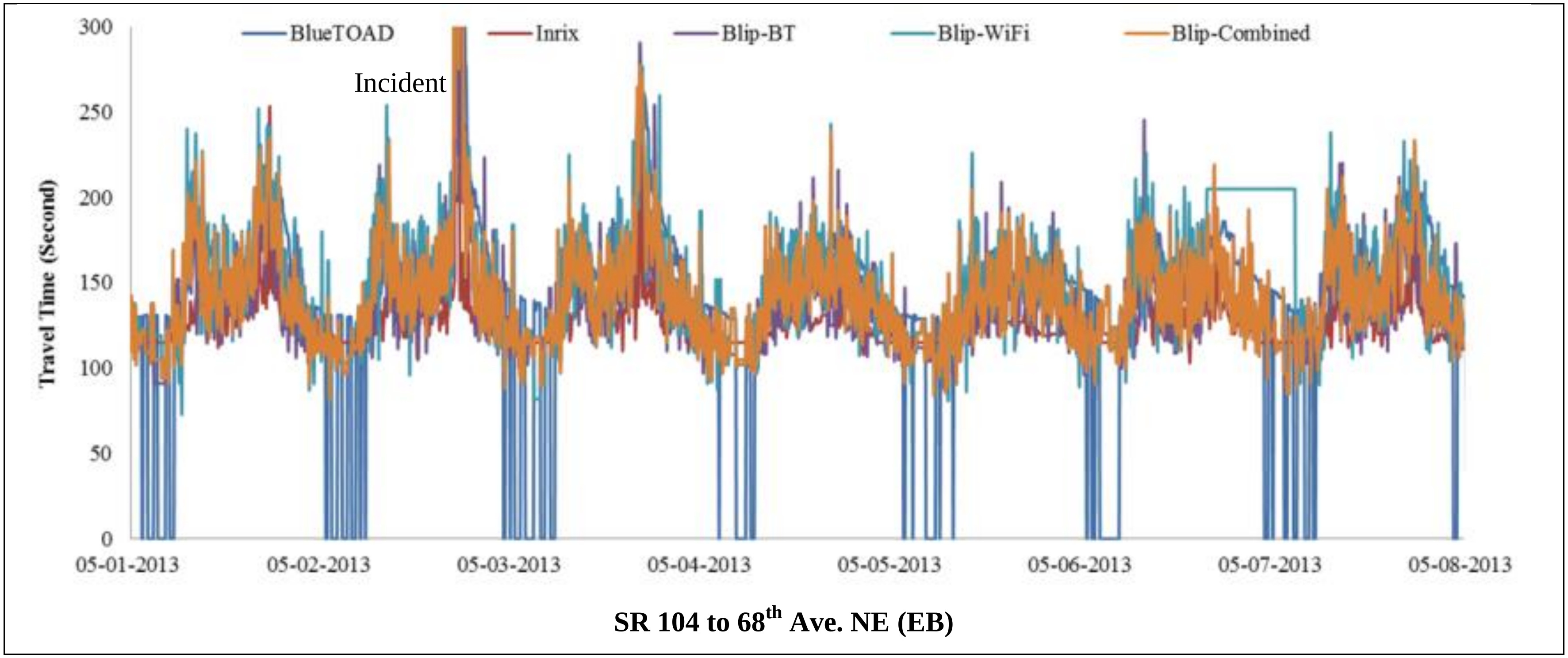
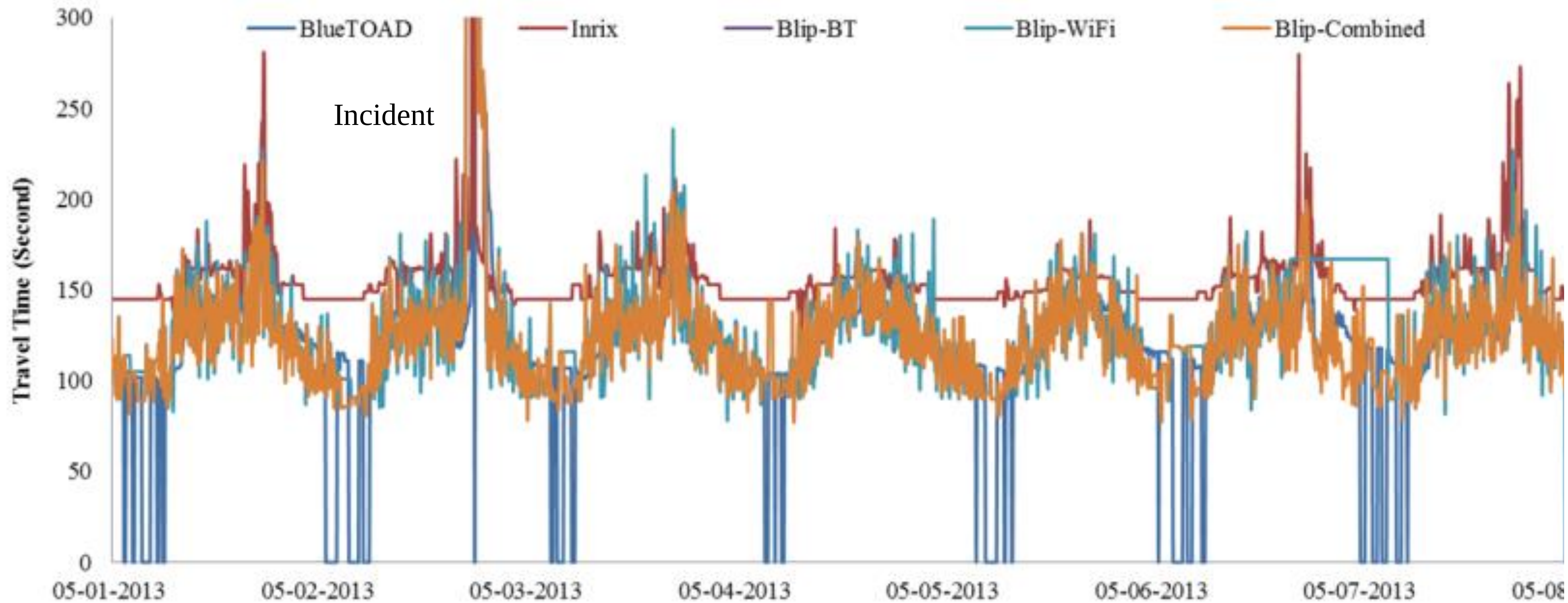


Figure 4.18 Travel time plot from SR 104 to 68th Ave. NE (EB) for May 1st, 2013 through May 8th , 2013

Figure 4.18 shows the overlaid profiles of travel time for all the sensors on SR 104 to 68th Ave. NE (EB) over the course of a week from May 1st, 2013 through May 8th, 2013. It is clear that all the sensors are capable of detecting the cyclical pattern of travel time over weekdays and weekend and also for the morning and afternoon peaks. Overnight, BlueTOAD was again observed to have a number of gaps in its data. The evening of May 2nd, an incident caused a significant spike in travel times registered by all sensors.



NE 153rd St. to SR 104 (EB)

Figure 4.19 Travel time plot from NE

153rd
St. to
SR
104
(EB)
for
May
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h May
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Figure 4.19 shows the overlaid profiles of travel time for all the sensors from NE 153rd St. to SR 104 (EB) over the course of a week from May 1st, 2013 through May 8th, 2013. It is clear that all the sensors are capable of detecting the cyclical pattern of travel time over weekdays and weekend and also for the morning and afternoon peaks. Inrix reports a significantly higher and highly smoothed travel time over the off-peak hours on this segment compared to others. Overnight, BlueTOAD was observed to have a number of gaps in its data. The evening of May 2nd, an incident caused a significant spike in travel times registered by all sensors.

Table 4.11 Hourly descriptive statistics for eastbound SR 522 over the period of April 5th, 2013 through June 8th, 2013

	Sensor	Sample Count	Std. Dev.	Min	1st Qtr	Median	Mean	3rd Qtr	Max
68th Ave. NE to 83rd Pl.NE	BlueTOAD	192	4.4	122.4	126.0	128.3	129.2	132.1	141.4
	Sensys	NA	NA	NA	NA	NA	NA	NA	NA
	Inrix	NA	6.5	149.0	159.8	162.0	162.0	162.0	184.0
	Blip-BT	465	16.2	95.0	113.0	123.0	125.7	139.3	173.0
	Blip-WiFi	484	17.2	87.0	120.8	133.5	132.3	143.0	180.0
	Blip-Combined	1007	13.4	99.0	118.0	127.5	128.5	137.3	163.0
	ALPR	NA	NA	NA	NA	NA	NA	NA	NA
SR 104 to 68th Ave. NE	Sensor	Sample Count	Std. Dev.	Min	1st Qtr	Median	Mean	3rd Qtr	Max
	BlueTOAD	210	8.2	151.5	170.0	176.0	175.0	181.5	190.5
	Sensys	NA	NA	NA	NA	NA	NA	NA	NA
	Inrix	NA	13.4	114.0	127.8	134.0	135.7	138.0	192.0
	Blip-BT	534	26.7	111.0	131.8	149.5	153.5	167.5	271.0
	Blip-WiFi	775	28.5	106.0	139.8	159.5	160.6	179.0	259.0
	Blip-Combined	1309	23.3	111.0	136.8	153.0	155.0	169.3	226.0
	ALPR	NA	NA	NA	NA	NA	NA	NA	NA
NE 153rd St. to SR 104	Sensor	Sample Count	Std. Dev.	Min	1st Qtr	Median	Mean	3rd Qtr	Max
	BlueTOAD	216	11.4	97.6	113.1	117.5	120.7	129.2	152.5
	Sensys	NA	NA	NA	NA	NA	NA	NA	NA
	Inrix	NA	9.0	67.0	83.0	86.0	86.3	90.3	120.0
	Blip-BT	396	24.0	78.0	111.8	127.5	128.0	143.5	188.0
	Blip-WiFi	392	29.8	51.0	109.5	131.5	131.3	151.0	217.0
	Blip-Combined	788	23.1	76.0	113.8	127.5	127.4	139.3	224.0
	ALPR	NA	NA	NA	NA	NA	NA	NA	NA

Table 4.11 presents the travel time samples recorded by each system grouped by segment as well as the sample penetration rate compared to the ALPR system. The travel time standard deviation in seconds, minimum travel time, 1st quartile, median, mean, 3rd quartile and max are also presented.

