Oklahoma Department of Transportation
200 NE 21st Street, Oklahoma City, OK 73105-3204

FINAL REPORT ~ FHWA-OK-19-04

VEHICLE CLASSIFICATION AND BLUETOOTH MACS FOR ORIGIN-DESTINATION MEASUREMENTS

Mohamed Afify, Graduate student
Samuel Chan, Graduate student
Munzer Alsallakh, Graduate student
Hazem Refai, Ph.D.

School of Electrical and Computer Engineering (ECE)
The University of Oklahoma
Norman, Oklahoma

September 2019

OKLAHOMA Transportation

The Oklahoma Department of Transportation (ODOT) ensures that no person or groups of persons shall, on the grounds of race, color, sex, religion, national origin, age, disability, retaliation or genetic information, be excluded from participation in, be denied the benefits of, or be otherwise subjected to discrimination under any and all programs, services, or activities administered by ODOT, its recipients, sub-recipients, and contractors. To request an accommodation please contact the ADA Coordinator at 405-521-4140 or the Oklahoma Relay Service at 1-800-722-0353. If you have any ADA or Title VI questions, please email ODOT-ada-titlevi@odot.org.

VEHICLE CLASSIFICATION AND BLUETOOTH MACS FOR ORIGIN-DESTINATION MEASUREMENTS

FINAL REPORT ~ FHWA-OK-19-04
ODOT SP&R ITEM NUMBER 2282

Submitted to:
Office of Research and Implementation
Oklahoma Department of Transportation

Submitted by:

Mohamed Afify, Graduate student
Samuel Chan, Graduate student
Munzer Alsallakh, Graduate student
Hazem Refai, Ph.D.
School of Electrical and Computer Engineering (ECE)
The University of Oklahoma

OKLAHOMA
Transportation

September 2019

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO. FHWA-OK-19-04	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Vehicle Classification and Bluetooth MACs for origin destination measurements		5. REPORT DATE Sept. 15, 2019
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Mohamed Afify, Samuel Chan, Munzer Alsallakh, Hazem Refai, Ph.D. .		8. PERFORMING ORGANIZATION REPORT The University of Oklahoma 202 W. Boyd St., Room 104 Norman, OK. 73019-0631
9. PERFORMING ORGANIZATION NAME AND ADDRESS School of Electrical and Computer Engineering, The University of Oklahoma		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO. ODOT SPR Item Number 2282
12. SPONSORING AGENCY NAME AND ADDRESS Oklahoma Department of Transportation Office of Research and Implementation 200 N.E. 21st Street, Room G18 Oklahoma City, OK 73105		13. TYPE OF REPORT AND PERIOD COVERED Final Report Sept. 2017 – Sept. 2019
		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

The U.S. Department of Transportation (USDOT) is actively researching intelligent transportation systems (ITS) aimed at reducing traffic incidents, improving safety, and gathering real-time travel time (TT) information. An important aspect of the process is specifying the characteristics of traffic schemes, which include vehicle classification, origin/destination (O/D), TT, and vehicle occupancy, in addition to other factors. The project proposes the development of an Internet of Things (IoT) systems that integrates a complex system using Bluetooth (BT) sniffing and vehicle classification for monitoring route choices per vehicle class. The system consists of a BT identification unit deployed at an Oklahoma port of entry, along with a number of BT identification stations deployed at various locations across Oklahoma's roadways. As vehicles travel over the magnetometer nodes, the changes in magnetic field are measured to identify vehicle length and speed. Algorithms were developed to associate detected BT addresses to the corresponding vehicles with exceptional accuracy. Research demonstrated that active monitoring of route choice and TT per vehicle class can be achieved using magnetometer nodes and BT stations.

17. KEY WORDS temporary traffic monitoring system, Intelligent Transportation System, BTA, Origin Destination	18. DISTRIBUTION STATEMENT No restrictions. This publication is available from the Office of Research and Implementation, Oklahoma DOT.		
19. SECURITY CLASSIF. (OF THIS REPORT) Unclassified	20. SECURITY CLASSIF. (OF THIS PAGE) Unclassified	21. NO. OF PAGES 90	22. PRICE N/A

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Contents

List of Figures

List of Tables

1. Abstract

The U.S. Department of Transportation (USDOT) is actively researching intelligent transportation systems (ITS) aimed at reducing traffic incidents, improving safety, and gathering real-time travel time (TT) information. An important aspect of the process is specifying the characteristics of traffic schemes, which include vehicle classification, origin/destination (O/D), TT, and vehicle occupancy, in addition to other factors. The project proposes the development of an Internet of Things (IoT) systems that integrates a complex system using Bluetooth (BT) sniffing and vehicle classification for monitoring route choices per vehicle class. The system consists of a BT identification unit deployed at an Oklahoma port of entry, along with a number of BT identification stations deployed at various locations across Oklahoma's roadways. As vehicles travel over the magnetometer nodes, the changes in magnetic field are measured to identify vehicle length and speed. At the same time, BT cellphone devices or vehicle on-board audio systems are detected. Algorithms were developed to associate detected BT addresses to the corresponding vehicles with exceptional accuracy. Research demonstrated that active monitoring of route choice and TT per vehicle class can be achieved using magnetometer nodes and BT stations.

2. Literature Review

The primary focus of the initial stage of this project was the literature review, which will, in turn, affect the methodology and research plan. Additionally, careful attention was devoted to selecting an appropriate antenna to mount to the data collecting system. The comprehensive literature review aided researchers in gaining an accurate overview of current technologies used to capture BTA (BT addresses) and their use in the transportation field. Literature was also accessed about current algorithms used to preprocess, analyze, and make decisions based on collected BTA data. Gathered information about IoT systems showed that they are now being used to resolve several issues challenging transportation systems. In fact, advancements in IoT technology have played a major factor in changing the volume, quality, and cost basis of collected data. Most aspects of current transportation systems (e.g. traffic lights, vehicles, roads) are now equipped with at least one IoT node for sensing the environment, analyzing the collected data, and, sometimes, taking actions. IoT is on course to reshape the world's transportation systems.

The research objectives of this proposal are four-fold. The study includes Bluetooth (BT)/class prototype design, BT-vehicle assignment algorithm development, system deployment, and accuracy analysis of detected BT-vehicle assignments.

3. Objectives

The *first objective* of this project aims to integrate a BT identification sniffer with the OU-designed, magnetometer-based vehicle detector and classifier for monitoring origin/destination (O/D) and travel times (TT) per vehicle class. Various hardware and software designs, including wireless technologies, antenna types, number of antennas, RF multiplexers, and time synchronization schemes, will be investigated with the goal of developing an inexpensive, flexible, modular embedded system that can be rapidly prototyped and deployed for collecting O/D measurements per vehicle class. The developed system will include at least two directional antennas for highway segmentation and will have the ability to communicate with multiple road- installed vehicle sensors for vehicle classification.

The *second objective* aims to develop algorithms to assign detected BT IDs to their corresponding vehicles. Assignment errors occur when a detected BT ID is assigned to the wrong vehicle class. This is an extremely challenging activity given many factors that influence BT-vehicle assignment accuracy. One factor is that a BT scanner can detect vehicle IDs located as far as 100 meters away from the scanning station, while vehicle sensors detect vehicle presence within only a few meters. Also, vehicle BT IDs located within the scanning coverage will be received irrespective of traveling lane or direction. Hence, BT scanners don't distinguish BT IDs of vehicles traveling a specific direction. Another factor is that a BT transmitter may not be functional or available for every passing vehicle, while vehicle sensors installed in every lane will detect and classify every passing vehicle. Yet another factor is that not all BT transmitters in every vehicle are synchronized. Therefore, BT signals are received by the scanner in random order instead of being related to coverage entry time. Various schemes, including sensor layout, highway segmentation, and varying coverage sectors, among others, will be investigated during the execution of this project.

The *third objective* aims to deploy the prototyped system in close collaboration with ODOT. The research team will conduct a field study to investigate optimal BT/class station configurations, including road sensor placements, number of antennas and highway segmentation, antenna polarization, gain, and directionality. Each of these has a significant impact on coverage sensing, hence, quality of collected BT data.

The *fourth objective* aims to develop schemes for investigating the accuracy of paired BT-vehicle assignments and designing techniques to improve accuracy. One simple technique is deploying a duplicate BT/class station to confirm assignments made by the first station detecting a vehicle. Another technique is strategically placing BT-only stations to measure vehicle TT and speed values to segregate large, slower trucks from faster small vehicles.

4. Equipment Testing

4-1. Antenna Configuration

Antenna selection for BTA capture is crucial for successfully detecting vehicles, as this equipment is an important factor for detection probability. Directional antennas enable

Ubertooth to capture BTA of vehicles passing through the detection zone at each site, and then report this information to the Roadside Embedded Extensible Computing Equipment (REECE). Accordingly, careful attention was given to selecting an appropriate antenna to mount to the system and collect data. Collected data effectiveness is impacted by antenna selection, as is the way in which iVCC sensors are assigned to road segments. Because the proposed system will utilize directional antennas, rather than omnidirectional antennas, several characteristics had to be carefully studied. Potential use of the several antennas was investigated (See Table 1).

Table 1 Characteristics of Directional Antennas

Company	L-com	L-com	L-com	Afar
3 dB angle (horizontal beam-width)	5.3 deg	6.5 deg	8 deg	8 deg
Type	Grid	Grid	Grid	Grad
Gain	30 dBi	26.5 dBi	24 dBi	24 dBi
Dimensions	59"Dia.	47.2" x 35.43"	39.5" x 23.5"	42" x 24"
3 dB angle (horizontal beam-width)	12 deg	21 deg	30 deg	45 deg
Type	Grid	Flat Panel	Enclosed Yagi	Enclosed Yagi
Gain	20 dBi	18 dBi	14.5 dBi	12 dBi

Table 2. Characteristics of Omnidirectional Antennas

Company	L-com
3 dB angle (horizontal beam-width)	N/A
Type	Omni
Gain	5 dBi
Dimensions	10" x 3" Ø

Afar's 21-degree 12-degree, and 30-degree antennas, as well as L-com's omnidirectional antenna were selected due to their compact size, relatively small beam-width, and high gain.

4-2. Selected Antennas’ Specification

Table 3. Specifications of Selected Antennas

Company	L-com	Afar	L-com	L-com
Type	Grid	Flat Panel	Enclosed Yagi	Omni
Frequency range	2.4 - 2.5 GHz	2.4 - 2.5 GHz	2.4 - 2.5 GHz	2.4 - 2.5 GHz
Gain	20 dBi	18 dBi	14.5 dBi	5 dBi
horizontal beam-width	12 deg	21 deg	30 deg	N/A
Vertical Beam-width	17 deg	21 deg	30 deg	N/A
VSWR	< 1:1.5	1:1.5	< 1:1.5	< 1:1.5
Impedance	50 ohms	50 ohms	50 ohms	50 ohms
Dimensions	15.7" x 23.6"	12.4" x 12.4" x 1"	18.2" x 3.0" Ø	10" x 3" Ø
Weight	3.3 lbs.	3.3 lbs.	1.8 lbs.	0.5 lbs.
Wind loading	100 mph->20 lbs. 120mph->31 lbs.	100 mph->34.7lbs. 125 mph ->54.2lbs.	100 mph->11.4 lbs. 125mph->17.8 lbs.	> 200mph
Max input power	100 watts	100 watts	50 watts	100 watts

4-3. Radio Frequency Antenna Gain Patterns

Antenna Gain Pattern (AGP) is important antenna information, as it characterizes antenna gain with respect to directionality and provides information regarding effects of directional antenna sending and receiving angles. Figures 1 through 4 show AGPs for selected antennas.

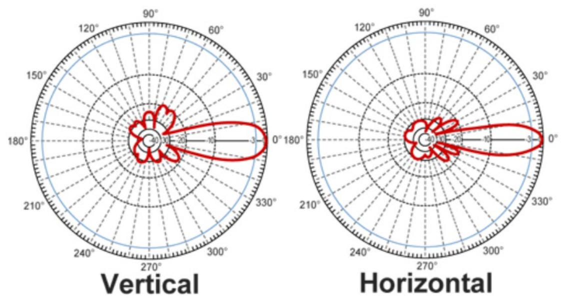


Figure 1. 12-degree antenna AGP.

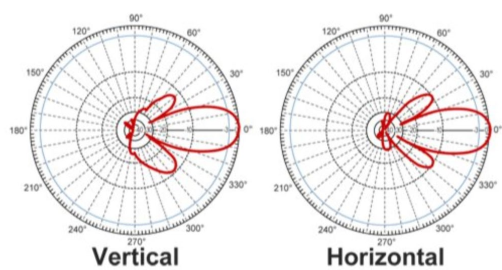


Figure 2. 21-degree antenna AGP.

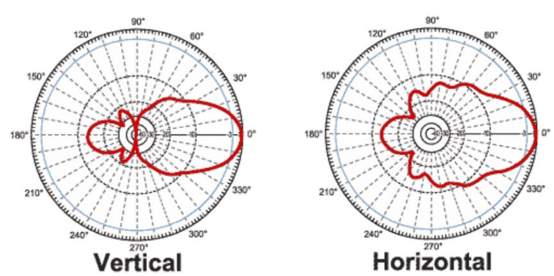


Figure 3. 30-degree antenna AGP.

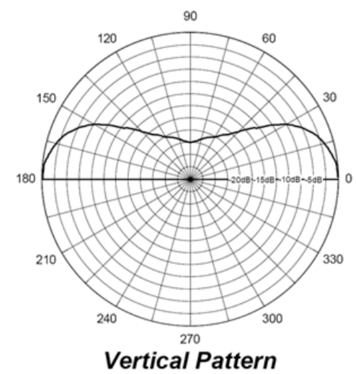


Figure 4. Omnidirectional antenna AGP.

4-4. Commercial BTA Sniffer Integration

Validating the proposed system's data collection is vital for the success of both the O/D study and the correct assignment of vehicle BTA pairs. Hence, a second method for sniffing BTA must be implemented. The research team found that most commercial BTA detection systems used in the transportation field calculate TT via Bluetooth sniffing. [Iteris Vantage Velocity] was chosen for comparison based on the manufacturer's long history and industry reputation for BT TT estimations and smart cities solutions.
The Iteris Vantage Velocity field unit was placed inside the roadside traffic cabinets for sniffing both Wi-Fi and BT addresses within the antenna's field of view. The unit is a Linux box equipped with several peripherals, including USB, Ethernet, and a serial port. During detection, received BTA are transmitted to a host software residing inside the Linux box. BTA can also be sent to a server, using UDP (User Datagram Protocol) messages in prespecified intervals.

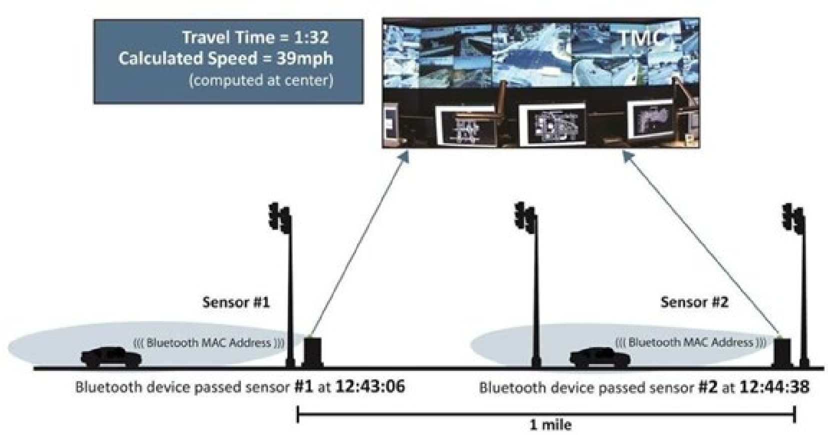


Figure 5. Vantage velocity traffic monitoring concept.

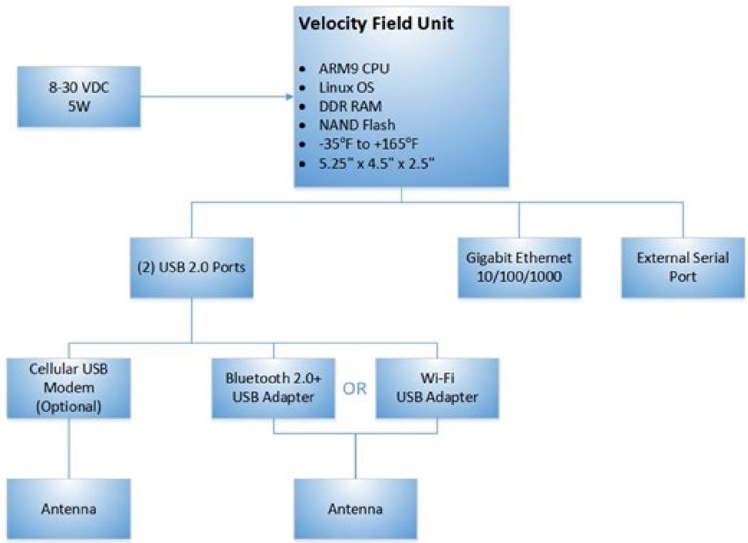


Figure 6. Velocity field unit overview

4-5. Data Collection

Several on-campus tests were conducted to determine data collection accuracy and to address issues prior to highway deployment. Tests were conducted on several days, each focusing on a specific issue. An antenna, Ubertooth, BeagleBone green, SD card, and portable charger were utilized for data collection. Data was collected locally in the SD card, with either a tablet or a computer leveraged to wirelessly access both the board and SD card. Notably, a cellular communication modem could be added for future IoT implementation.