4.5 Data Analysisfor I-90

The analysis of sensors placed on I-90 differs from the analysis of sensors installed on SR 522 in that there is not a system comparable to the ALPR system on SR 522 to use as a ground truth travel time measurement. This restricts the analysis of I-90 data to be more qualitative than the SR 522 analysis. Specifically, the evaluation of I-90 data looks at data availability, daily pattern variation, and reaction to traffic events such as closures due to construction and snow removal.

Figure 4.20, Figure 4.21, and Figure 4.22, show daily travel times for the westbound links from May 1st, 2013 through May 8th, 2013. Note that I-90 from milepost 56 to 61 has been closed occasionally for rock blasting related to construction. These closures are typically about an hour in length and close both directions. The evening of May 2nd, 2013 includes one such closure which shows as a travel time peak in Figure 4.21. This event is shown more closely in Figure 4.23, and a similar closure on May 15th, 2013 is shown in Figure 4.24.

Figure 4.23 and Figure 4.24 show how the Inrix and BlueTOAD data react to the absence of traffic. The BlueTOAD system continues to report the last travel time for approximately a half hour until ceasing to report travel times pending new vehicle identification. The Inrix data has a more variable response. The Inrix travel time data is the sum of data from many smaller segments. This factor is of limited impact on the SR-522 corridor due to smaller segment size and fewer segments involved. For I-90, the longer distance between sensor placements means that instead of one to three Inrix segments, ten to twenty may be involved. The difference in Inrix response between Figure 4.23 and Figure 4.24 is that is that a number of segments reverted to average travel time on May 15th and on May 2nd they reported null values instead.

However, other data produced by the systems are useful in identifying the closures. Inrix reports a confidence level for its segment readings that can be used to judge the reliability of the data. For both closures, the Inrix data reported significant decreases in average confidence and complete absence of confidence for specific segments. The BlueTOAD data includes a useful data point, the last reported matching vehicle. When the closure occurred, no more vehicles were being detected to update the travel time information. After a half hour with no new samples the BlueTOAD data ceased reporting a travel time.

It is important to note that calculating the travel time by averaging Inrix segment data is very limited in the case of closures. This is because it is nearly impossible to accurately judge the delay from being backed up and held at the closure site without some kind of arrival information. This is a non-issue for BlueTOAD data, which presents a reasonable travel time, once traffic flow has resumed, to judge by the travel times of approximately an hour reported after reopening the road.

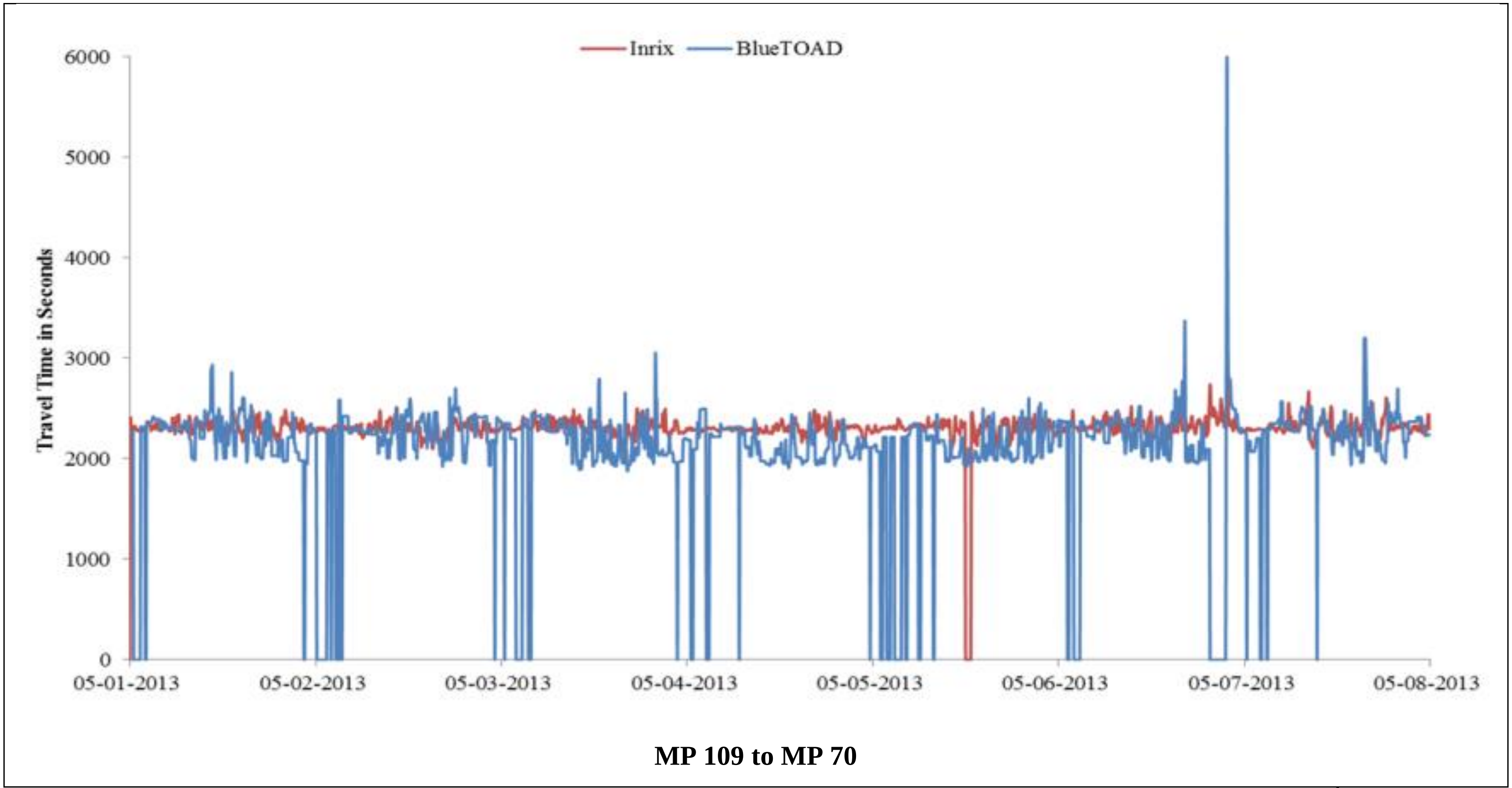


Figure 4.20 Travel times on I-90 from Ellensburg (MP 109) to Easton (MP 70) for May 1st, 2013 through May 8th, 2013

Figure 4.20 shows a comparison of the travel time generated by BlueTOAD and Inrix from milepost 109 to Milepost 70 on I-90. This segment has relatively lighter traffic and therefore shows little day to day variation. Of note is a possible blocking incident on May 7.

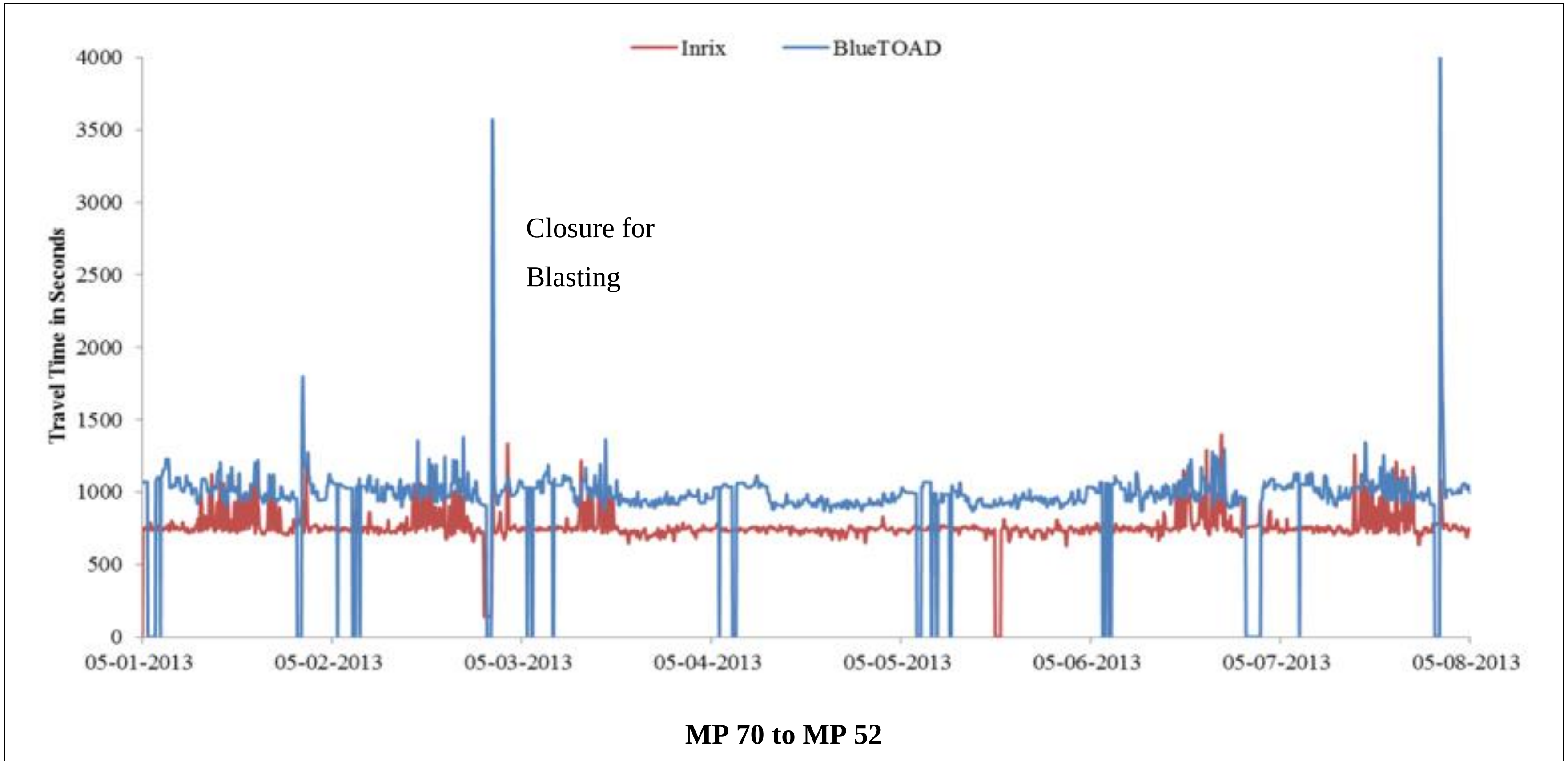


Figure 4.21 Travel times on I-90 from Easton (MP 70) to the Snoqualmie Pass (MP 52) for May 1st, 2013 through May 8th, 2013