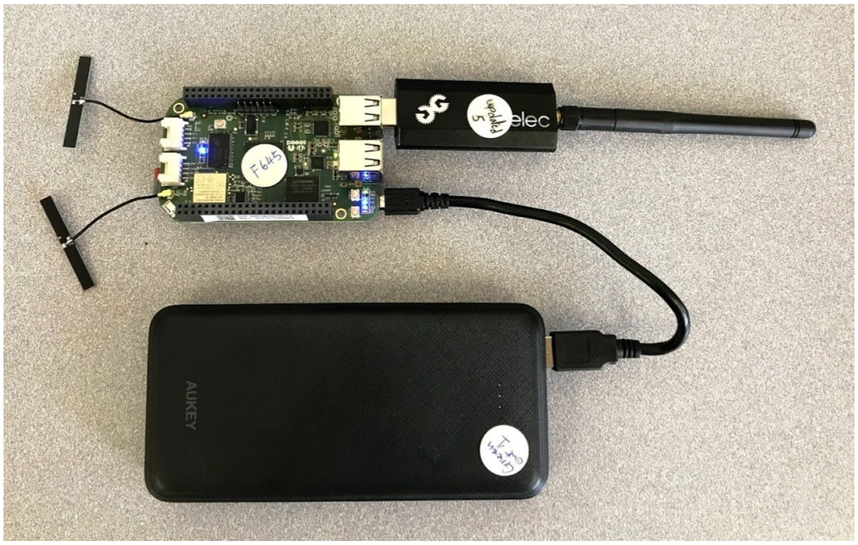


Figure 7. Date collector with Ubertooth, demo antenna, BeagleBone green, and a portable charger.

5. Development Testing

Many experiments were established on campus to test equipment performance detailed in Section 4. The antennas were tested to verify which had the highest capability of collecting data from random vehicles on the campus. Testing also improved sniffer performance.

5-1 On-campus Roadside Test

Several setups were designed for comparing antenna data. The first included a pair of 21-degree antennas pointing to the side and to the main road with a 30-degree antenna pointing to the Learning Center. A second setup featured a pair of 12-degree antennas with the 30-degree antenna pointing in similar fashion. Antenna direction and on-campus site location is shown in Figure 8. The test commenced at 4 pm and ended at 5 pm.

The second setup introduced the importance of omnidirectional antenna orientation. Two perpendicular antennas were mounted on the top rear, driver side of a van roaming through heavy traffic nearby campus.

The third setup determined the plausibility of mounting a directional antenna on the roof of a vehicle. For this test, one directional antenna was mounted on the van, and another was placed on the ground.

Figure 8. A map view of the Initial setup with antenna POV at university Campus

5-1.1 Initial Setup

The initial test commenced during peak morning drive-time hours and was collected for one hour between 7:45 and 8:45 am, using three Ubertooth devices—each attached to a REECE and an antenna.

- ***Detected BTA***

Table 4. Number of Captured BTA per Antenna during Morning Test

Antenna	Collected BTA
Main	723 (52.7%)
Side	249 (18.1%)
Learning	402 (29.2%)
All	1374

Table 4 indicates that the majority of the 723 vehicles traveled through the Learning Center antenna driving zone (DZ), with most vehicles passing through both the Side and Learning Center antenna DZ. The Learning Center/Main road is typically busier than Side/Main road, also reflected in Table 4 (i.e., learning Center/Main O/D pair had more detected BTA than the Main/Side pair during morning drive-time). The number of matched BTA detected by antenna pairs is described in Table 5.

- ***Matched BTA***

Table 5. Number of Matched BTA on Each Antenna Database

	Main	Side	Learning
Main		197	284
Side	169		182
Learning	270	195	

- Main antenna detected 79.1% (197/249) and 70.6% (284/402) of BTA captured by Side and Learning Center antennas, respectively.
- Side antenna detected 23.3% (169/723) and 45.3% (182/402) of BTA captured by Main and Learning Center antennas, respectively.
- Learning Center antenna detected 37.3% (270/723) and 78.3% (195/249) of BTA captured by Main and Side antennas, respectively.
- Given the numbers characterizing traffic flow throughout the testing period, the following statements can be made:
  Most vehicles entered campus from the Main road with a larger portion traveling on the Learning Center road rather than the Side road.

Table 5 suggests that most vehicles passing through the Side and Learning Center antenna DZ also passed through the Main antenna DZ. The table also shows that the Learning/Main O/D pair had more detected BTA during morning than the Main/Side pair. Traffic flow between the Side/Learning pair was larger than the Side/Main pair.

- ***Unmatched BTA***

Table 6. Number of BTA Captured by One Antenna During Morning Test

Antenna	Unmatched BTA
Main	430 (59.47%, 430/723)
Side	58 (23.30%, 58/249)
Learning	110 (27.36%, 110/402)

- ***Repeated BTA***

Given that the test occurred on a campus sideroad, it is likely that several vehicles passed the same DZ several times during the test. Figures 9 through 11 show the frequency of repeated BTA per antenna.

a. Main antenna

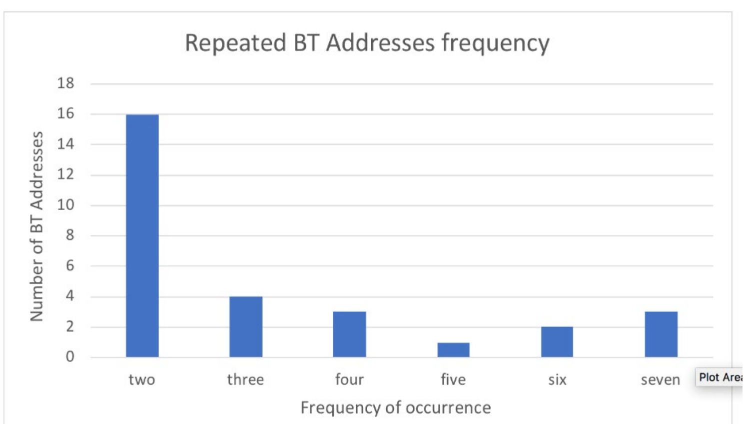


Figure 9. Repeated BTA frequency during the morning test for the Main antenna.

b. Learning antenna

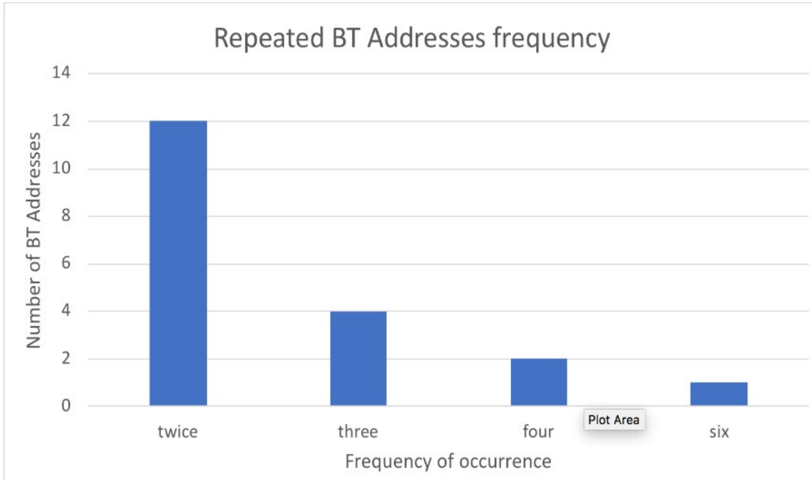


Figure 10. Repeated BTA frequency during the morning test for the Learning antenna.

c. Side antenna

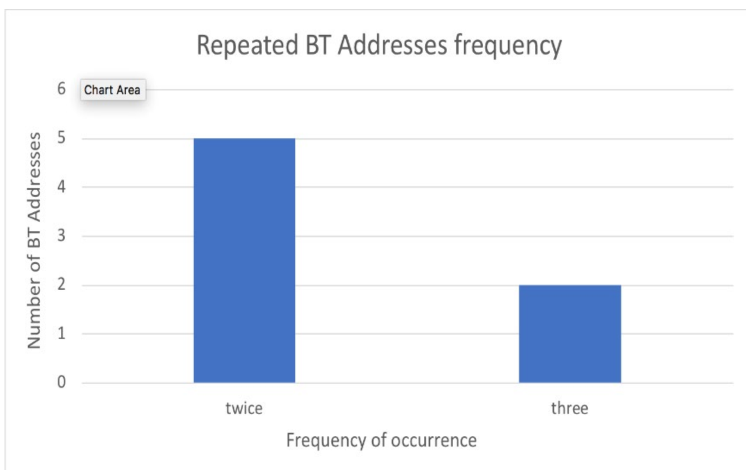


Figure 11. Repeated BTA frequency during the morning test for the Side antenna.

5-1.2 Second Setup

The second test was conducted for one hour during a peak evening drive-time, beginning at 4 pm. Data was collected for one hour using three Ubertooth devices—each attached to a REECE and an antenna.

- ***Detected BTA***

Table 7. Number of Captured BTA Detected by System Antenna

Antenna	Collected BTA
Main	443 (37%)
Side	303 (25.3%)
Learning	449 (37.7%)
Total	1195

Table 7 describes various aspects of peak evening rush hour traffic flow. Most vehicles passed through the Main and Learning DZ. More specific insights about traffic directionality can be extracted from the percentage of matched BTA.

- ***Matched BTA***

Number of matched BTA detected by antenna pair is described below.

- Main antenna detected 74.2% (225) and 65% (292) BTA captured by Side and Learning Center antennas, respectively.
- Side antenna detected 45.8% (203) and 43.2% (194) BTA captured by Main and Learning Center antennas, respectively.
- Learning Center antenna detected 67.1% (297) and 72.6% (220) BTA captured by Main and Side antennas, respectively.

Given that the numbers characterize traffic flow during the test period, the following statements can be made:

1. Percent of vehicles taking Main/Learning Center and Main/Side pairs is relatively close, meaning that during the evening peak drive-time, drivers had no dominant tendency to select a specific route on testing day. However, the Main/ Learning Center antenna pair was dominant over Main/Side antenna pair.
2. Unlike the morning rush-hour test, traffic flow during peak evening drive-time was the same for Side/Learning Center and Side/Main antenna pairs.

- ***Unmatched BTA***

Table 8 shows unmatched BTA detected from the antennas.

Table 8. Number of Unmatched BTA Captured by One Antenna

Antenna	Unmatched BTA
Main	121 (27.31%)
Side	79 (26%)
Learning	131 (29.17%)

- ***Repeated BTA***

  Many BTA addresses were repeated. The following figures show frequency of repeated addresses in each antenna—after filtering out each one.

a- Main antenna

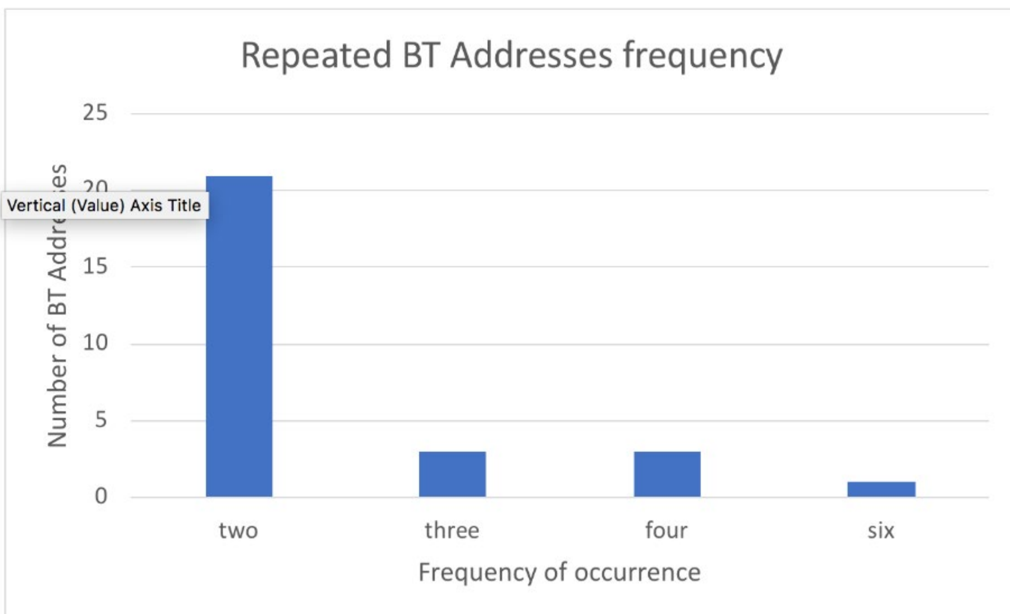


Figure 12. Repeated BTA frequency for the main antenna during the peak evening drive-time test.

b- Side antenna

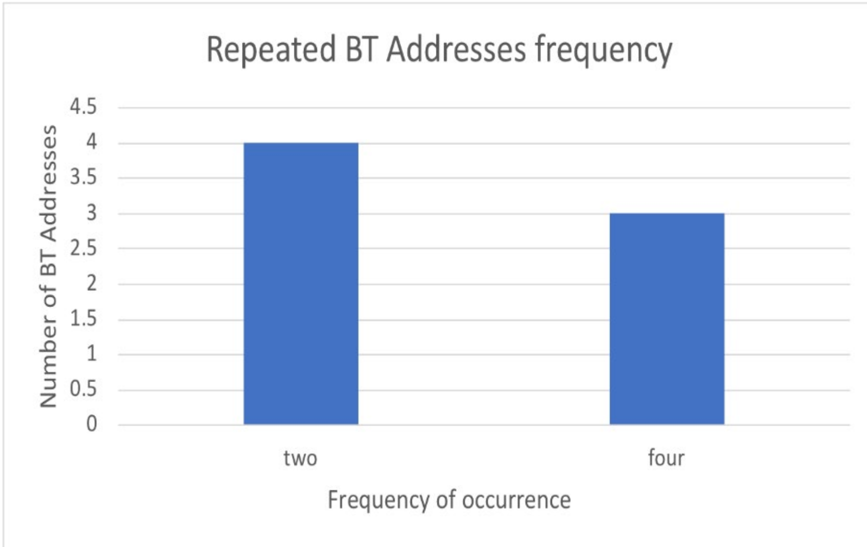


Figure 13. Repeated BTA frequency for the Side antenna during the peak evening drive-time test.

c. Learning antenna

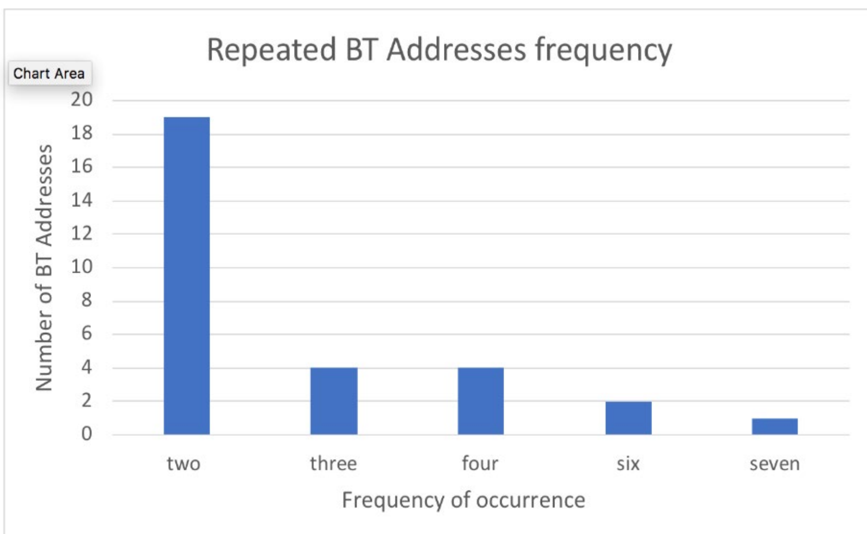


Figure 14. Repeated BTA for Learning antenna frequency during the peak evening drive-time test.

5-2. BTA Randomization

The release of BT 4.0 core specification brings with it BT Smart privacy (i.e., LE privacy). This feature enables the Master device in a communication link to advertise a random BTA that changes at timing intervals determined by the manufacturer. The O/D study will thus be affected, as it is unable to capture the same BTA. The research team studied BT address randomization for both iOS and Android systems and conducted several tests to determine properties of randomization. Results indicated that BT address is randomized only in BLE (Bluetooth Low Energy) connections. Given that a mobile phone is connected to a watch or another BLE device, captured addresses are not actual addresses. Eventually the addresses will be randomized and useless. However, when using classic BT (i.e., devices that transfer media via BT, like headphones, car monitors, and BT adapters inside cars), the real address will be detected and written to the database. It is important to note that Android devices can be discovered without a connection.

5-3. On-campus Roadside Test using RF Multiplexer

A proposed research task suggests investigating the addition of an RF MUX (Radio Frequency Multiplexer) into the design, thus enabling the system to utilize one REECE with one Ubertooth for multiple antennas and to reduce system cost. Figure 15 illustrates a two-way RF signal combiner operating on a dual 2.4 GHz and 5 GHz band.

Figure 15. Two-way, 2.4 GHz radio frequency MUX.

A test was conducted using the aforementioned specifications with the addition of the MUX. Figure 16 provides a depiction of the site location.