Figure 4.21 shows the BlueTOAD and Inrix travel time data from milepost 70 to milepost 52. It is noteworthy that this segment has a hint of cyclic daily pattern for the weekdays (May 1-3 and 6-8). The large spike on May 2 is due to closure for blasting. The spike on May 8 is another possible incident. It is noteworthy that the Inrix and BlueTOAD data show similar activity during peak periods, but have significantly different travel times. The Inrix data is suggestive of one or more missing segments, given that at 60 mph, the 18 mile trip should take 18 minutes or 1080 seconds.

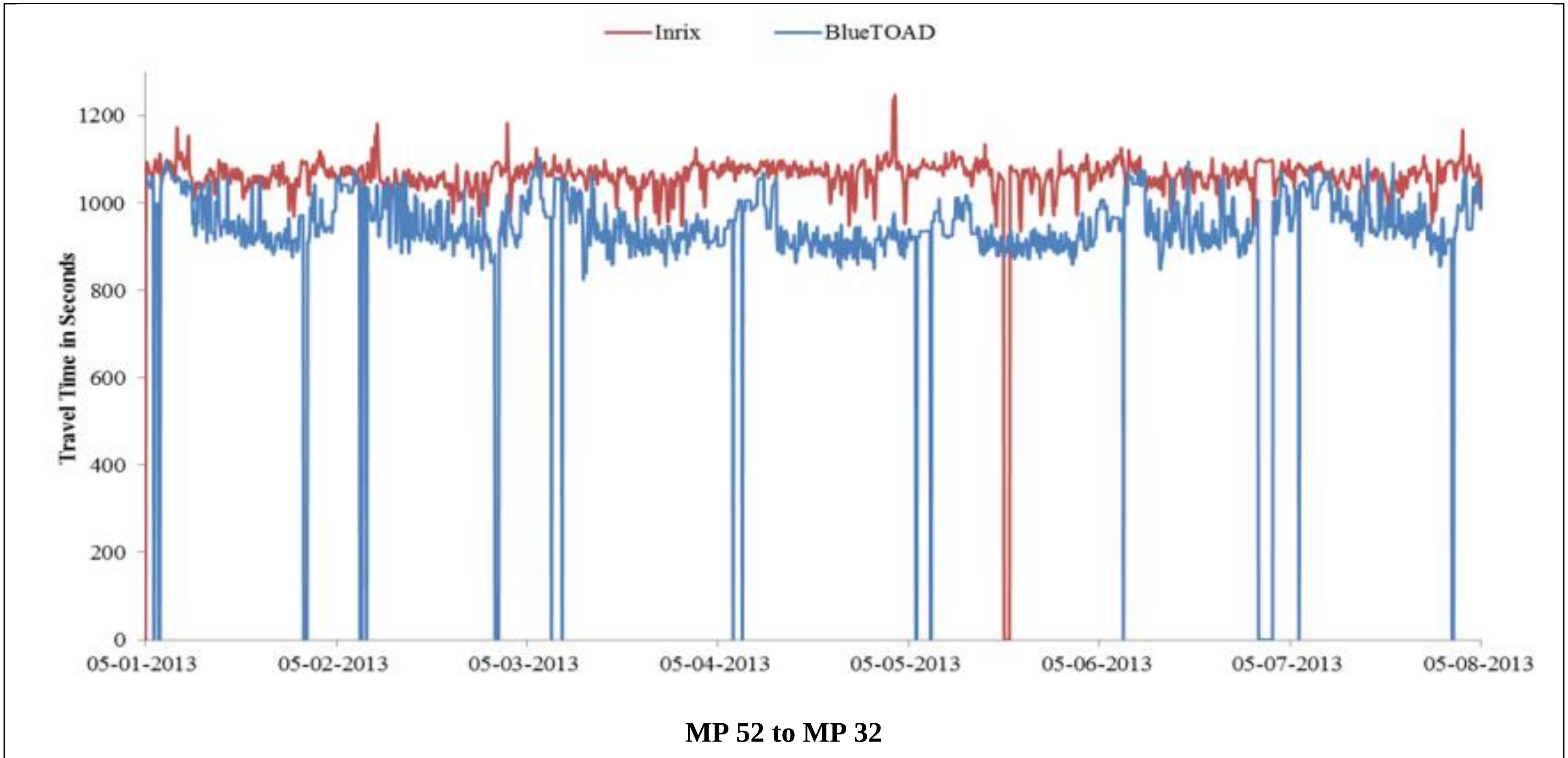
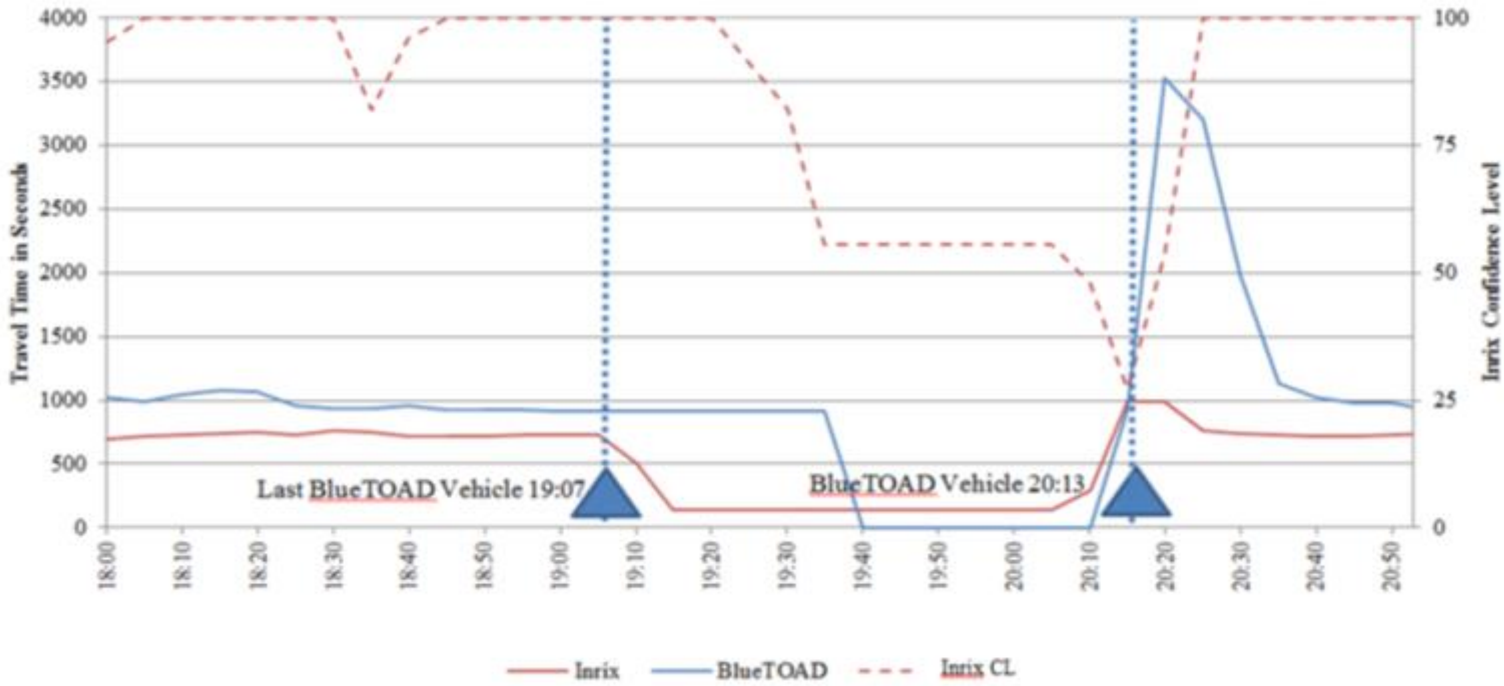


Figure 4.22 Travel times on I-90 from the summit (MP 52) to North Bend (MP 32) for May 1st, 2013 through May 8th, 2013