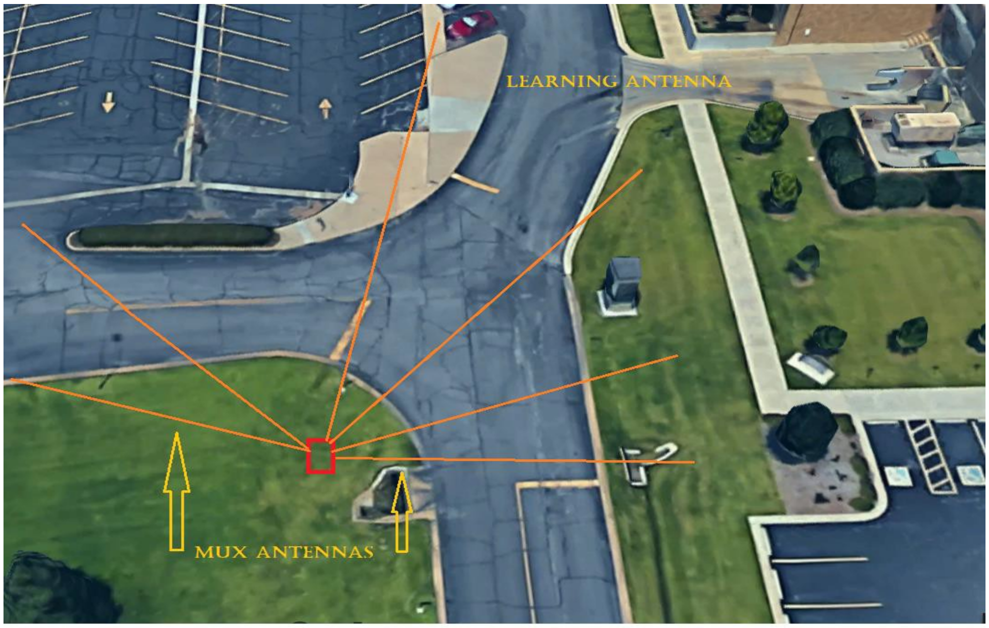


Figure 16. A map view of Second setup location with antennas DZ and MUX on Campus.

Procedures are listed below.

1. The first setup utilized a 30-degree beam-width angle antenna (Learning antenna) pointed toward the Learning Center. Two 12-degree beam-width angle antennas were pointed toward the Side road and Main road (MUX antenna). Both were connected to an RF MUX. Test duration was 90 minutes during peak evening drive-time hours.
2. The second setup utilized the same setup with the exception of two 21-degree beam-width angle antennas were pointed toward the Side road and Main road (MUX antenna). Test duration was the same as the first setup.

5-3.1 First Setup

The first setup tested detected BTA, matched BTA and unmatched BTA between antennas. MUX detected 80.26% of BTA addresses, as shown in Table 9.

- ***Detected BTA***

Table 9. Number of Captured BTA per Antenna with MUX (First Test)

Antenna	Matched BTA
MUX antenna	2650 (55%)
Learning	2169 (45%)
All	4819

- ***Matched BTA***

MUX antenna detected 80.26% (1741) of BTA captured by Learning antenna.

- ***Unmatched BTA***

Table 10. Initial Test of Number of Unmatched BTA per Antenna Detected with MUX and BTA System

Antenna	Unmatched BTA
MUX	866 (32.7%)
Learning	427 (19.7%)

5-3.2 Second Setup

The second setup tested MUX and, as shown in Table 11, which detected 55.18% of BTA.

- ***Detected BTA***

Table 11. Number of Captured BTA per Antenna with MUX (Second Test)

Antenna	Matched BTA
MUX antenna	3855 (44.4%)
Learning	4819 (55.6%)
All	8674

- ***Matched BTA***

MUX antenna detected 55.18% (2650) of BTA captured by Learning antenna.

- ***Unmatched BTA***

Table 12. shows the number of unmatched BTA per Antenna that were captured by only one antenna.

Table 12. Number of Unmatched BTA per Antenna with MUX (Second Test)

Antenna	Matched BTA
MUX	598 (15.5%)
Learning	289 (6%)

Since RF MUX was utilized, there was no evidence of directionality. This is due to the fact that when BTA is captured by the MUX antenna, the information is immediately written to the database without source indication. Hence, the issue cannot be resolved, and results will undermine the entire purpose of the O/D study. Accordingly, RF MUX use was discontinued.

For data processing the code used in this test was similar to that used in a previous test, with the addition of a function to remove false positive BTA. As stated in the Ubertooth manual, the device might detect some LAPs that are not originally BTA. These should be considered noisy data. The code is discussed in Appendix A.

5-4. On-campus Sideroad Test (Two Simultaneous Setups)

The tests described above were conducted to provide information about data collected from various antenna types and to compare captured data quality. However, to achieve optimal results, both setups had to operate in the same environment under identical conditions. Figure 17 shows a depiction of the simultaneous test setup.

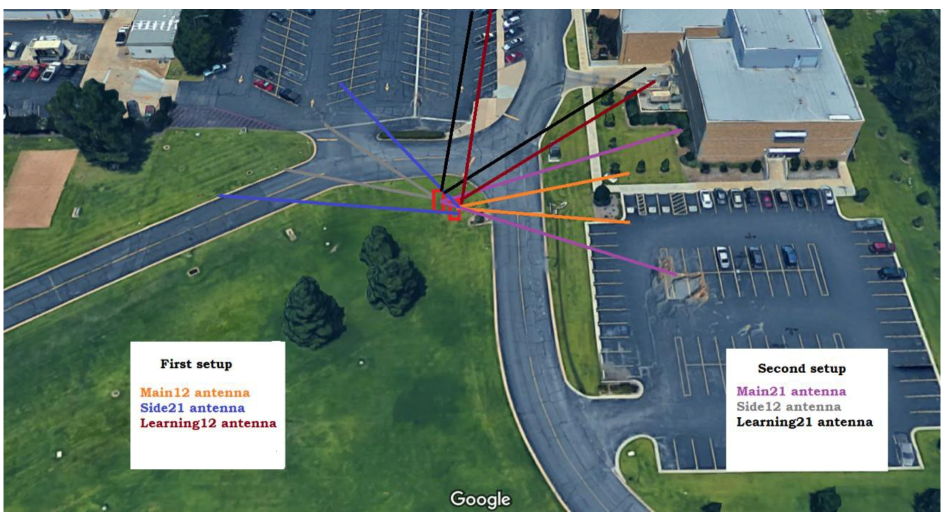


Figure 17. A map view of Test setup three for simultaneous testing of two systems with DZ antenna.

Configuration for test setups:

1- The first setup utilized a 30-degree antenna (Learning1) pointed toward the Learning Center; a 21-degree antenna pointed toward the Side road (Side21); and a 12-degree beam-width angle pointed toward the Main road (Main12).
2- The second setup utilized a 30-degree antenna (Learning2) pointed toward the Learning center; a 12-degree beam-width angle pointed toward the Side road (Side12); and a 21- degree antenna pointed toward the Main road (Main21).

A picture of two poles holding antennas, each pole's antennas are directed in opposite direction. Each pole is holding three antennas. The nine-hour test began at 8:42 am and ended at 5:45 pm. The system recorded all BTA, without exception.

Figure 18. Antenna Setup on the poles used in third test.

5-4.1 First setup

Table 13 shows the high quality of the learning1 antenna, with 38% of total detections.

Table 13. Number of Captured BTA per Antenna for the First of Two Setups

Antenna	Detected BTA
Side21	79,280 (35%)
Learning1	84,477 (38%)
Main12	60,169(27%)
All	223,926

5-4.2 Second setup

The second setup had similar results, with high detection rate from the side12 antenna.

Table 14. Number of Captured BTA per Antenna for the Latter of Two Setups

Antenna	Detected BTA
Side12	73,157 (40%)
Learning2	72,298 (39.6%)
Main21	37,054 (20.4%) *
All	182,509

*Main21: Started at noon due to a technical problem.

- ***Matched BTA***

  - Side21 detected 95% (70,079) of BTA captured by Side12.
  - Learning2 detected 98% (70,963) of BTA captured by Learning1.
  - Main21 detected 93% (34,579) of BTA captured by Main12.

- ***Unmatched BTA***

Table 15. Number of Unmatched BTA Between Both Setups

Antenna	Unmatched BTA*
Side12/Side21	3,079/ 5,147
Learning1/Learning2	3,424/ 1,336
Main12/Main21	5,699/ 2,476**

* Detected by one antenna only
** Starting afternoon

- ***Unique BTA***

Table 16. Number of Unique BTA Collected by Both Setups

Antenna	Unique BTA
Side12	1,285
Side21	1,729
Learning1	1,741
Learning2	1,393
Main12	2,276
Main21	920

5-5.3 Distribution

The following charts reflect BTA distribution throughout the day for each antenna. The Charts 19 to 24 shows same distribution dense of the BT codes throughout the 24 hours data collection. The dense of distribution tends to be high in the late hours of the afternoon.

a) Side12 antenna

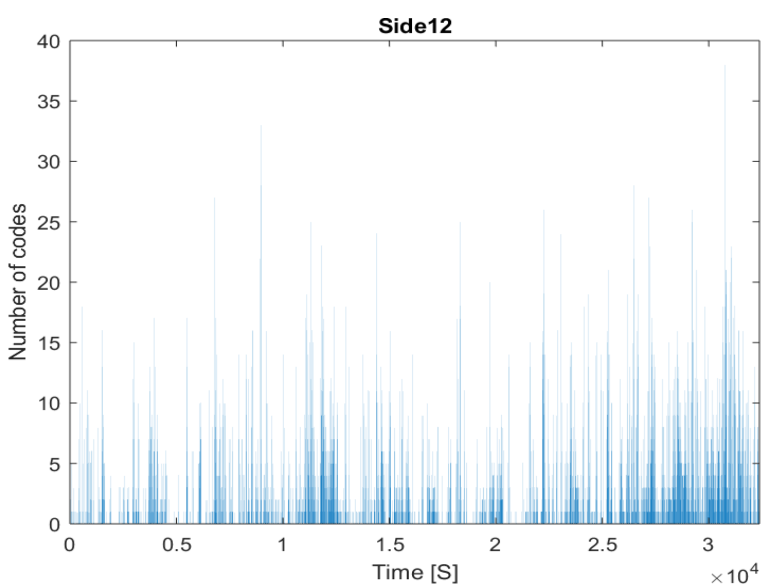


Figure 19. BTA distribution over test time for antenna Side12.

b) Side21 antenna

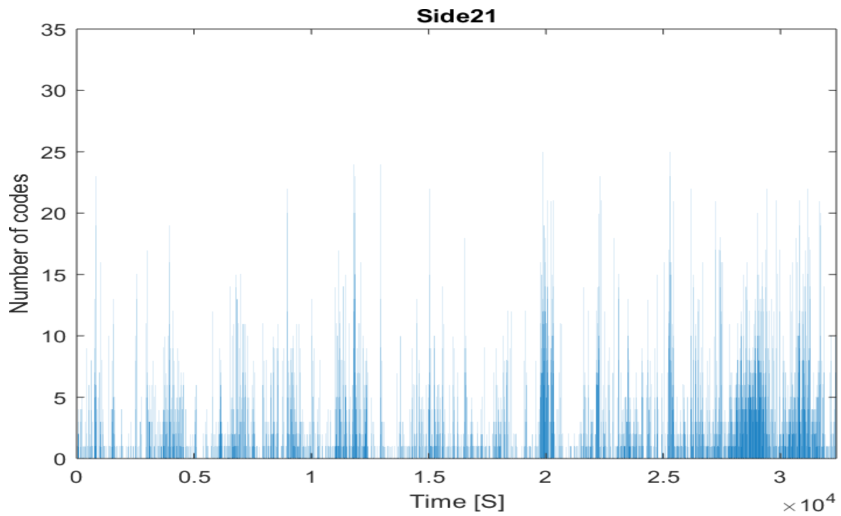


Figure 20. BTA distribution over test time.

c) Learning1 antenna

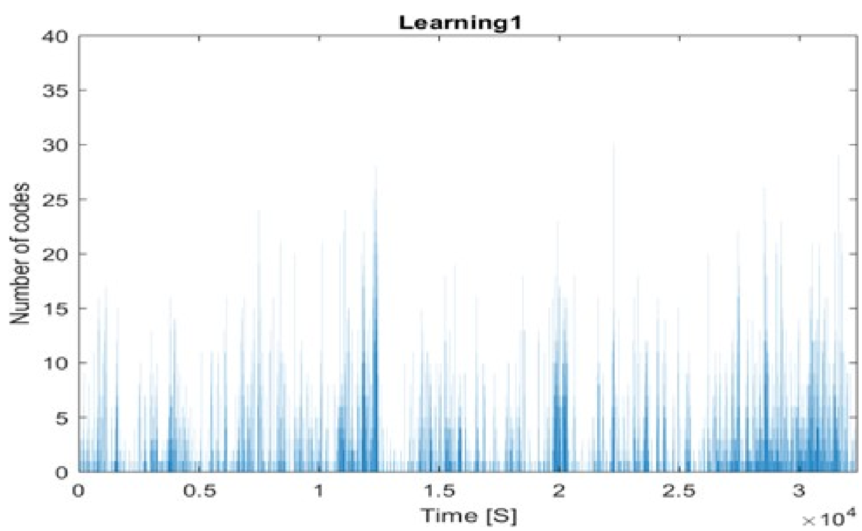


Figure 21. BTA distribution over test time.

d) Learning2 antenna

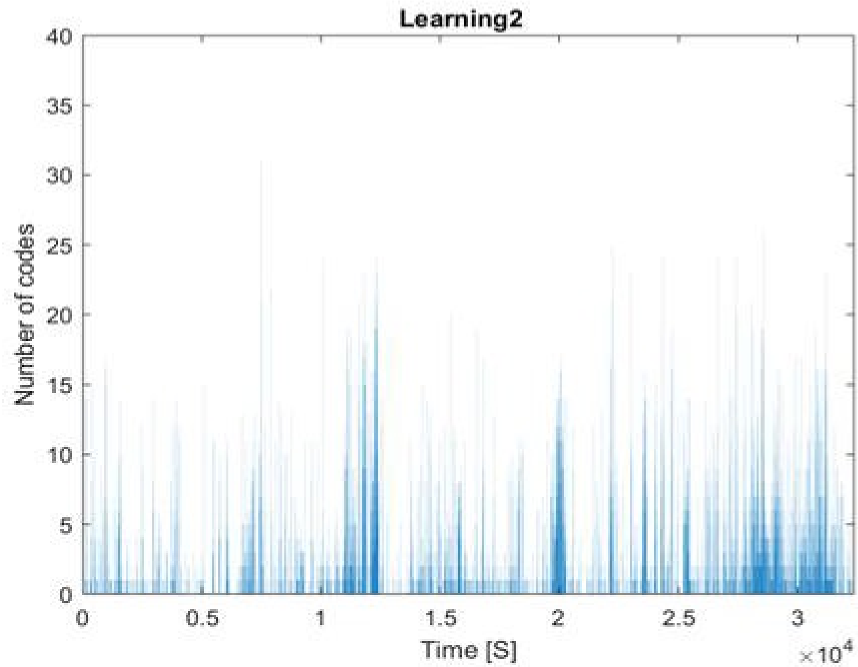


Figure 22. BTA distribution over test time.

e) Main12

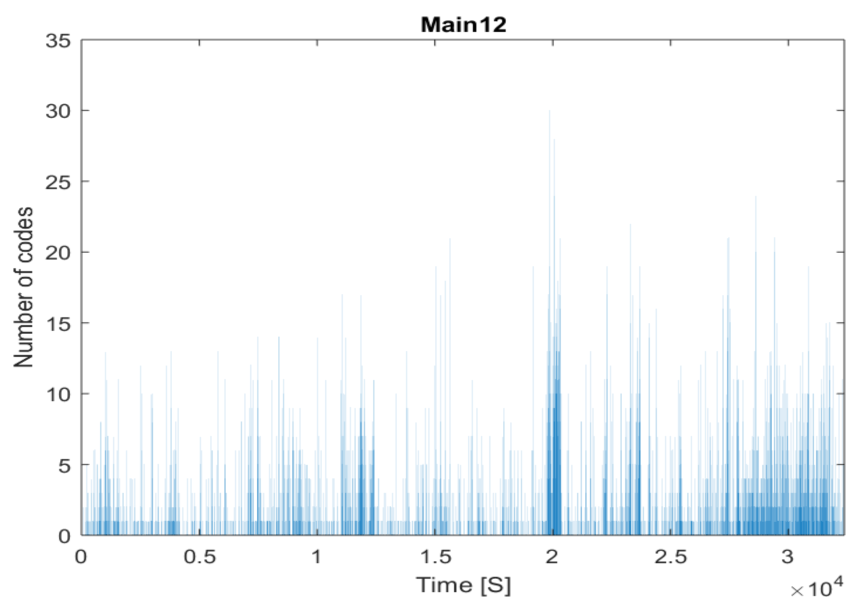


Figure 23. BTA distribution over test time.

f) Main21

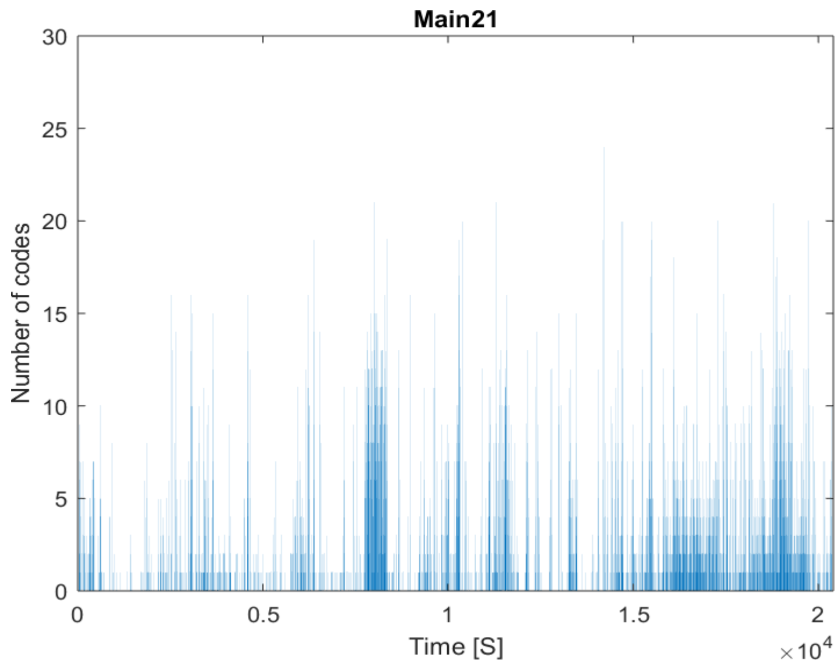


Figure 24. BTA distribution over test time for antenna Main21.

5-5. Integration of commercial system

5-5.1 First test

The initial part of the first test was comparing BTA detected by our system to BTA detected by Iteris Velocity. Two Iteris devices with omnidirectional antennas were utilized with two REECE equipped with 12-degree antennas. The test was conducted between 7 and 8 pm on David Boren Blvd. at Yale Ave. in Tulsa, OK, during which time 700 vehicles traveled across DZ. Figure 25 shows a depiction of both setups.

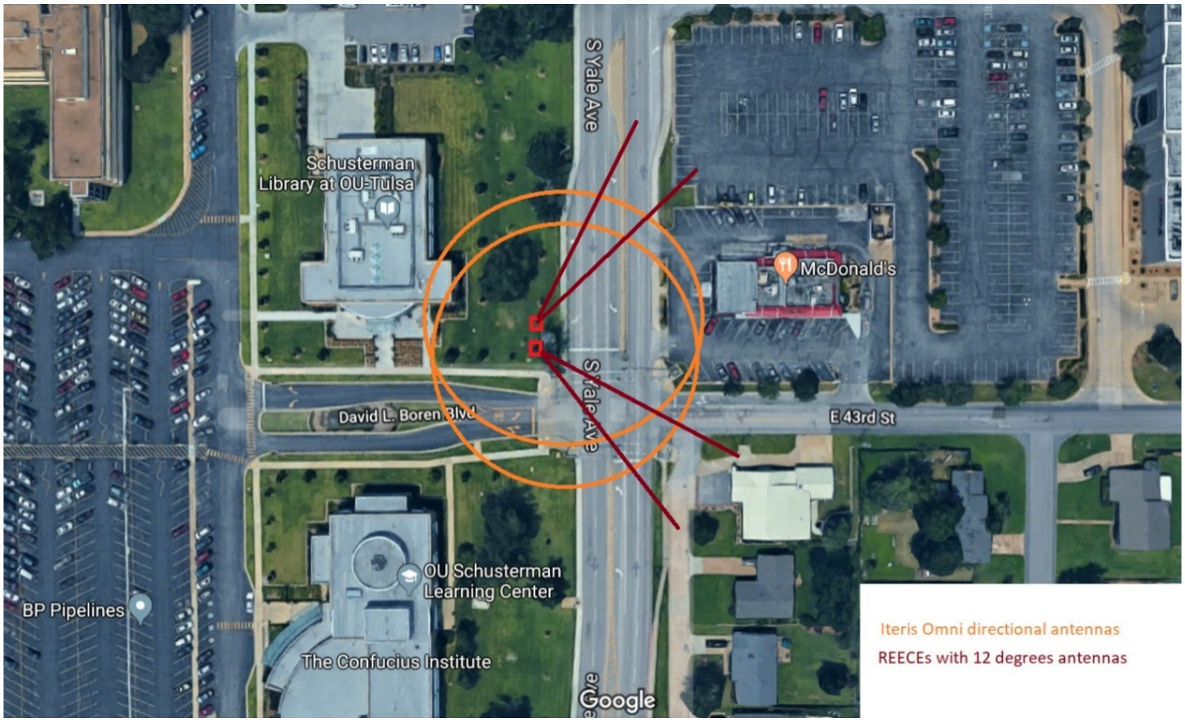


Figure 25. Two setups with DZ antenna.

Collected data shows a huge error gap between the Iteris and the REECE in the detected BTA.

- **Detected BTA**

Table 17. Comparison Between Iteris- and REECE-collected Gata with Omnidirectional Nntenna

Direction	Iteris	REECE
Right Side	60	2413*
Left Side	52	12307

- **Unique BTA**

Table 18. Number of BTA Collected by Both Systems using Omnidirectional Antenna

Right Side	52	285
Left Side	50	395

- **Matched BTA**
    - Right-side Iteris unit detected 6% (17) BTA detected by corresponding REECE.
    - Left-side Iteris unit detected 10% (39) BTA detected by corresponding REECE.

5-5.2 Second test

The second test utilized a 12-degree antenna for both systems to compare BTA detected by both systems. The test was conducted between 7:40 and 8:40 pm on David Boren Blvd. at Yale Ave., with 600 vehicles traveling past DZ. Figures 26 and 27 show a depiction of both setups.

Figure 26. A depiction of two setups with D antenna.

Figure 27. Depiction of two systems.

- **Detected BTA**

Table 19. Comparison between Iteris- and REECE-collected Data utilizing 12-degree Antenna

	Iteris	REECE
Number of BTA	218	14257*

- **Unique BTA**

Table 20. Number of Unique BTA Collected by Both Systems utilizing 12-degree Antenna

	Iteris	REECE
Number of unique BTA	101	529

- **Matched BTA**

Iteris unit detected 15% (79) of BTA detected by our system. Detected BTA increased, primarily because utilized antenna had greater power gain than Iteris omnidirectional antenna.

5-5.3 Third test

In addition to collecting data, the research team drove a car equipped with a BT device connected to a cell phone across DZ to determine the number of times each system detected pre-known BTA. This test was completed twice for each of the following setups:

1- Iteris Vantage and REECE with omni directional antenna.
2- Iteris Vantage and REECE with 12-degree antenna.

Table 21. Comparison Between Detection Times of Pre-known BTA for the Proposed System and Iteris Velocity

	Iteris	REECE
Omnidirectional antenna	0/2	1/2
12-degree directional antenna	1/2	2/2

Results surpassed researcher expectations, primarily because Iteris Vantage Velocity detected the full BTA, which requires more time than our developed system's ability to detect only the lower half of the BTA-LAP. Responding to a need for additional system inspection, the research team plans to deploy both systems in a highway environment for longer periods of time.
*The current system archives all detected BTA without removing duplicates or utilizing queues.

5-6 BTA Capturing by Two Omnidirectional Antennas on a Van

A pair of perpendicular omnidirectional antennas was mounted on the top rear driver side of a van. Data was collected between 1:05 pm to 1:35 pm for 30 minutes. Antenna were connected to an Ubertooth and BeagleBone green.

- ***Objective***

The research team's objective was determining which omnidirectional antenna orientation was most suitable for roadside BTA detection.

Figure 28. Omnidirectional antenna mounted on a van.

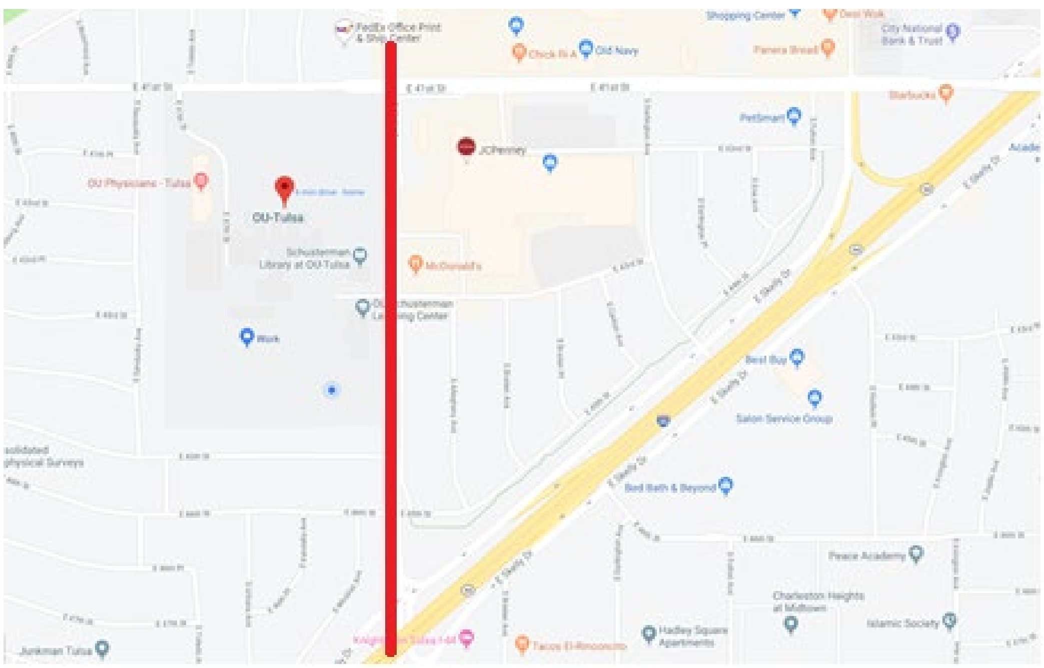


Figure 29. Testing and data collection location.

- ***Detected BTA***

Table 22. Number of Captured BTA Per Antenna

Antenna	Collected BTA
Vertically oriented	424
Horizontally oriented	514
Matched	402(78.21%)

Results showed that omnidirectional antenna should be oriented horizontally to maximize data capture.

- *BTA Captured by Two Fixed Directional Antennas*

Researchers compared a pair of directional antennas—one mounted on the top rear driver side of the van and another placed on the ground. Both antennas shared similar height and were aimed at the same point. The experiment occurred between 10:52 and to 11:20 am.

Figure 30. Directional antennas setup comparison.

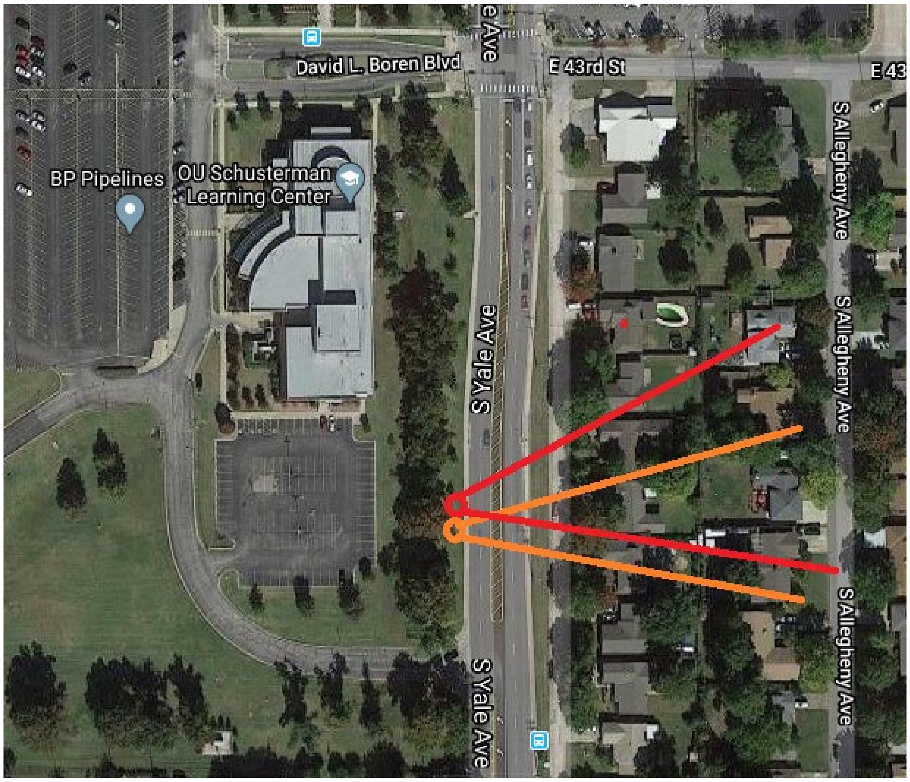


Figure 31. Map location of the Directional antenna's setup comparison.

- *Detected BTA*

Table 23. Number of Captured BTA per Antenna

Antenna	Collected BTA
On the van	225
On the ground	223
Matched	198 (88.79%)

Similar BTA were captured, proving that the mobile solution is plausible.

6. Highway Deployments

After several tests were conducted on the OU-Tulsa campus and after several software and hardware issues were resolved, the research team deployed the system on a highway environment for various tests.

6-1.1 First deployment

The research team deployed the system on Highway 169 in Tulsa. Two sites measuring 5.5 miles in length were deployed at AVC10 and AVC68 Located on Highway 169, as shown in Figure 32.

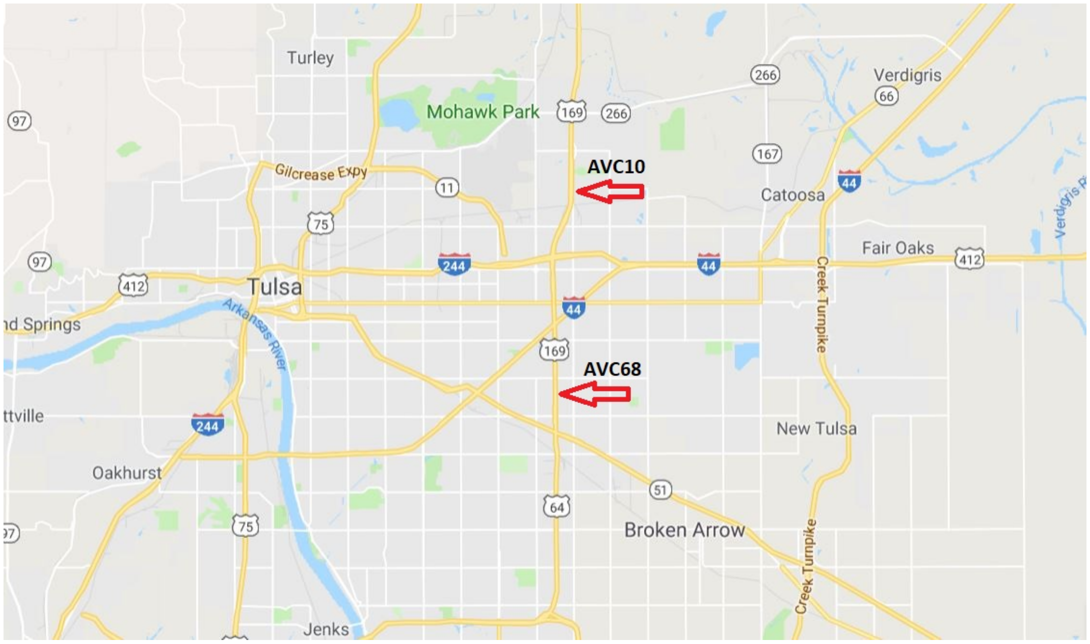


Figure 32. Location of the two test setups.

The research team deployed both the proposed system and an Iteris unit at each site.

1- AVC10 was equipped with a 12-degree antenna and an Iteris unit with an omni-directional antenna.
2- AVC68 was equipped with a 21-degree antenna and an Iteris unit with an omni-directional antenna.

The following results were reported after capturing BTA for 24 hours, beginning at 3 pm.

- **Detected BTA**

Table 24. Number of BTA Detected by Both Systems

AVC10_REECE	27,892
AVC10_Iteris	11,392
AVC68_REECE	35,941
AVC68_Iteris	8,946

- **Matched BTA**

Number of matched BTA detected by a pair of antennas is shown below.

- AVC10_REECE antenna detected 24.1% (8,664) of BTA captured by AVC68_REECE.
- AVC10_Iteris antenna detected 1.5% (416) of BTA captured by AVC10_Iteris.
- AVC68_REECE antenna detected 33.5 % (9,350) of BTA captured by AVC10_ REECE.
- AVC68_Iteris antenna detected 1.3 % (473) of BTA captured by AVC68_ Iteris.

- Distribution

The following figures show the distribution of collected BTA during the 24-hour test.

- AVC10:

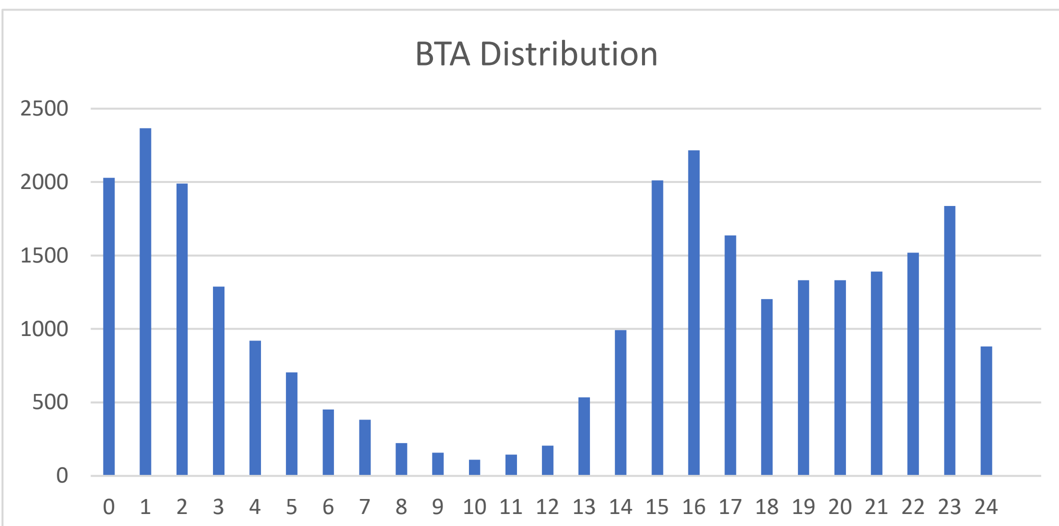


Figure 33. Distribution of BTA during a 24-hour period at AVC10.