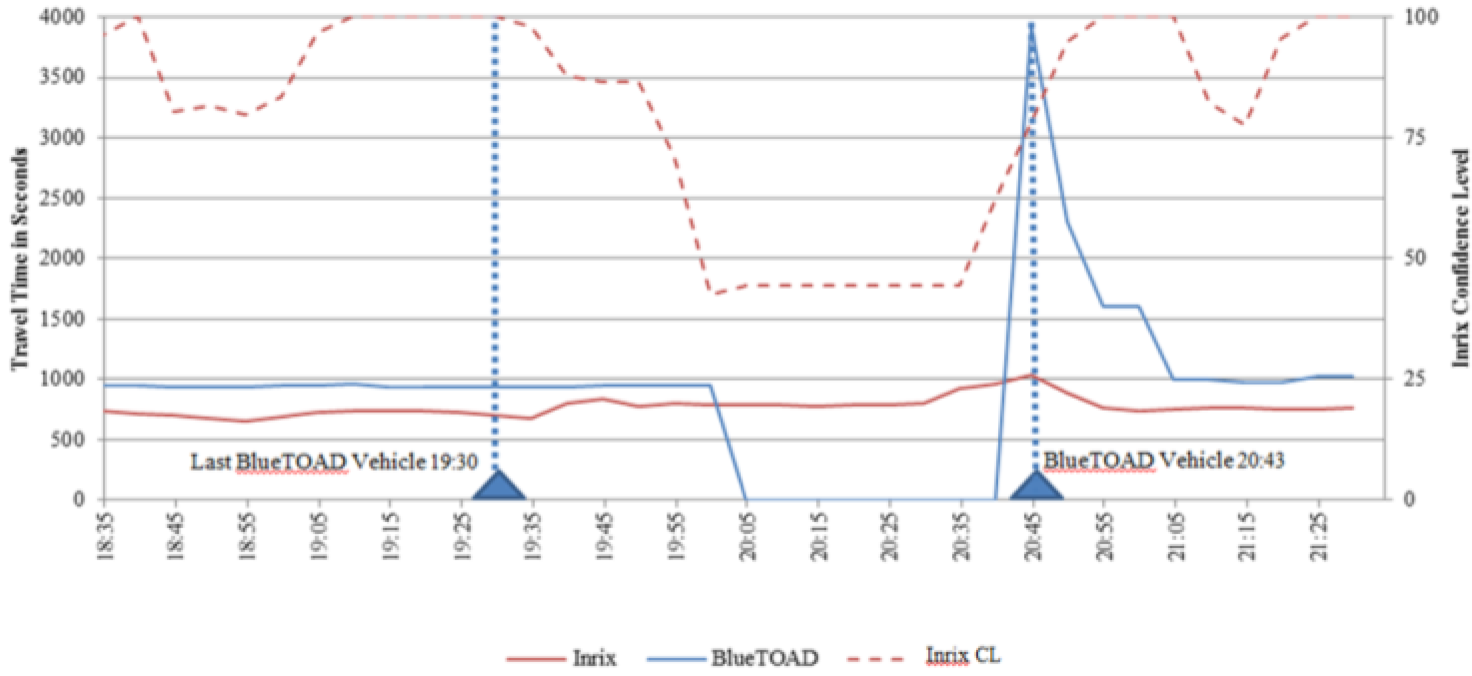
Figure 4.22 shows the travel time data for Inrix and BlueTOAD from milepost 52 to milepost 32. This time it appears that BlueTOAD is underestimating the travel time. The 20 mile segment should take 1200 seconds at 60 mph. Considering that this segment is downhill from the Snoqualmie Pass summit it is reasonable to assume that speeds may be higher than expected by the speed limit. However, the BlueTOAD travel time corresponds to a speed near 75 mph (which is quite possible on this section of I-90). There may be differences in vehicle populations detected, with a bias towards commercial vehicles for Inrix and cars for BlueTOAD.



MP 70 to MP 52 Closure During Blasting May 2nd, 2013

Figure 4.23 May 2nd closure of I-90 and sensor response

Figure 4.23 shows a detailed view of the data for May 2nd, 2013 on I-90. The vertical blue dotted lines indicate the start and end of the closure. The blue triangles show the times of the last and first detected vehicles by BlueTOAD and the red dashed line indicates Inrix's average confidence value for the data. In this case the Inrix travel time responds immediately, but actually indicates a faster travel time than during free flow. The BlueTOAD data shows a travel time for the segment for 30 minutes before ceasing to report data until detecting the next vehicle. Of note is that the BlueTOAD data reflects a reasonable travel time upon resumption of traffic flow and Inrix's travel time quickly returns to normal.



MP 70 to MP 52 Closure During Blasting May 15th, 2013

Figure 4.24 May 15th closure of I-90 and sensor responses

Figure 4.24 shows a similar event on May 15th, 2013. The vertical blue dotted lines indicate the start and end of the closure. The blue triangles show the times of the last and first detected vehicles by BlueTOAD and the red dashed line indicates Inrix's average confidence value for the data. This time the Inrix data does not respond to the closure, but the confidence level drops dramatically during the interval. Note that the confidence level shown in this figure is an average across multiple segments. Individual segments have zero or near zero confidence during the closure.

4.6 Data Manipulation and Sensor Evaluation Conclusions

One of the major tasks of this project was collecting and manipulating the data from each of the vendors. Each vendor uses different data formats, algorithms and frequently, technologies making the task of collecting and organizing the data one that bears closer inspection. Collecting and organizing data from an individual vendor is not an overly daunting task. Coordinating data from four vendors and the WSDOT with seven distinct systems each generating multiple datasets is a significant resource investment.

The major points of note in the data collection for this project are ease of data collection, completeness of data, ease of mapping to existing data structures and consistency of availability. Each vendor has a different means of distributing data, typically web based, though the WSDOT ALPR and loop data and Inrix data came through email and network connections. The Sensys, BlueTOAD and BlipTrack data all came through websites of differing utility.

Over the course of the project several changes were made to the vendor websites. Specific issues encountered during the project were limitations in length of time, number of sensors and speed of download. Initially, the Sensys website was a major limitation with small data download limits requiring significant manual effort to collect all of the project data. The BlueTOAD and BlipTrack websites were not as labor intensive but still required significant effort to collect and collate all of the desired data.

Mapping the data collected to existing data structures; in this case, the data and sensor placement of the ALPR system on SR 522 and the milepost/exit pattern for I-90 was trivial in some cases and more difficult in others. For SR 522 WB, the sensor sites were chosen to match existing westbound ALPR locations, making the matchup between each set of data easy. Eastbound SR 522 has a different ALPR setup in that there is no ALPR at the SR-104 intersection for eastbound traffic. The nearest ALPR for eastbound traffic is located 0.2 miles west at the Beach Drive NE intersection. This makes a direct mapping of sensors to eastbound

ALPR data impossible. Incidentally, the ALPR data for eastbound experienced a data collection failure during the analysis period, precluding an analysis in any case.

Inrix data has been the major source of issues mapping data to existing data structures. Inrix data is keyed to a different base mapping system than the other systems and the ALPR data. Inrix data uses TMC codes to identify roadway segments in a system developed for GPS systems instead of the route and milepost or arbitrary sensor number/placement data systems used by the other systems. Where Inrix TMC segments do not exactly map to existing segments; its travel time will be over or underestimated compared to the other systems as seen in the SR 522 analysis in particular. Another consequence of this difference in mapping is that an analysis segment composed of more than one Inrix TMC segments will need to reconcile potentially very different travel times on an individual TMC segment and normal travel times on others. Specifically, this occurs when delay or stoppage is incurred. For example at an intersection or blockage on a freeway, an individual TMC segment may report a high travel time (even exceeding the 5 minute reporting interval) while the surrounding TMC segments report normal travel times. The sum of travel time across TMC segments used in this research fails when significant stoppage or delay occurs, because the sum of travel time across the relevant TMC segments will include free flowing segments beyond the blockage as seen in the I-90 data analysis.

An additional point of interest that falls under data mapping is the inclusion of different data collected by each system and different smoothing algorithms. Each system includes time and travel time information in its basic data formats. BlueTOAD data includes its match rates in a separate file system at 15 minute time intervals instead of the 5 minute intervals used for the other data. Inrix data does not include a capture rate as such, but does have a confidence value as shown in the I-90 analysis. The remaining systems report their matches and travel times in the same files and data structures. The Sensys system has the most additional data associated with it. Specifically Sensys includes travel time measurements at 10% intervals, measured speeds and upstream and downstream volumes. For this research the 90% travel time was chosen to represent the Sensys travel time, as that was the value used by Sensys to represent travel times in their presentation to the lab. This is a conservative measure that can underestimate the accuracy of the

Sensys system. It should be noted that even with this potential handicap, the Sensys system proved to have acceptable levels of accuracy in several cases.

Data availability is a multifaceted problem. First, the data must be collected by the system in question. This includes all of the communications and storage endemic to collecting the data. The second aspect is that the data must be retrievable by the system. Finally, there are temporal availability considerations. These include considerations of delay between collection and accessibility of the data and how long the data is available after collection. In this project, immediate temporal availability has not been of primary concern, however it should be noted that the data delivery methods for data from the WSDOT and Inrix included delays between collection and availability.

To help readers get a better feel for the behavior of the various systems and to disseminate data the research team has developed a webpage as part of the Digital Roadway Interactive Visualization and Evaluation Network (DRIVE Net). DRIVE Net is a University of Washington Smart Transportation Applications and Research Lab (STAR Lab) data management and analysis tool developed to showcase research results. Figure 4.25 and Figure 4.26 show the I-90 and SR 522 data analysis interfaces. The webpage may be accessed at sensors.uwdrive.net.

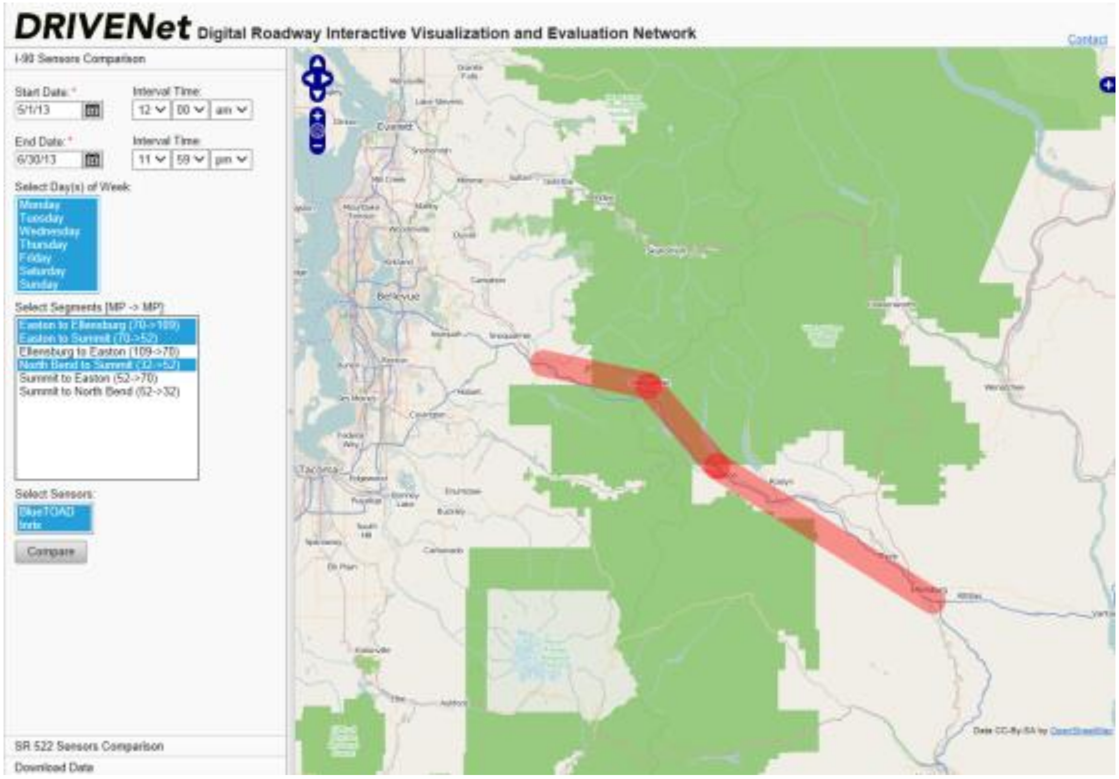


Figure 4.25 I-90 data analysis interface for sensors.uwdrive.net

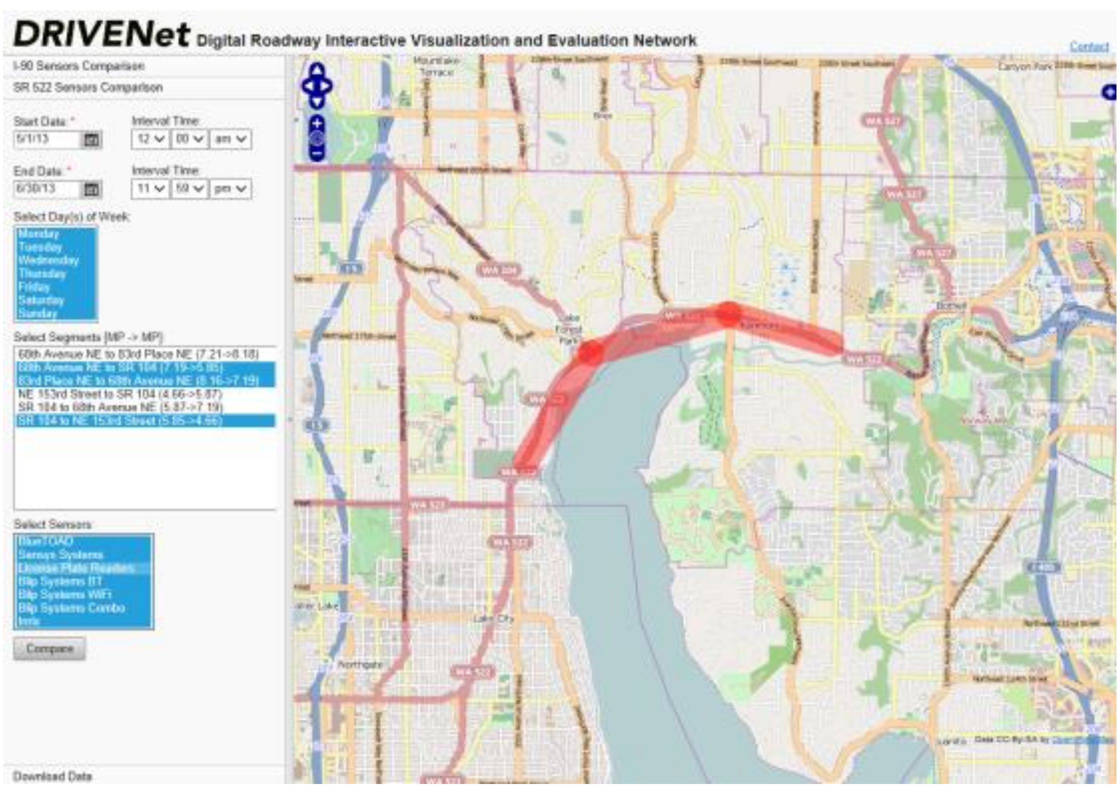


Figure 4.26 SR 522 data analysis interface for sensors.uwdrive.net

Chapter 5 Summary of the results and discussions

Note that high level conclusions are presented here. For detailed observations see the relevant chapters. Readers are encouraged to review Figure 1.1, Figure 4.1, Figure 4.9, Figure 4.10 and Figure 4.24 specifically. Also, remember that the relationship between accuracy of the information obtained by ATIS and the benefits for the users was determined for a case study in Los Angeles (see Figure 1.1). The researchers found that when accuracy drops below a critical point, users are better off not using the data provided by the ATIS and relying instead on experience with historical traffic patterns. One of the goals of this research was to provide decision makers with sufficient information to select an appropriate system for the corridor in question.

Travel time information is a valuable commodity for ITS and operations. Road users benefit from accurate travel time information that allows them to plan their trips. Accurate travel time information will also allow road users to avoid congestion and incidents, potentially reducing the severity of congestion caused by incidents and recurring congestion. Engineers can use travel time data to analyze the effectiveness of various changes to corridor operations, such as signal retiming and geometric changes.

This study focuses on two test corridors. The first test corridor is State Route 522 between the NE 153rd Street and 83rd Place NE intersections. This section of SR 522 is an urban arterial with frequent intersections. This corridor experiences heavy daily commuting traffic and has frequent incidents that can make travel times unpredictable. An automated license plate reader system has been in place on the SR 522 corridor for a number of years with three westbound segments in the study area, from 83rd Pl. NE to 68th Ave. NE, 68th Ave. NE to SR 104 and SR 104 to NE 153rd St. For this analysis, even though the ALPR system has different segments on eastbound SR 522, the analysis used the same segments for eastbound because every other system used the same segments eastbound and westbound.

The second test corridor is on I-90 from milepost 109 (Ellensburg, WA) to milepost 32 (North Bend, WA). This section of I-90 is a rural freeway from western Washington to eastern Washington over the Snoqualmie Pass whose summit is at milepost 52. There were no pre-existing travel time measurement systems on I-90 before this study. Segments on I-90 are described by mileposts 32, 52, 70 and 109.

The sensor systems deployed on SR 522 include the pre-existing ALPR system, a Sensys emplacement on westbound SR 522, the TrafficCast BlueTOAD system, Blip Systems BlipTrack sensors and a 3rd party feed from Inrix. The I-90 corridor was instrumented with the BlueTOAD system in addition to using the Inrix data feed. The ALPR system reads the license plates of vehicles passing the sensors and holds the license plate number in memory until the vehicle passes the next sensor location. The Bluetooth and WiFi sensors built into the BlueTOAD and BlipTrack systems function similarly by reading the MAC address of wireless electronic devices from location to location. The Sensys system reads the magnetic signature of passing vehicles and attempts to match vehicles based on signature and platoon organization. The Inrix data is based on cellphone and GPS data from its users.

Collecting the data for this project has been a significant expenditure of effort. Collecting data from the WSDOT, Inrix, Sensys, TrafficCast, and Blip Systems has required the research team to visit multiple websites and databases. Collating and organizing data with different temporal resolutions, included data and segments required the research team to find common intervals and expend significant effort just to make the different data sets comparable.

There are two important factors to consider in analyzing the sensor results. The first is the accuracy of the reported travel time. To address this each sensors' data is compared against the ALPR system on westbound SR 522. The ALPR system has been previously evaluated and deemed accurate enough to serve as the ground truth for this study. The lack of ALPR data or other similarly dependable travel time data source limits the research team's ability to analyze eastbound SR 522 and the I-90 corridor. A number of accuracy measures have chosen for this analysis to give readers more insight into the frequency, severity and directionality of errors.

The westbound SR 522 analysis found that the accuracy of the systems varied by segment with every system reporting their least accurate travel times on the 83rd Pl. NE to 68th Ave.NE segment. The daily analysis revealed that the systems experienced error spikes during the morning peak period on all segments. With the exception of the Inrix data, all systems generally reported satisfactory results, with the Bluetooth and WiFi based systems staying below the 25% error threshold except during overnight hours and some spikes in the peak periods. It should be noted that the Sensys travel time used was the 90th percentile travel time, where the other systems reported mean or median values, yet still the Sensys system posted acceptable accuracy in most cases. The Sensys travel time error may be reduced by selecting another one of the ten provided travel time values.

The systems did have some notable accuracy limitations. Specifically, the BlueTOAD system can be less reliable overnight when sampling is low. The Inrix system was generally the least responsive to traffic changes and tended to have systematically high or low travel times, probably the results of conservative free flow travel time estimation.

The I-90 and eastbound SR 522 analysis of travel time focused on more qualitative aspects of system performance. For I-90, the research team was looking for reasonable travel times and daily traffic patterns as well as response to known road closure events. The eastbound SR 522 results met expectations based on the westbound analysis, with most patterns repeating, including the systematic over or underestimation of travel time by Inrix. The I-90 analysis noted that both systems were able to respond to daily patterns; however, Inrix and BlueTOAD reported significantly different results on some segments. When the road closure time periods were examined, both systems had their flaws. The BlueTOAD system continued to report a travel time for 30 minutes after the road closure and the Inrix data either failed to react significantly to the closure or reported impossible travel times. Both systems include specific data that can be used to identify when such event occur.