- AVC68:

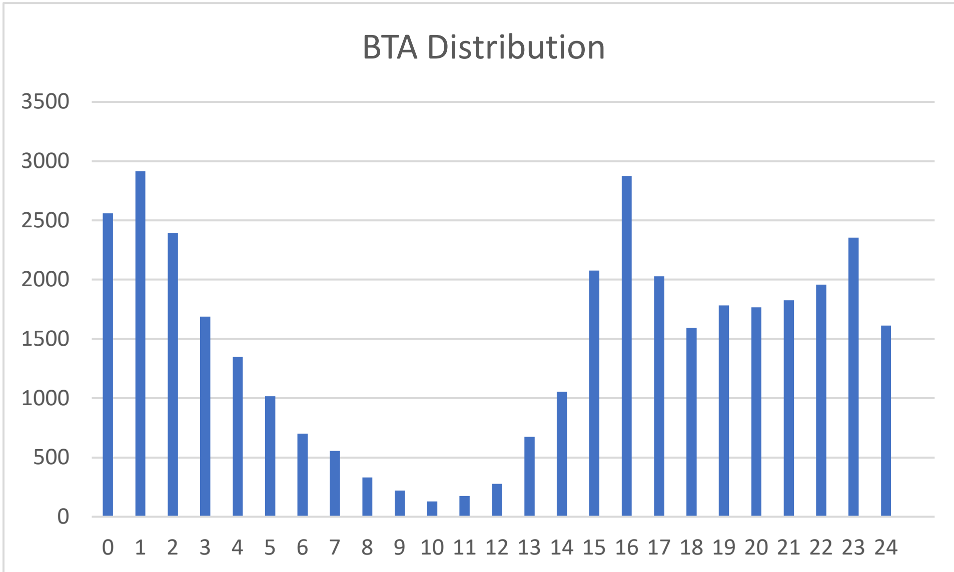


Figure 34. Distribution of BTA during a 24-hour period at AVC68

Next, the research team designed an O/D algorithm for pairing the origin and destination for each BTA, as well as calculating TT. The algorithm first sorts both datasets collected by the deployed systems according to time. Subsequently, BTA detected by only one antenna are removed. The algorithm then pairs O/D for each BTA and eliminates pairs with TT longer than 10 minutes, as these were considered outliers. The algorithm detected 5700 O/D pair with an average 5-minute TT. Table 25 provides an example of captured BTA and their O/D pairing.

Table 25. O/D Pairs Detected by Developed Algorithm

BTA	Origin	Destination	TT[S]
03ca5e	AVC68	AVC10	286
da21ae	AVC10	AVC68	280
2d1a5b	AVC68	AVC10	333
811e65	AVC68	AVC10	271
f4c12d	AVC68	AVC10	290
b61c76	AVC10	AVC68	292
77ecdb	AVC68	AVC10	275
5aaf74	AVC68	AVC10	306
c475f3	AVC68	AVC10	289
f7000c	AVC68	AVC10	305
e81cd6	AVC68	AVC10	289
178e1b	AVC10	AVC68	490
66c185	AVC68	AVC10	262
8ee09d	AVC68	AVC10	314
cb4458	AVC68	AVC10	320
55be5d	AVC68	AVC10	321
479911	AVC68	AVC10	323
5bc414	AVC68	AVC10	321
c650d6	AVC68	AVC10	319

Results reported that 52.14% (2,972) of BTA heading to AVC68 started at AVC10.

6-1.2 Second Deployment

After testing the MAC collection system in the previous setup, further deployments were needed to validate the integrity of both systems (i.e., MAC collection and Vehicle Classification) and to determine the best positioning scheme for sensors within the DZ. Accordingly, the full system was deployed on I-44 at one of ODOT’s data collection stations (AVC19). The test lasted 3.5 hours each day for three days, beginning on April 24. Figure 35 illustrates deployment layout and location.

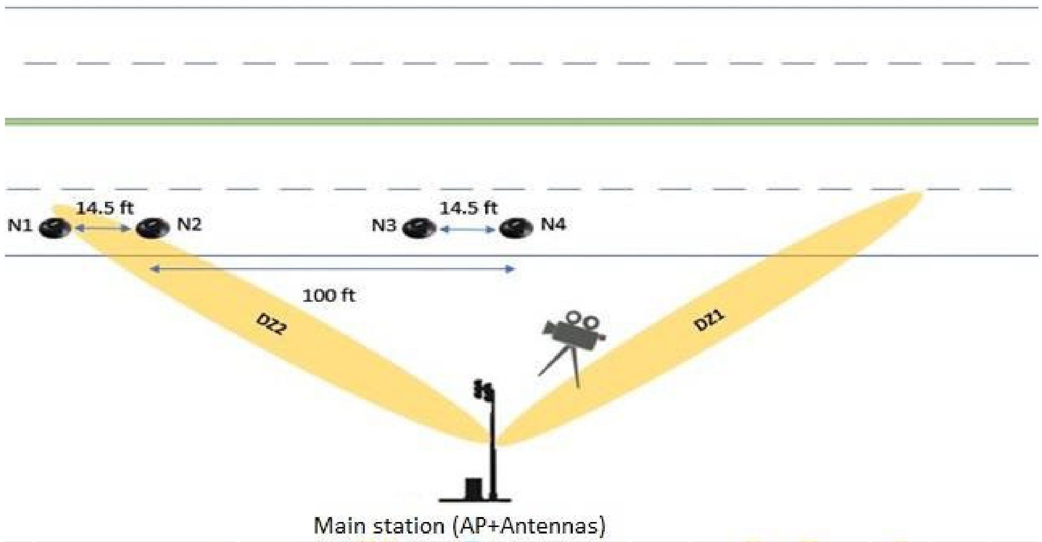


Figure 35. A depiction of deployment layout.

Figure 36. Deployment location.

A digital camera was used to record vehicles passing through the DZ during deployment. The recording was used as a validation measure for classification system accuracy, as well as to understand conditions underlying the system decision-making. Vehicle classes driving on the first lane were extracted from the recording and archived in a database. The following chart was used to manually classify vehicles according to class.

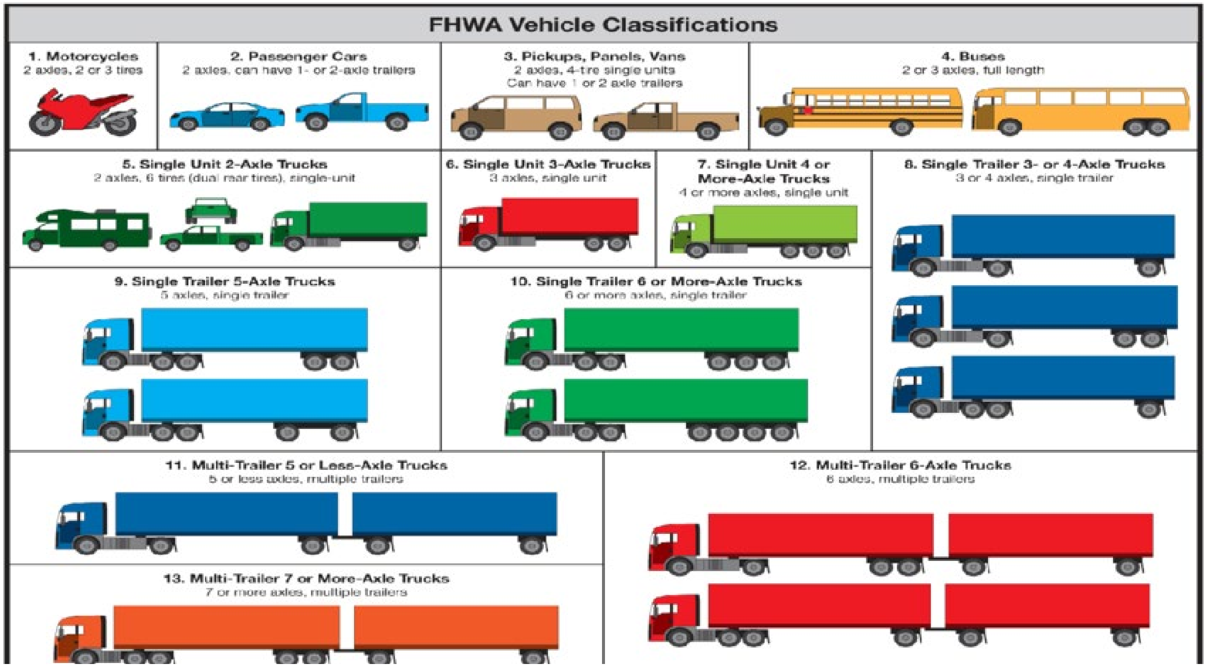


Figure 37. FHWA vehicle classification.

Collected data statistics are illustrated in the following tables.

Table 26. Collected MAC Statistics (First Day)

04/24/2019		
	Left Antenna	Right Antenna
Start time	12:29:48 PM	12:31:30 PM
End time	3:28:14 PM	3:29:12 PM
Number of records	8389	46534
Number of unique records	1428	3725

Table 27. Collected MAC Statistics (Second Day)

04/25/2019		
	Left antenna	Right antenna
Start time	2:17:45 PM	2:14:13 PM
End time	6:33:29 PM	6:33:27 PM
Number of records	130700	131233
Number of unique records	7246	6910

Table 28. Collected MAC Statistics (Third Day)

04/26/2019		
	Left antenna	Right antenna
Start time	11:26:18 AM	11:30:04 AM
End time	2:37:37 PM	2:37:35 PM
Number of records	65683	48589
Number of unique records	5133	4352

- ***Data processing***

Several data processing algorithm were developed to analyze collected data.

1- MAC filtering. Spatial analysis of the collected MAC addresses requires prober detection of traveling MAC-address directionality. The algorithm was designed to facilitate filtering MAC addresses based on their directionality. It considers data sets of MACS collected by both antennas and filters them, retaining only MAC traveling from one DZ to another.

After applying the algorithm on the datasets, the following results were obtained.

Table 29. Number of Matched MAC Between the Two Antennas (First Day)

Traffic Direction	Number of records
West bound traffic	5
East bound traffic	6

Table 30. Number of Matched MAC Between the Two Antennas (Second Day)

Traffic Direction	Number of records
West bound traffic	3422
East bound traffic	3625

Table 31. Number of Matched MACs Between the Two Antennas (Third Day)

Traffic Direction	Number of records
West bound traffic	2126
East bound traffic	2061

Table 32. Output of the MACs filtering algorithm (Left DZ to Right DZ)

codes	TA	First RSSI	TD	Second RSSI
158857	1556296195	-18.4643	1556296204	-17
570451	1556296200	-16.7778	1556296210	-29
102154	1556296202	-16	1556296207	-6
771171	1556296203	-20	1556296208	-23
107192	1556296208	-16	1556296221	-22
459316	1556296212	-5	1556296217	-25
318711	1556296213	-17	1556296219	-13.6
144962	1556296214	-22	1556296215	-27
124999	1556296217	-18	1556296219	-27.5
489138	1556296219	-24	1556296224	-23.5

- Codes: Detected MAC address
- TA: First occurrence of MAC address in left antenna database
- First RSSI: Average value of RSSI calculated from left antenna database
- TD: Last occurrence of MAC address in right antenna database
- Second RSSI: Average value of RSSI calculated from right antenna database

2- A video-sensor matching algorithm matches timestamps of vehicles passing the DZ traveling in the monitored lane with those reported by the sensors. After checking all timestamps, the algorithm ceases operation by archiving matched timestamps into a database (See Table 33).

Table 33. Output of the Video-Sensor timestamps matching algorithm

ID	Vehicle Class	Sensor	TA	TD
2	2	364099	1556296584.92	1556296585.14
3	2	364099	1556296591.67	1556296591.86
4	5	364099	1556296597.27	1556296597.62
5	3	364099	1556296602.67	1556296602.91
6	3	364099	1556296609.38	1556296609.63
7	3	364099	1556296610.48	1556296610.74
8	2	364099	1556296620.67	1556296620.88
10	3	364099	1556296638.66	1556296638.73
11	9	364099	1556296649.69	1556296650.51
12	6	364099	1556296658.11	1556296658.72
13	6	364099	1556296661.22	1556296661.83

- ID: ID of vehicle within the video database
- Vehicle Class: Vehicle class with provided ID
- Sensor: ID of the sensor matched with vehicle timestamp
- TA: Vehicle time of arrival at sensor
- TD: Vehicle time of departure at sensor

Table 34. Results of Video-Sensor Timestamps Matching Algorithm

Number of vehicles(video)	Number of matched Vehicles (Sensor1)	Number of matched Vehicles (Sensor2)
793	287	692

Number of detected vehicles traveling on the sensor side was low during deployment as a result of several issues:

a- Sensors could not establish a stable connection link with the AP due to high attenuation in the deployment environment.

b- Sensor2 and Sensor3 were unable to save timestamps to flash memories installed on the board due to sensor hardware problems.

c- Sensor2 and Sensor4 lost sync with GPS satellites for a period of time, causing incorrect timestamps. This data was not considered in the algorithm.

After using the algorithm to process each sensor's dataset, the classification algorithm was applied. The video recording was used to validate classification algorithm accuracy, which was 85% for 276 vehicles. Classification accuracy is expected to improve after solving sensor issues.

3- **MAC to vehicle assignment**. After using timestamps reported by the sensors to classify vehicles passing through DZ, timestamps were also used to match each detected MAC address for vehicles traveling from DZ left side to right side.

The algorithm was designed to find all MAC addresses captured within a threshold prior to vehicle detection by the first sensor (Sensor1). Table 35 shows an example of matching algorithm output.

Table 35. Output of the BT-Vehicle Assignment Algorithm

MAC address	Group	BT Detection Time	STA	STD	BT Departure Time
941544	3	1556296657	1556296658.11	1556296659.99	1556296671
899086	2	1556296662	1556296663.94	1556296665.31	1556296669
96284	2	1556296738	1556296739.37	1556296740.69	1556296745
721944	2	1556296742	1556296744.73	1556296745.96	1556296747
127167	2	1556296764	1556296766.60	1556296767.87	1556296765
744044	2	1556296769	1556296769.58	1556296771.10	1556296774
778122	2	1556296787	1556296787.45	1556296788.85	1556296794
136411	2	1556296807	1556296809.25	1556296810.48	1556296812
869021	2	1556296824	1556296826.50	1556296827.87	1556296825

- MAC address: Address assigned to the vehicle
- Group: Vehicle group assigned to the MAC address
- BT Detection Time: First occurrence of MAC address within DZ

- STA: Time of arrival to first sensor (Sensor 2)
- STD: Time of departure from second sensor (Sensor 4)
- BT Departure Time: Last occurrence of MAC address within DZ

The algorithm matched 125/276 vehicles with their corresponding MAC addresses. (276 is the number of vehicles classified by the classification algorithm, as mentioned above).

- ***Data analysis***

Collected data was analyzed after applying the processing algorithms. Following is a list of information extracted from the data.

1- Vehicle Classes

a. Distribution of classes for vehicles traveling on the first lane that passed through DZ during the full day of deployment on the third day, and then extracted from the video recording.

Table 36. Number of Detected Vehicles and Their Classes (Part of Third Day–Camera)

Number of vehicles	G1	G2	G3	G4
275	0 (0%)	225 (81.8%)	18(6.5%)	32(11.6%)

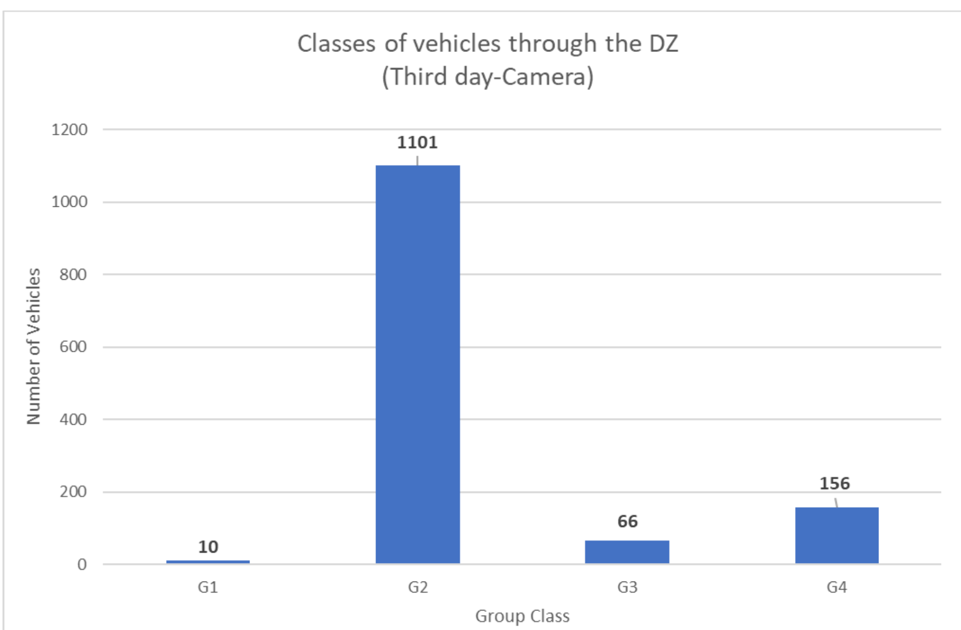


Figure 38. Distribution of the classes passing through the DZ (Third day -Camera).

b- Distribution of classes for vehicles traveling on the first lane passing through DZ during the time sensors were working, and then extracted from the video recording.

Table 37. Number of Detected Vehicles and Their Classes (Part of Third day–Camera)

Number of vehicles	G1	G2	G3	G4
275	0 (0%)	225 (81.8%)	18(6.5%)	32(11.6%)

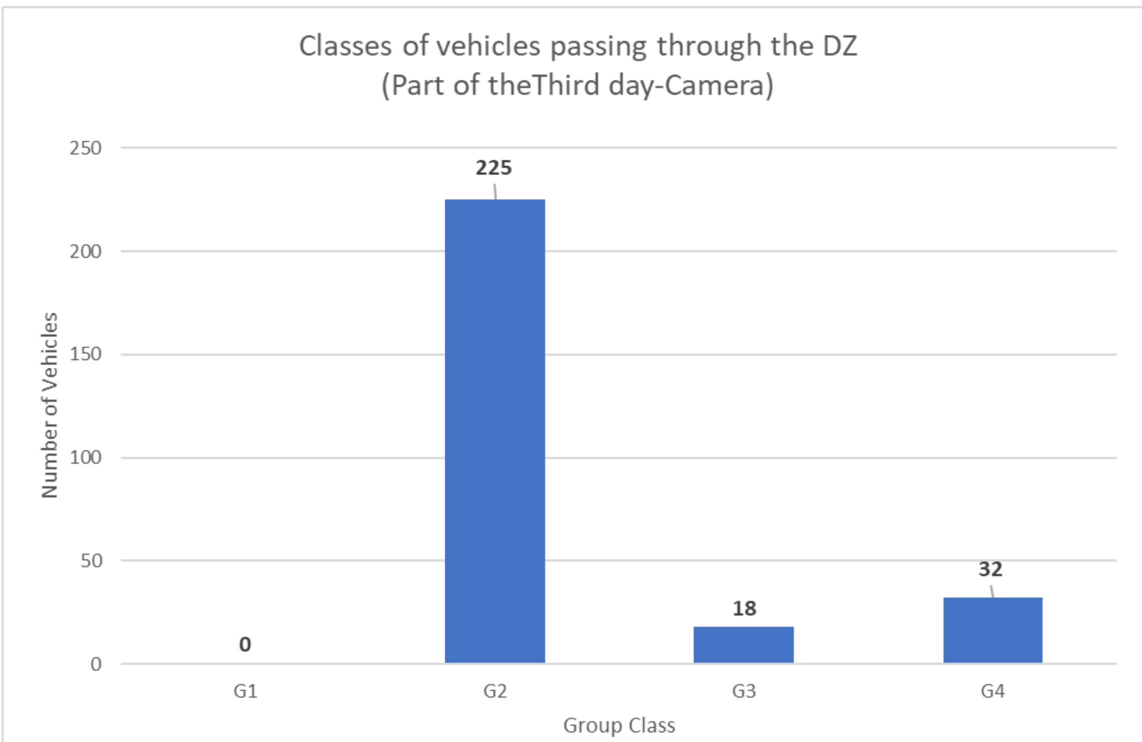


Figure 39. Distribution of the classes passing through the DZ (Part of the Third day -Camera).

c- Distribution of classes for vehicles traveling on the first lane, passing through the DZ during the time sensors were working, and then extracted from the following classification algorithm.

Table 38. Number of Detected Vehicles and Their Classes (Part of the Third Day–Sensors)

Number of vehicles	G1	G2	G3	G4
275	3 (1.08%)	223 (81.15%)	13(4.7%)	36(13.04%)

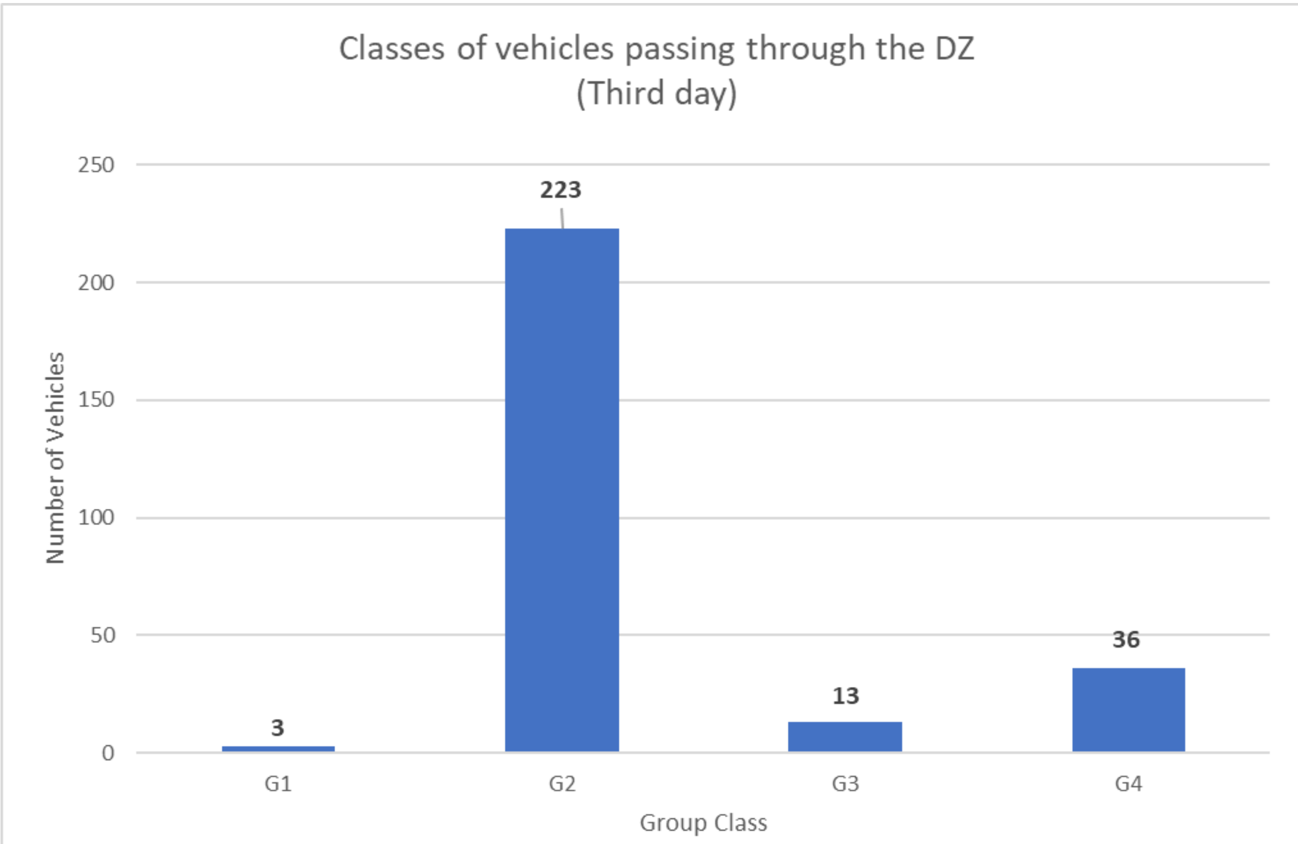


Figure 40. Distribution of the classes passing through the DZ (Third day - Sensors)

2- Detected MACs

a. Distribution of unique MACs detected by left antenna.

Total number of Unique MACs: 5133

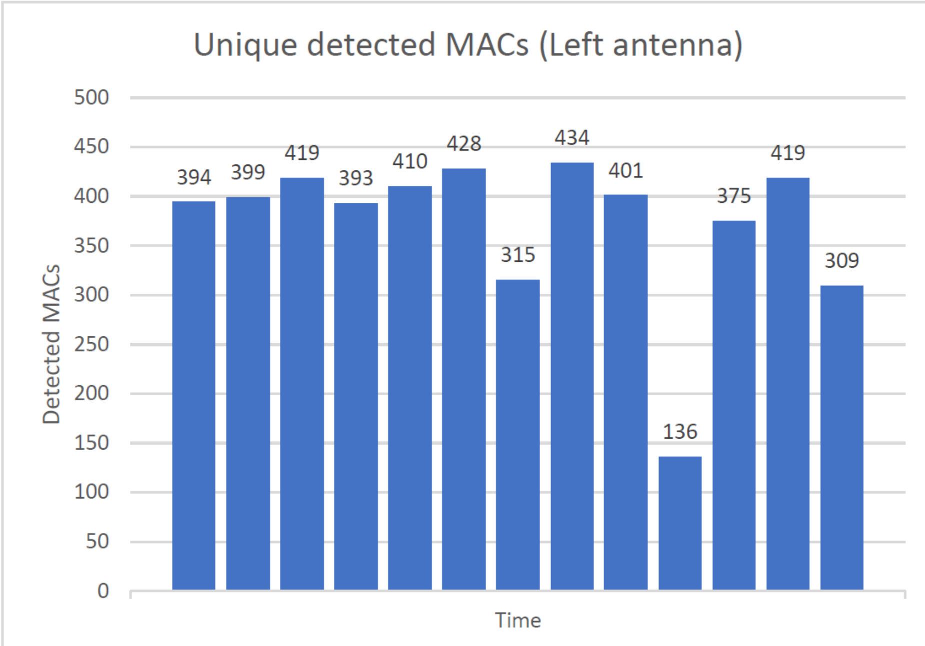


Figure 41. Distribution of the unique detected MACs (left antenna).

b. Distribution of unique MACs detected by right antenna.

Total number of unique MACs was 4353.

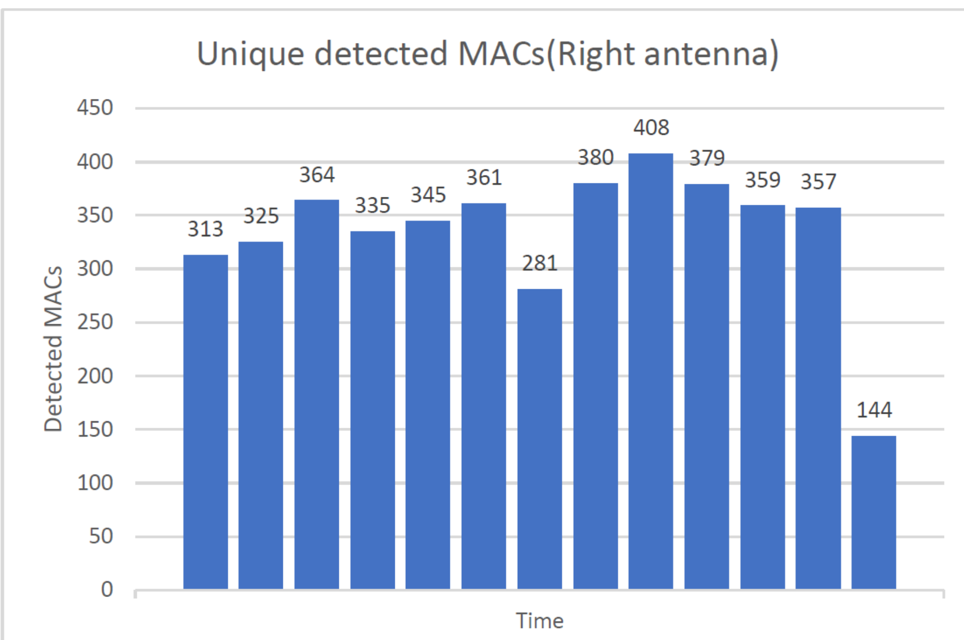


Figure 42. Distribution of the unique detected MACs (right antenna).

c. TT from left DZ to right DZ was 5 seconds, with an SD of 3.63.
d. TT from right DZ to the left DZ was 6.6 seconds, with an SD of 5.1.
e. Average vehicle speed was 58.16 mph with an SD of 18.27. Results were extracted from vehicles that were matched using video recording.

6-1.3 Third Deployment

In this test, the system was deployed at ODOT's AVC516 site for 4.5 hours on June 10. The test aimed to examine the newly developed algorithms and the solutions that were suggested to maintain a better communication link between AP and sensors. Figures 43 and 44 show the deployment location and layout.

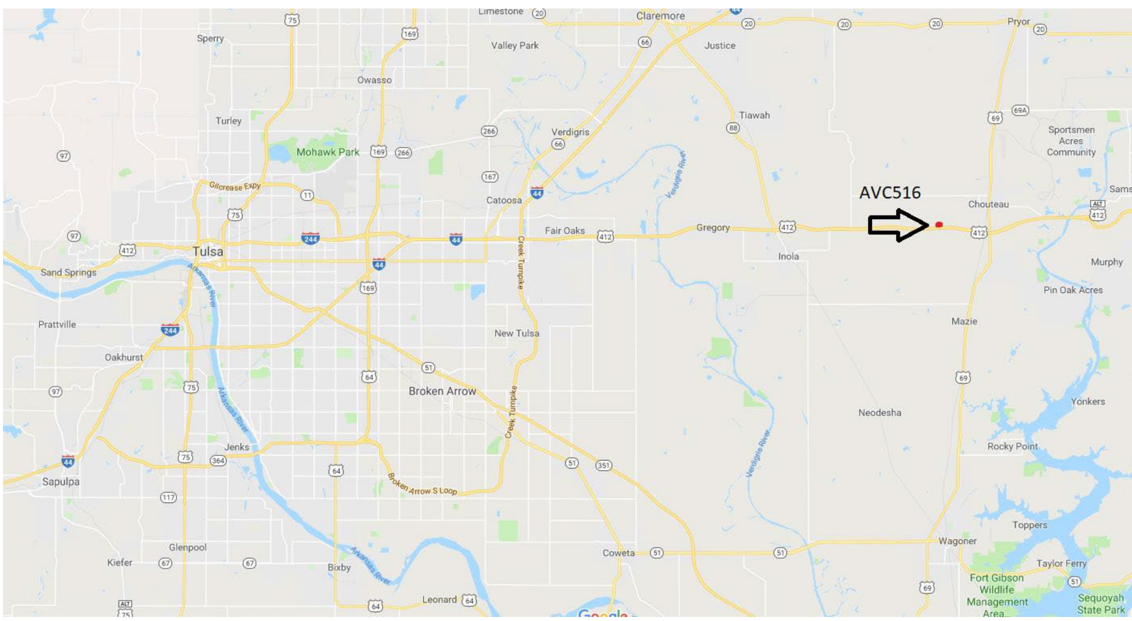


Figure 43. Location of the third deployment.

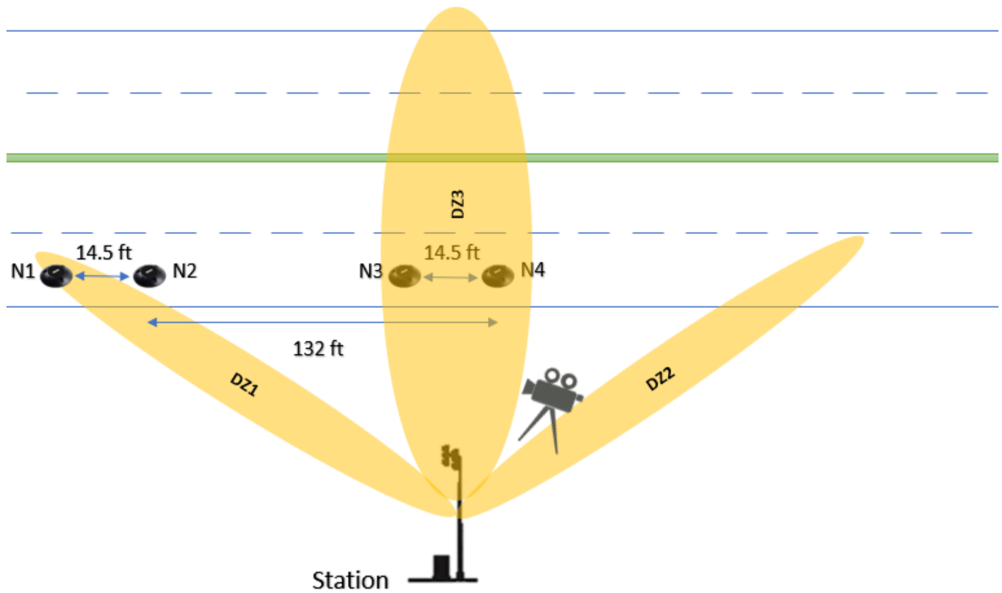


Figure 44. Depiction Layout of the third deployment.

Figure 44 illustrates the designated 30-degree unidirectional antenna used to establish an improved communication link. During deployment, the antenna was instrumental in achieving exceptional results, as the AP was able to receive data from sensors during the full length of the deployment.

All algorithms used in the previous test were modified to enable the system to assign BTA to its associated vehicle in real time. To accomplish this, the following changes were made.