The second important factor to consider in the sensor analysis is the sample size used to calculate the travel time. If the sample size is too small, the travel time may not be representative. Sample size is affected by several factors, including traffic volume and mobile device penetration rates (for Bluetooth and WiFi sensors). For westbound SR 522 the ALPR and Sensys systems have comparable absolute detection rates with between 25% and 50% of traffic being detected, depending on time of day and location. The Bluetooth and WiFi systems detect significantly fewer vehicles. BlueTOAD captured about 6% of the volume captured by the ALPR system for an absolute capture rate near 2% of total traffic The BlipTrack system captured roughly double the number of Bluetooth readings and two and a half times as many on WiFi. The BlipTrack sensor also reports combined totals for its Bluetooth and WiFi sensors, which pushes the combine BlipTrack system to approximately 25% of the ALPR capture rate. Because of the nature of the Inrix data, there is no capture rate to analyze.

The collection of sensors assembled for this study is impressive. By setting up so many sensors on the same corridor and having reliable ground truth data in the form of an established ALPR system, the WSDOT has made it possible to perform an in-depth analysis of the different systems. This work shows that sensors of different types and complexities can accomplish the goal of measuring travel time.

Ultimately, each system in the analysis has different strengths and weaknesses that should be considered in addition to their accuracy and sample rates. Some systems can provide additional data; others trade accuracy and coverage for cost or portability. Ultimately, engineers will need to weigh their requirements for accuracy and sample rates against the other engineering constraints imposed on their system. For example, the BlueTOAD units installed on SR 522 and I-90 are solar powered and use cellular data networks, reducing infrastructure and deployment costs. The BlipTrack units have higher sampling rates and marginal accuracy superiority in exchange for power requirements. The Inrix data does not require any DOT infrastructure and has wide availability. ALPR units have high accuracy and a comparatively high installation cost. The Sensys system has perhaps the most complicated set of tradeoffs. Sensys magnetometers can be used as replacements for loop detectors in intersection operations, making the marginal costs of adding Sensys re-identification lower at some intersections than others.

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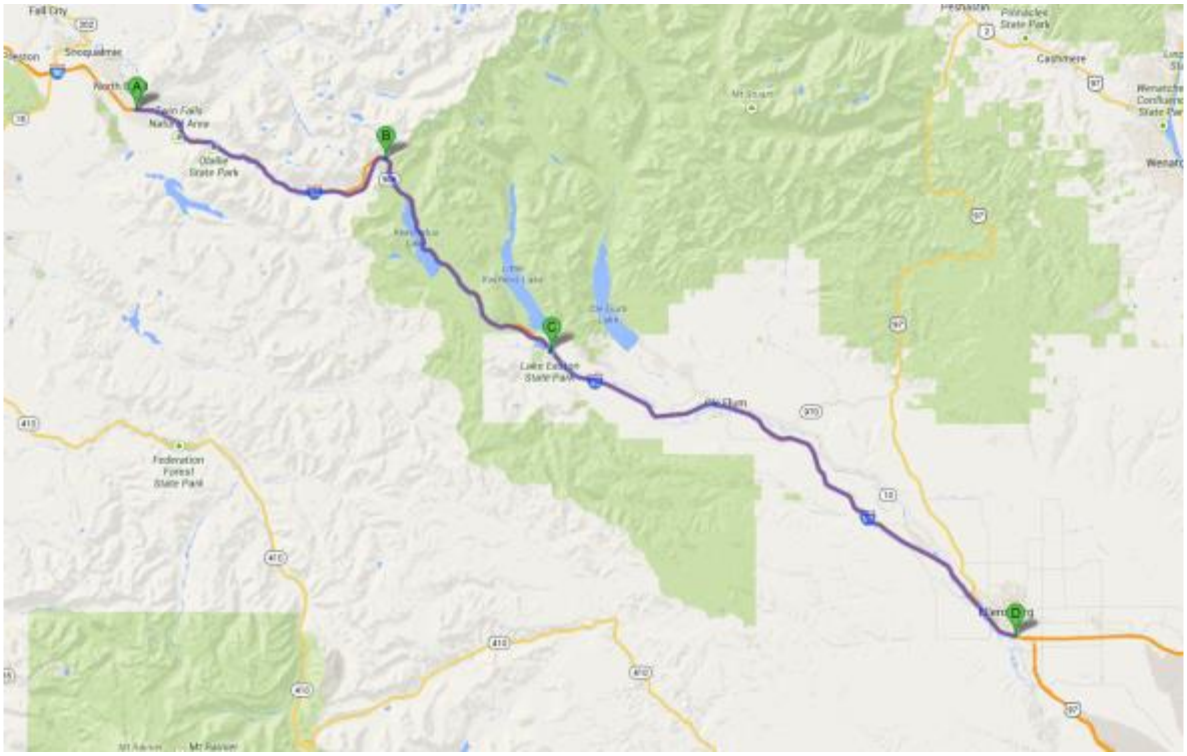
Appendix A: SR 522 and I-90 Corridor Details



I-90 Study Route

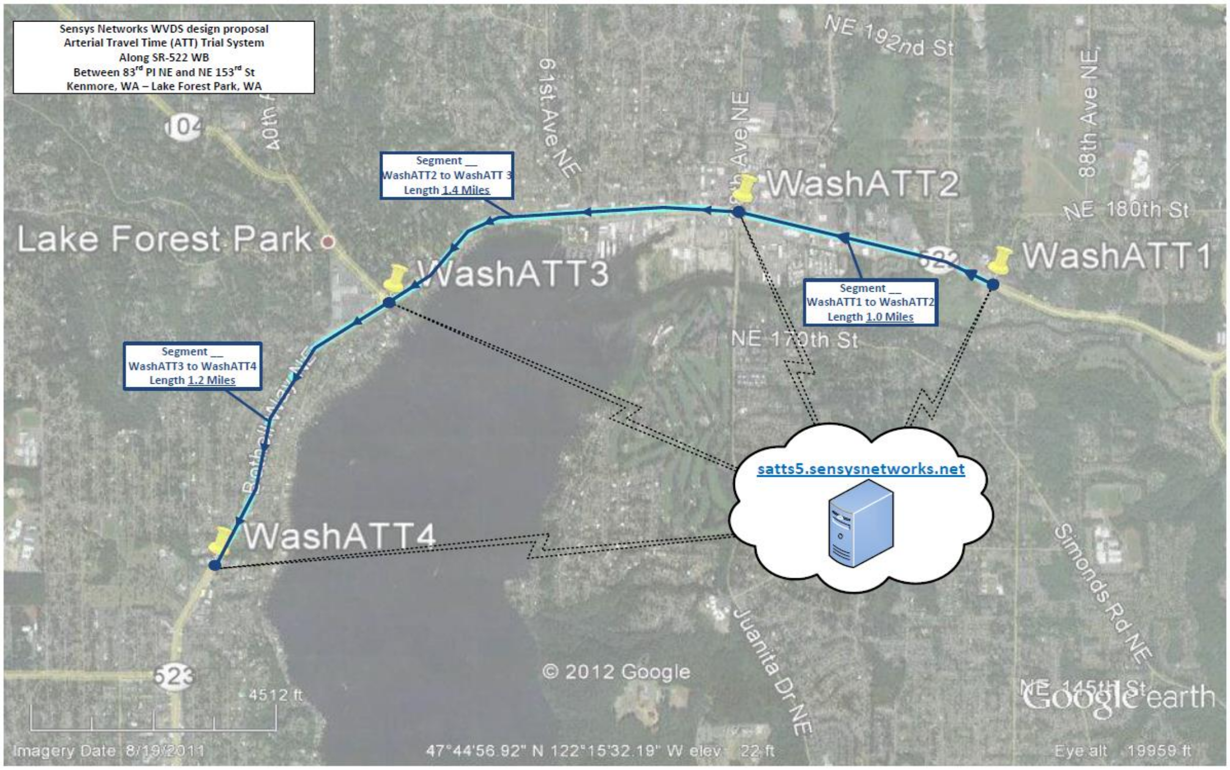
Site A, Milepost 32, North Bend, WA (BlueTOAD Circled)

Site B, Milepost 52, Snoqualmie Pass Summit (BlueTOAD Circled)

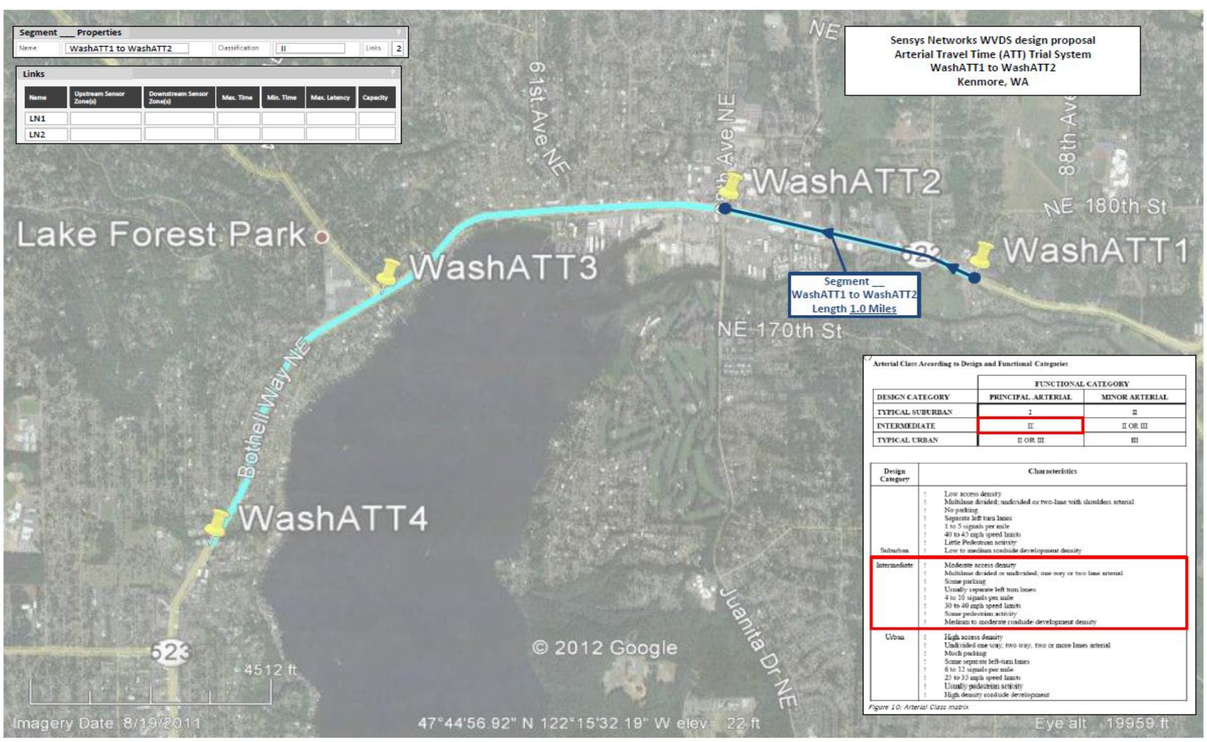
Site C, Milepost 70, Easton, WA

Site D, Milepost 109, Ellensburg, WA (BlueTOAD Circled)

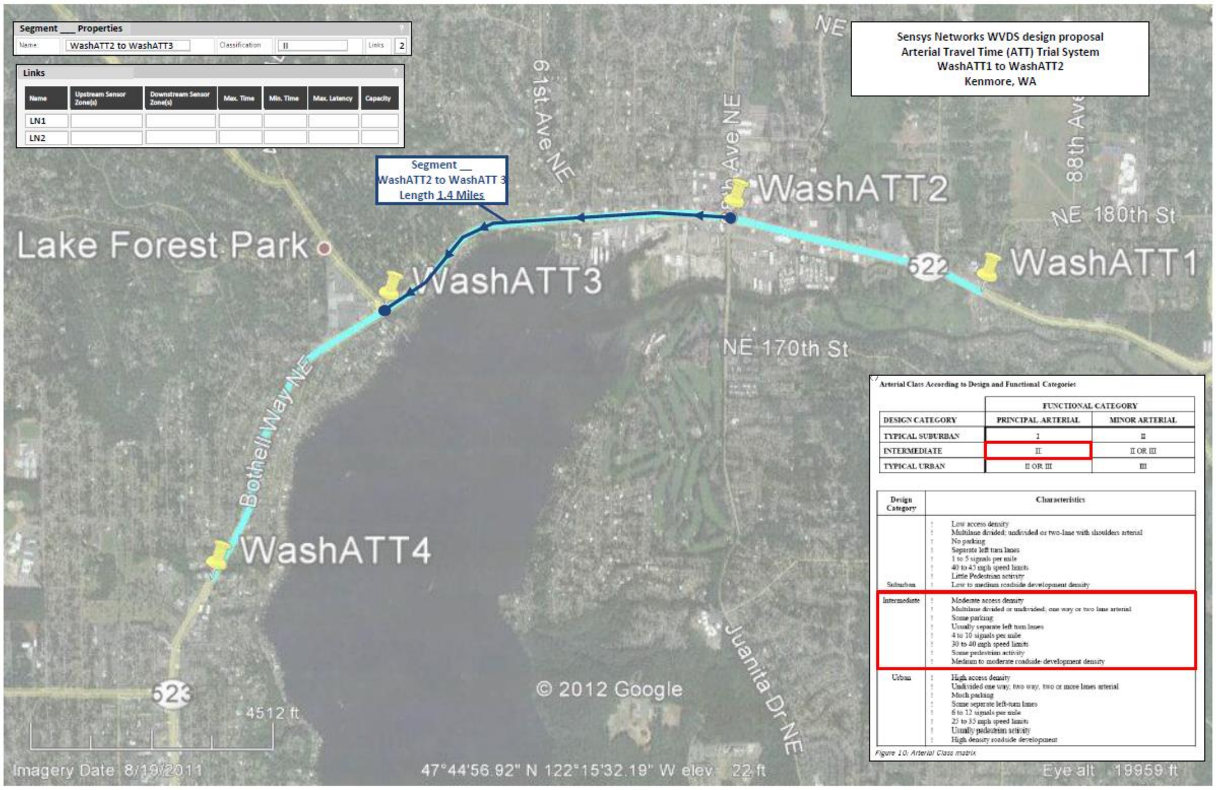
Appendix B: Architecture of Sensys Technology



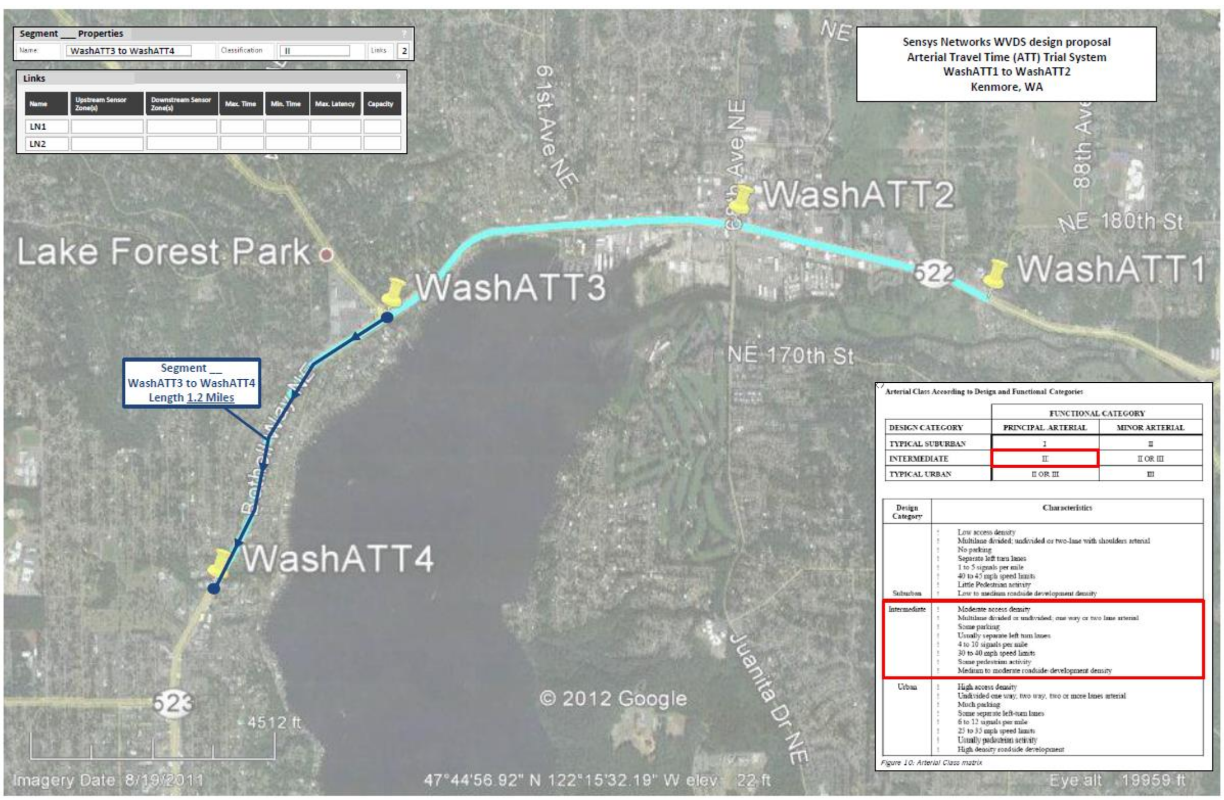
Architecture of Sensys on SR 522



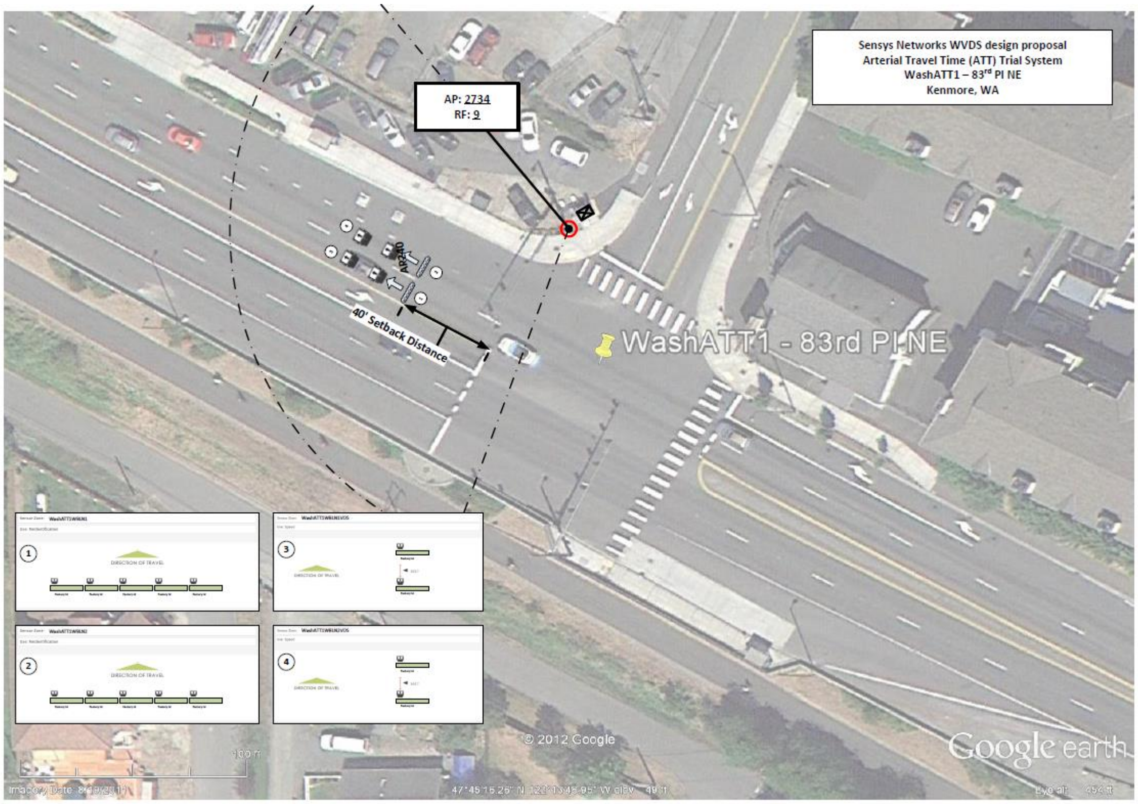
Architecture of Sensys sensors on 83rd Pl. NE to 68th Ave. NE