1- REECE that collected BTA from the right side of the road sent data to the other REECE via a serial cable.
2- REECE responsible for collecting BTA on the left side were watching the serial port and reading all data sent by the other REECE; information was then archived into MACs2_DB database.
3- A python script utilized threads monitored in classified vehicle databases and verified number of unassigned vehicles before commencing the assignment script for each.

All scripts are discussed in Appendix A.

- ***Data Processing:***

Collected data was analyzed after applying processing algorithms. Following is information extracted from the data.

1- Vehicle Classes

a- Camera

Data represents vehicle groups that were recorded during the full length of deployment. Total number of vehicles was 1076.

Table 39. Number of Detected Vehicles and Their Classes (Camera)

Group	G1	G2	G3	G4
	(3) 0.27 %	(883)82.06%	(59)5.4%	(131)12.7%

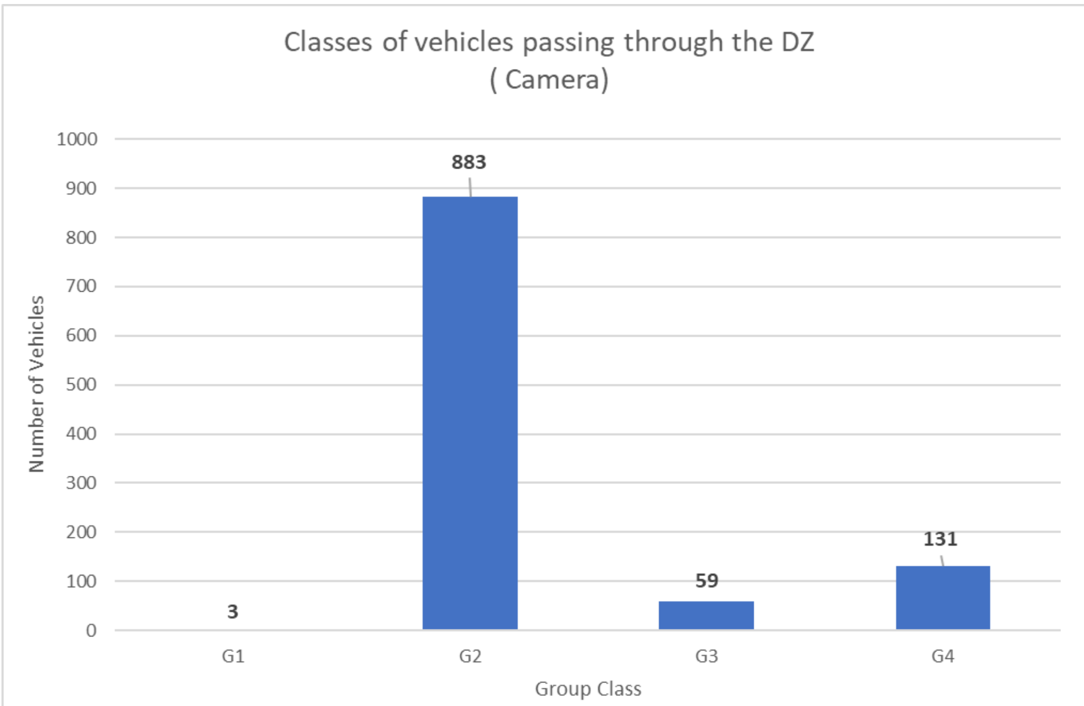


Figure 45. Distribution of the classes passing through the DZ (Camera).

b- Sensors

This data represents vehicle group information extracted from the developed classification algorithm based on reported sensors timestamps. Total number of vehicles was 777.

Table 40. Number of Detected Vehicles and Their Classes (Sensors)

Group	G1	G2	G3	G4
	23 (2.9%)	(626) 80.56%	(29) 3.7%	(99)12.74%

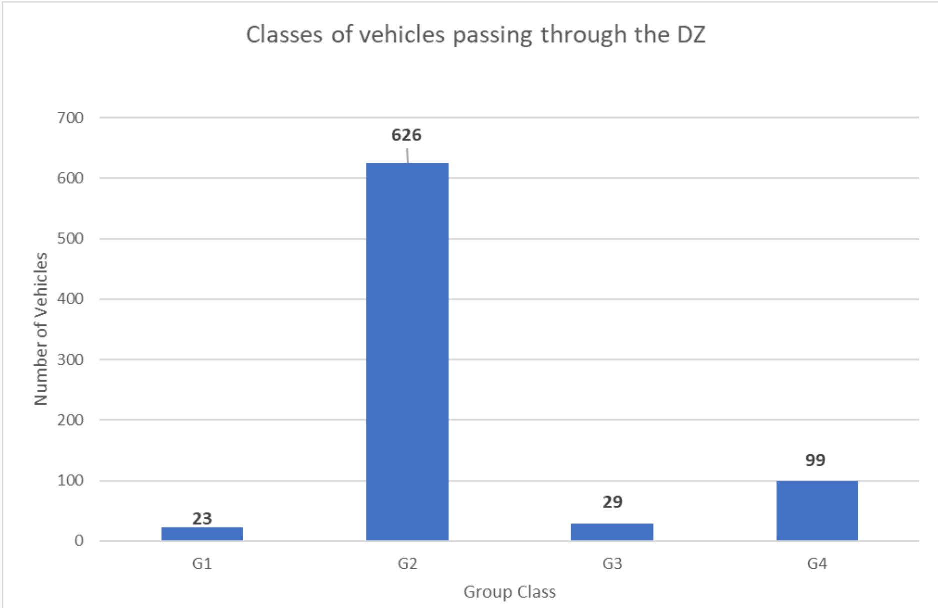


Figure 46. Distribution of the classes passing through the DZ (Sensors)

Table 41offers results of real time, MAC directionality, and BTA-vehicle assignment algorithms.

Table 41. Results of Real-time MACs Directionality and BTA-vehicle Assignment Algorithms

Traffic Direction	Number of Unique MACs	Assigned MACs
East bound traffic	337	96

Table 42 shows percentages of each group of assigned vehicles:

Table 42. Percentages of assigned vehicles

Group	G1	G2	G3	G4
	8.54%	81.69%	5.63%	4.22%

The results of the deployment suggest the following:

1- Only a third of MACs traveling from the left DZ to the right DZ were assigned to possible corresponding vehicles.
2- Algorithms were not able to assign all of MACs to corresponding vehicles due to the following reasons:
   a- Sensors were deployed only on one of the two lanes, which prevented assigning MACs to vehicles travelling on the second lane.

b- In cases where vehicles had multiple MACs, only one MAC was assigned
c- Sensors reported erroneous timestamps in some periods during deployment, which prevented accurate detection and classification of vehicles during these periods.

6-1.4 Fourth Deployment

In this reporting period, the research team deployed the investigated system at ODOT AVC516 site for five hours on July 23. The test was designed to examine the newly developed algorithms and suggested solutions for maintaining an improved communication link between AP and sensors. Figure 47 shows a map of the location. Figure 48 illustrates the layout of the deployment. The test included two lanes equipped with two magnetometer sensors to classify the mac address in both lanes and to maximize data collection.

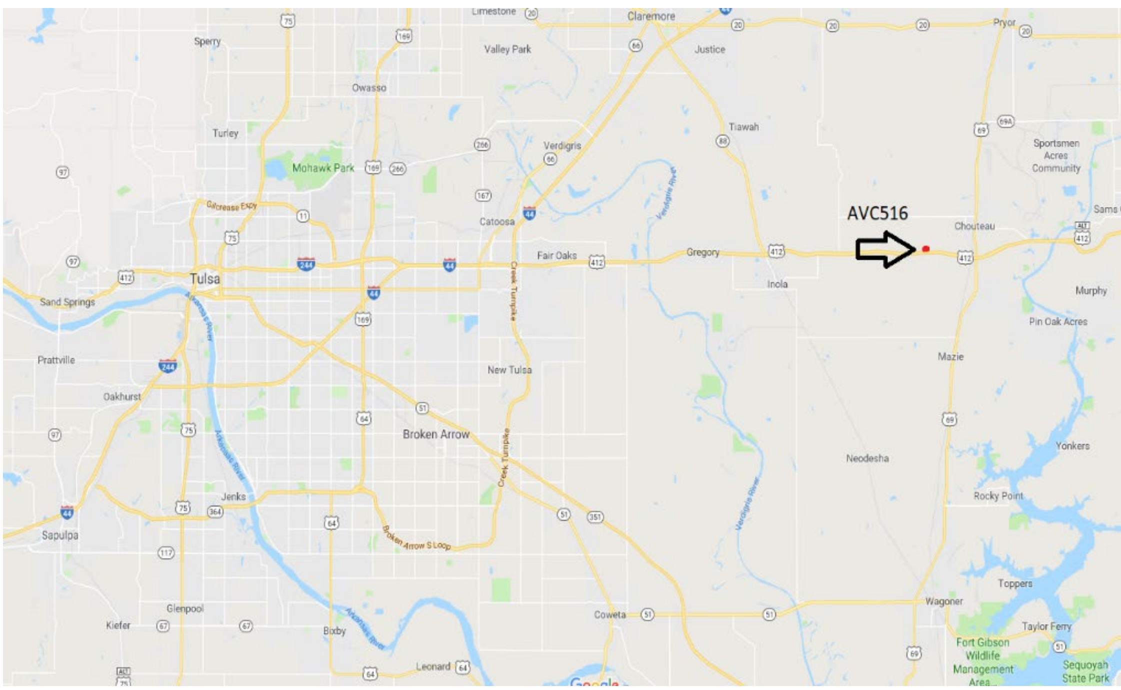


Figure 47. Location of the Fourth deployment.

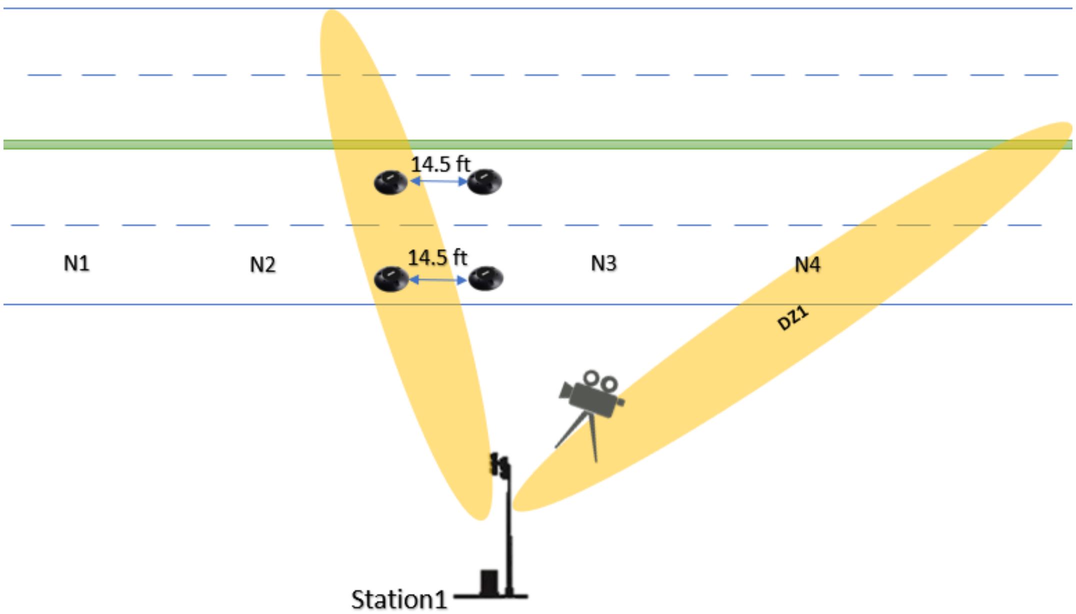


Figure 48. Depiction Layout of the fourth deployment.

- ***Data Processing:***

1- Vehicle classes:

The AVC516 deployment experienced an outage in the directional antenna for three hours. Data were collected for three hours.

a. Camera:

This data represents vehicle groups that were recorded during the full length of the deployment on either the first or second road lane. Total number of vehicles was 1135.

Table 43. Vehicles Groups Extracted from Full Recording on Lane 1

Group	G1	G2	G3	G4
Lane 1	(5) 0.66 %	(620)81.26%	(54)7.08%	(84) 11.01%

Table 44. Vehicles Groups Extracted from Full Recording on Lane 2

Group	G1	G2	G3	G4
Lane 2	(7) 1.88 %	(321)86.29%	(17)4.57%	(27) %7.26

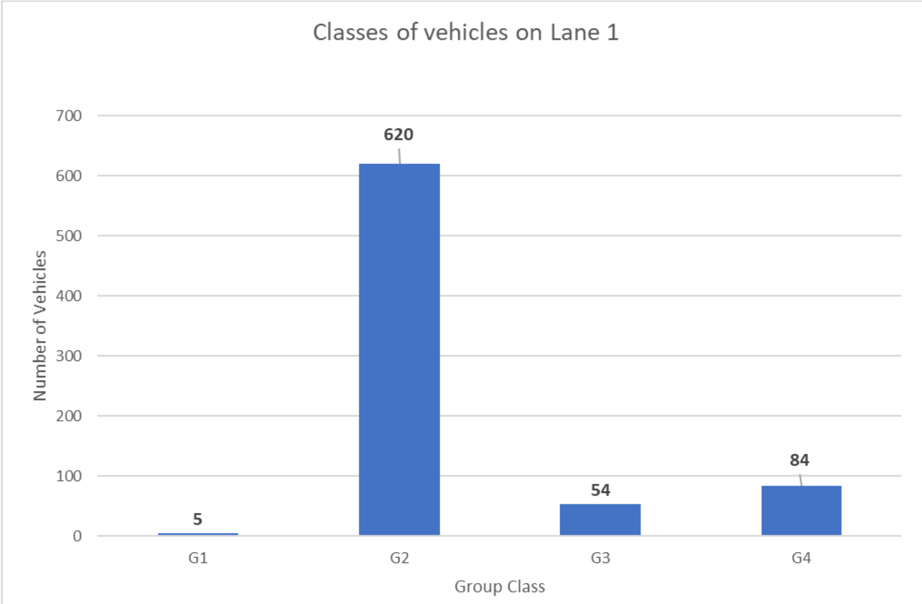


Figure 49. Vehicles classification based on Videos for lane 1

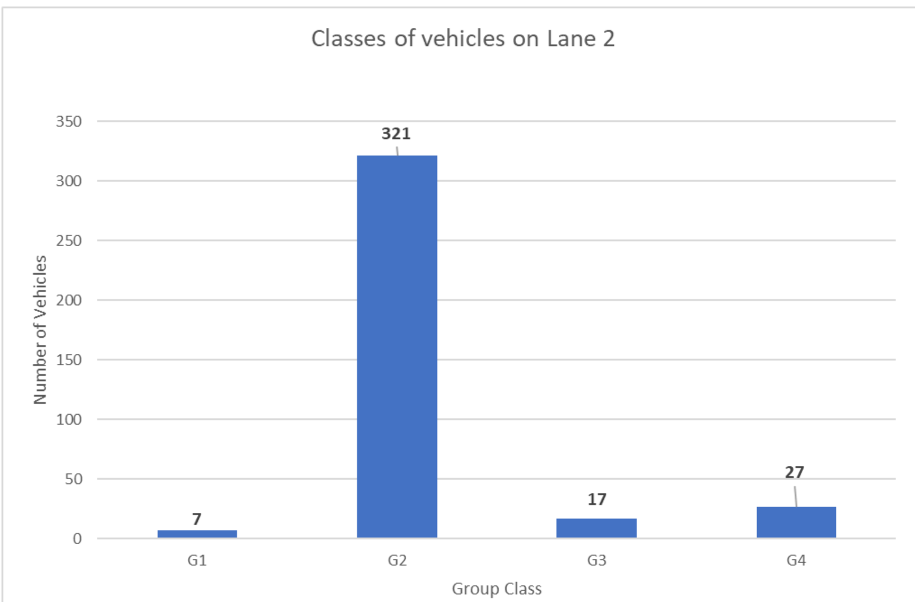


Figure 50. Vehicles classification based on Videos for lane 2

b. Sensors

This data represents vehicle groups extracted from the developed classification algorithm and was based on reported sensor timestamps in the database.

Detected Vehicles on Lane 1: 604
Detected Vehicles on Lane 2: 320

An offline script compared data recorded in the sensor database with Ground Truth data recorded by the video sensor. To accomplish this, the script will compare timestamp and the group classification.

Filtered Vehicles on Lane 1: 322
Filtered Vehicles on Lane 2: 303

Sensor accuracy:
Lane 1: 53.31 %
Lane 2: 94.69 %

Note: Results indicate a technical error in a Lane 1 sensor. A detailed examination indicated Sensor 96 caused errors in output values, which lowered accuracy on Lane 1 to 53.31 %.

c. Matched Data Charts on Lanes 1 and 2

Table 45. Vehicles Groups Extracted from Sensors Matched with Video on Lane 1

Group	G1	G2	G3	G4
Lane 1	0	307	2	13

Table 46. Vehicles Groups Extracted from Sensors Matched with Video on Lane 2

Group	G1	G2	G3	G4
Lane 2	0	272	6	24

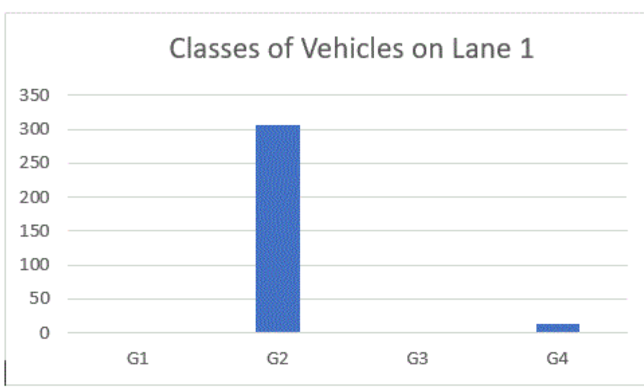


Figure 51. Vehicles classification based on Matched Sensors for lane

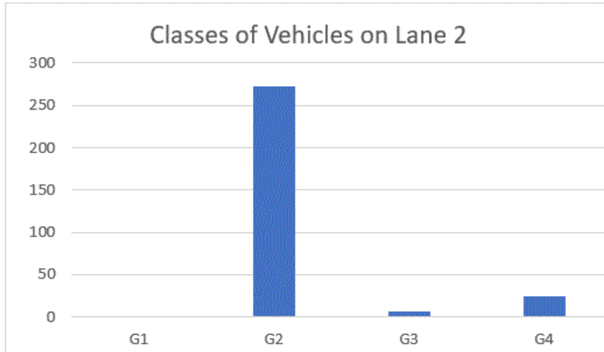


Figure 52. Vehicles classification based on Matched Sensors for lane 2

The following tables show real time results, MAC directionality, and BTA-vehicle assignment algorithms.