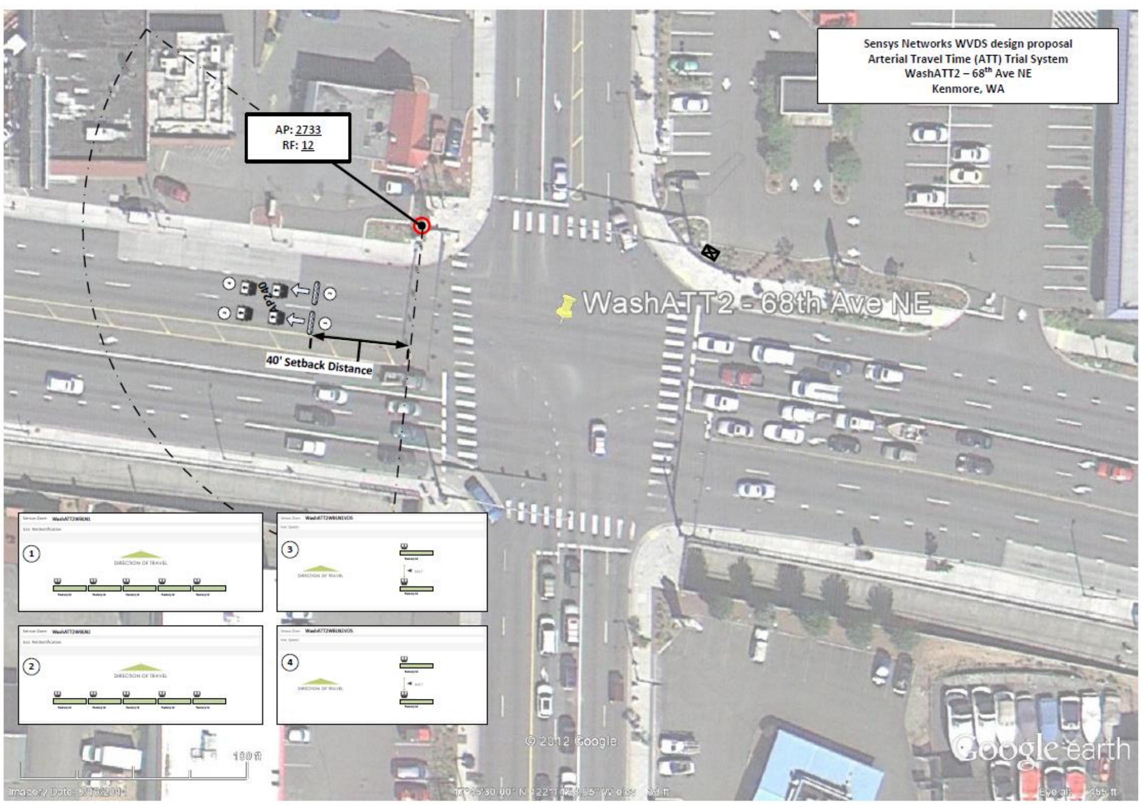
Architecture of Sensys sensors on 68th Ave. NE to SR 104



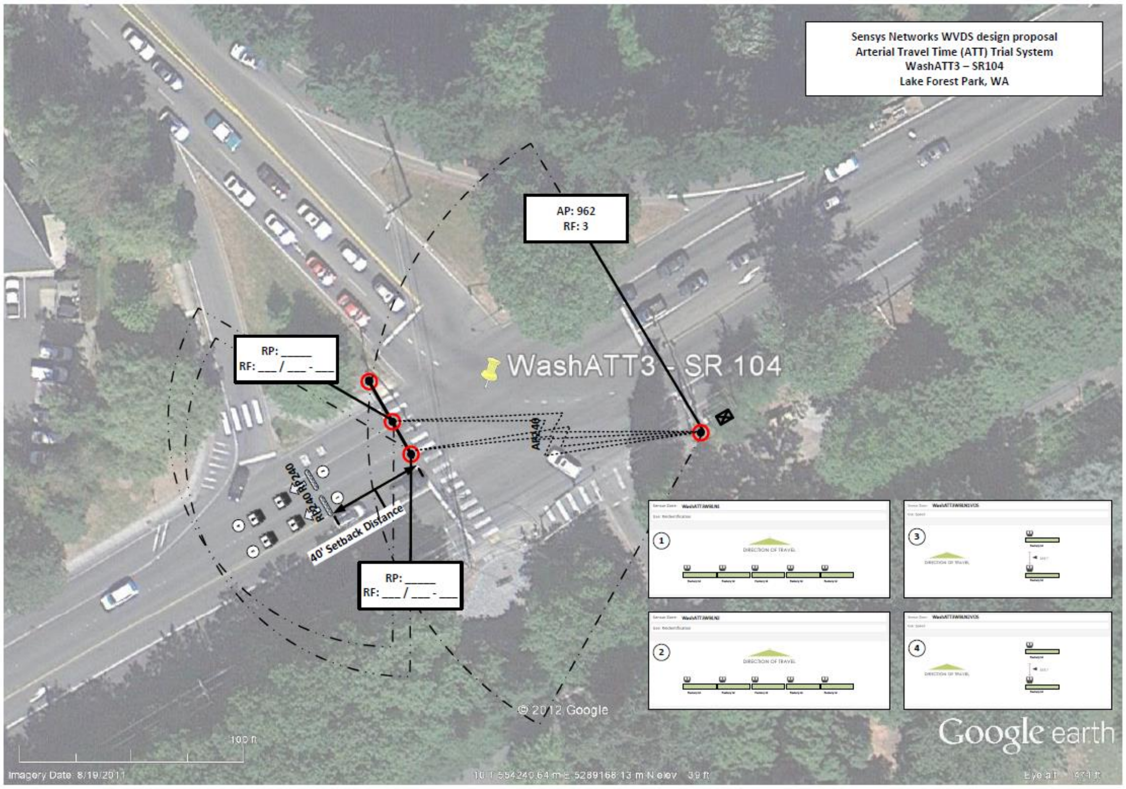
Architecture of Sensys sensors on SR 104 to NE 153rd St.



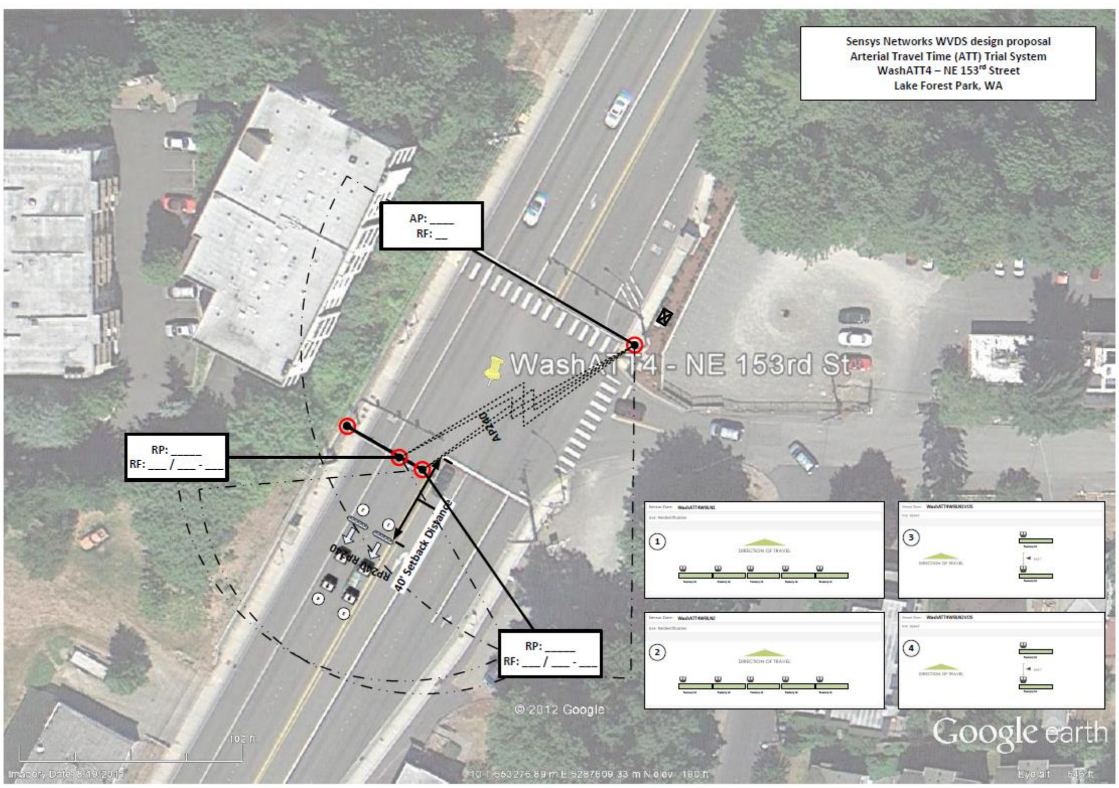
Location of Sensys sensors on 83rd Pl. NE Intersection



Location of Sensys sensors on 68th Ave. NE Intersection



Location of Sensys sensors on SR 104 Intersection



Location of Sensys sensors on 153rd St. Intersection