Total number of Unique MACs is: 389
Table 47 lists the number of vehicles traveling on Lane 1 and 2 that were assigned both Mac address and Class.

Table 47. Number of Vehicles Matched to Mac and Classified

Number of Assigned MACs	Lane 1	Lane 2
East bound traffic	52	61

Duplicate MACs sensed on Lane 1 and Lane 2, which was filtered out to the values shown in the table below:

Table 48. Number of Vehicles Matched to Mac and Classified with Filtering

Number of Assigned MACs	Lane 1	Lane 2
East bound traffic	40	54

6-1.5 Fifth Deployment

In this reporting period, the research team deployed the system at ODOT AVC516 site. The deployment also included other three stations: one main station on I-44 and another on I-244, as well as a mobile station. The six-hour test occurred on August 15 and evaluated newly developed algorithms along with suggested solutions for maintaining an improved communication link between AP and sensors. The following tables indicate deployment location and layout. The test also examined vehicle TT between the fixed station on AVC516 and the other two locations. The mobile station affixed on the van collected data in five different locations. Results were compared with the main station and included two lanes with two magnetometer sensors for classifying the MAC address in both lanes and maximizing data collection.

- ***Data processing at the Main station***

a. Video:

The data below represent vehicle groups recorded during deployment on both lanes. Total number of vehicles on Lane 1 and 2: **1437**

Table 49. Vehicle Groups Extracted from Full Recording on Lane 1

Group	G1	G2	G3	G4
Lane 1	(5) 0.56 %	(716) 80.63%	(57) 6.41%	(110) 12.38%

Table 50. Vehicle Groups Extracted from the Full Recording on Lane 2

Group	G1	G2	G3	G4
Lane 1	(5) 0.91 %	(489) 89.07%	(24) 4.37%	(31) 5.65%

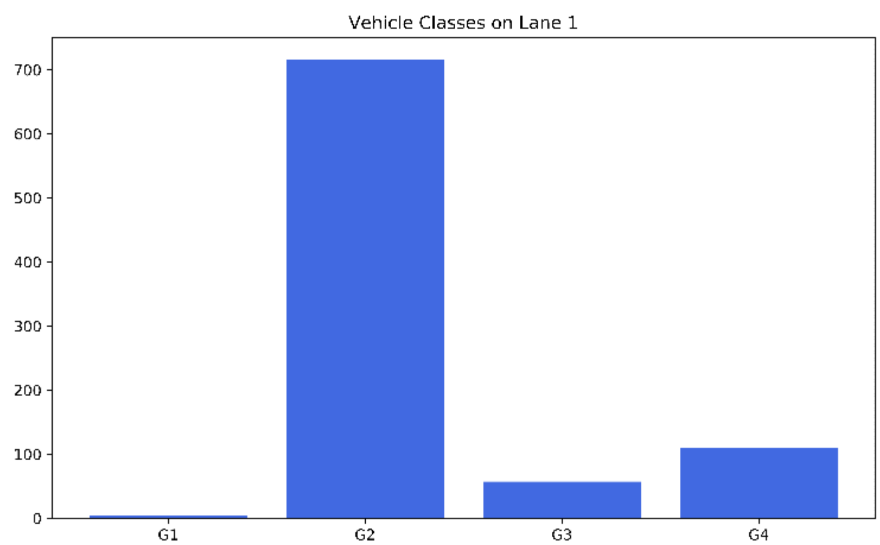


Figure 53. Vehicle groups based on videos for Lane 1.

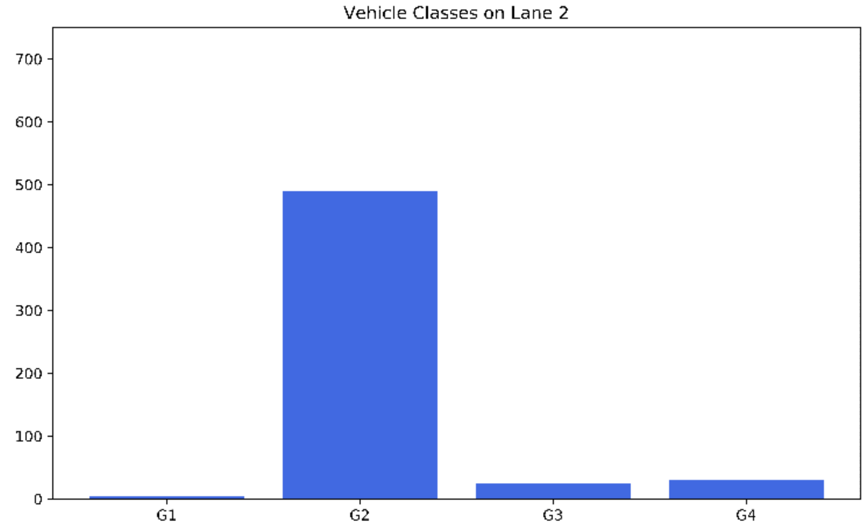


Figure 54. Vehicle groups based on videos for Lane 2.

b. Sensors:

The data below represent vehicle groups extracted from the developed classification algorithm, which were based on reported sensor timestamps in the database.

- Detected Vehicles on Lane 1: **695**
- Detected Vehicles on Lane 2: **342**

An offline script compared data on the sensor database with ground truth data gathered by the video sensor. The script compared the time stamp and group classification.

- Filtered Vehicles on Lane 1: **505**
- Filtered Vehicles on Lane 2: **314**

Sensor accuracy:

- Sensors on Lane 1: **72.66%**
- Sensors on Lane 2: **91.81%**

Matched data charts on Lane 1 and 2:

Table 51. Vehicle Groups Extracted from Sensors Matched with Video on Lane 1

Group	G1	G2	G3	G4
Lane 1	0	421	13	71

Table 52. Vehicle Groups Extracted from Sensors Matched with Video on Lane 2

Group	G1	G2	G3	G4
Lane 2	4	284	4	22

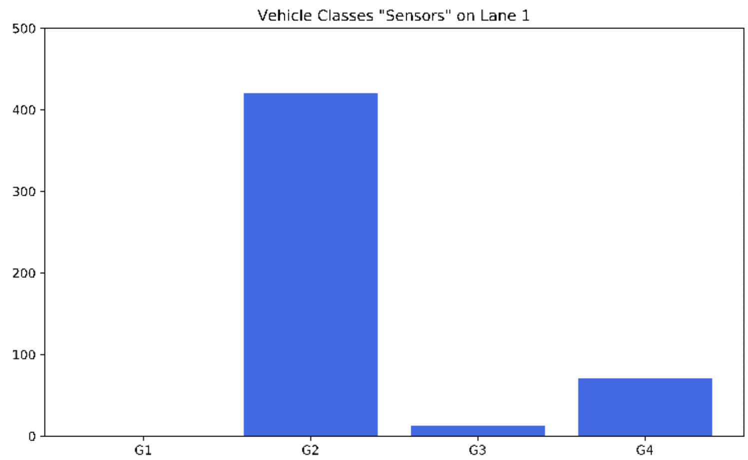


Figure 55. Vehicle classification based on matched sensors from Lane 1.

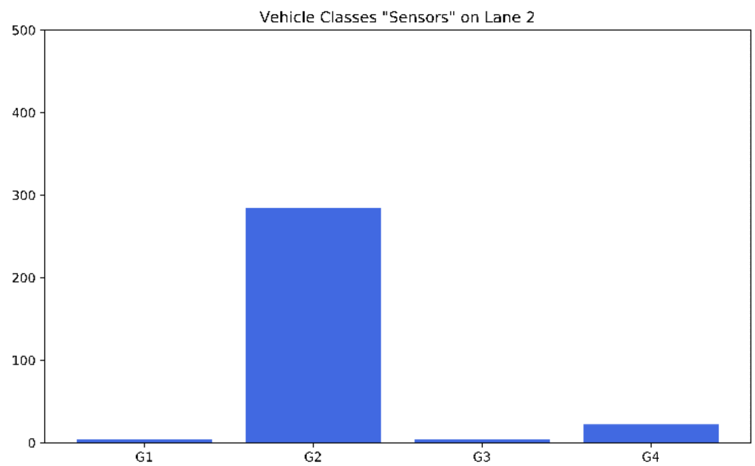


Figure 56. Vehicle classification based on matched sensors from Lane 2.

c. MAC Matched with Vehicles Classes

After collecting the MAC ID from the antenna and the classes values from the sensors facing the antenna. We matched the timestamp between the sensors and the antenna, Once two timestamps are matched with a given tolerance; the vehicle will be classified with a group value and a unique MAC ID.

Table 53 lists the number of vehicles assigned to both MAC address and class on Lane 1 and 2.

Table 53. Vehicle Number Matched to MAC and Classified with Filtering on Lane 1 and 2

Number of Assigned MACs	Lane 1	Lane 2
East bound traffic	173	105

As a conclusion for the deployment to test the origin destination, the percentage of total vehicles that were classified with a group value and unique MAC ID on the main station AVC516:
Lane 1: **19.48 %**
Lane 2: **19.12%**
Figure 57 show a data outlook of the detected vehicles that were classified with a MAC ID and a Group value at the other two located stations on I-44 and I-244. As shown below, the total value of vehicles with a Class/MAC is 278 with a total of 19.34% of what is actual numbers of vehicles recorded by the video. 41 vehicles were recorded on I-44 and 25 vehicles on I-244.

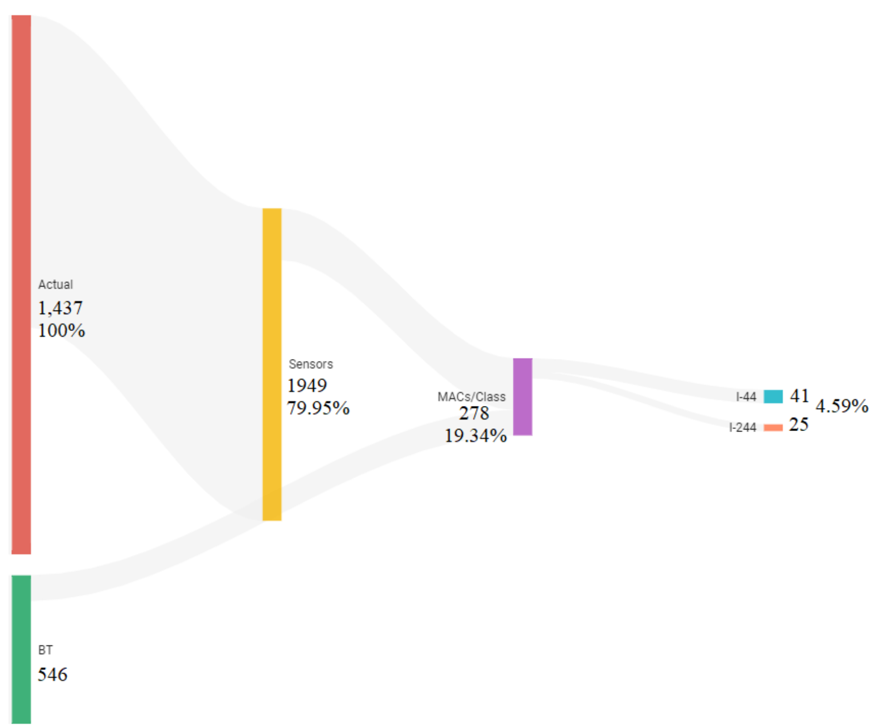


Figure 57: Data Outlook for O/D

- ***Travel Time***

One antenna in the main station was vertical at zero degrees, and the other was positioned at 45 degrees to sense vehicle direction on both roads. To match main station MAC with the other two fixed stations and the mobile station, information from only one antenna detected all vehicles traveling in both directions. Detected MAC on the zero-degree antenna was 1415; 45-degree antenna detected 1636. The difference was caused by the fact that antenna coverage is approximately 300 meters, which covers additional roads, as shown in Figure 58. The figure demonstrates that the antenna detected an additional road, which increased MAC number.

Figure 58. antenna coverage on AVC516

Two fixed stations on I-44 and I-244 and another mobile station were used to verify arrival times (See Figure 58). The directional antenna was equipped with Ubertooth, Beaglebone green, and an AP to verify collected matches in real time between the main and mobile stations.

Figure 59. Mobile station

User can access the mobile station from any location by adding host name and port number. For the test reported here, the research team used the Ngrok host for accessing the station (See Figure 60). A real time counter will display the number of matching vehicles at a fixed refresh rate of 2 seconds.

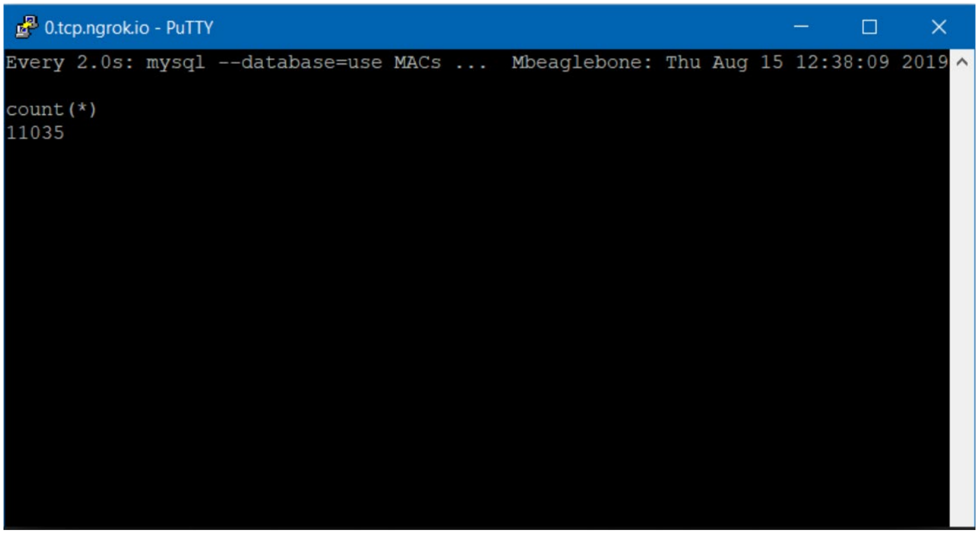


Figure 60. Real time counter

a. **Main Station:**
- Location: 36.170143, -95.383698.
- Number of MAC detected: 1415

b. **Station I-244:**
- Location: 36.1666671, -95.8436227.
- Google Maps distance and arrival time: 27 miles, 25 Minutes.
- Matched MAC from main station: 172

Mean of TT is 1397.7174 seconds, which is equal to 23.3 minutes.

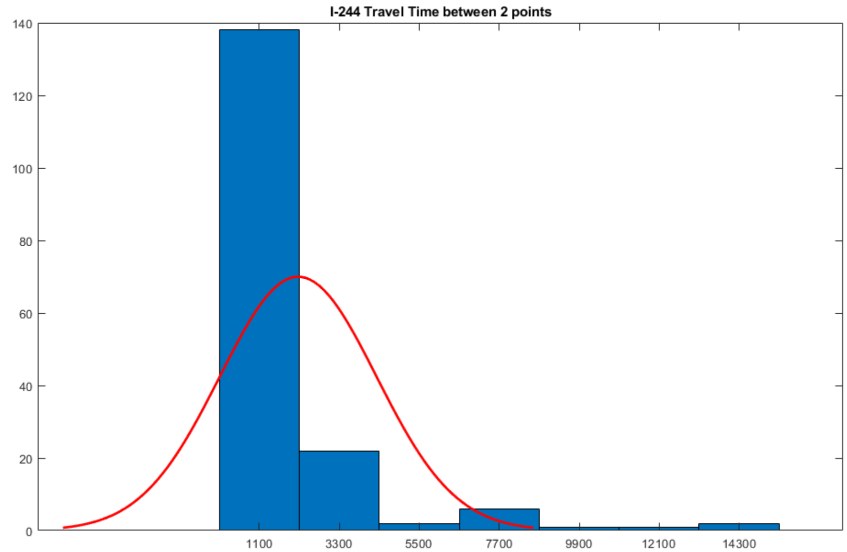


Figure 61. Matched MACs Arrival Time.

c. Station I-44:

- Location: 36.1519992, -95.8425476
- Google Maps distance and arrival time: 26.9 miles, 25 minutes
- Matched MAC from main station: 245

TT mean is 1405.48 seconds, which is equal to 23.4 minutes.

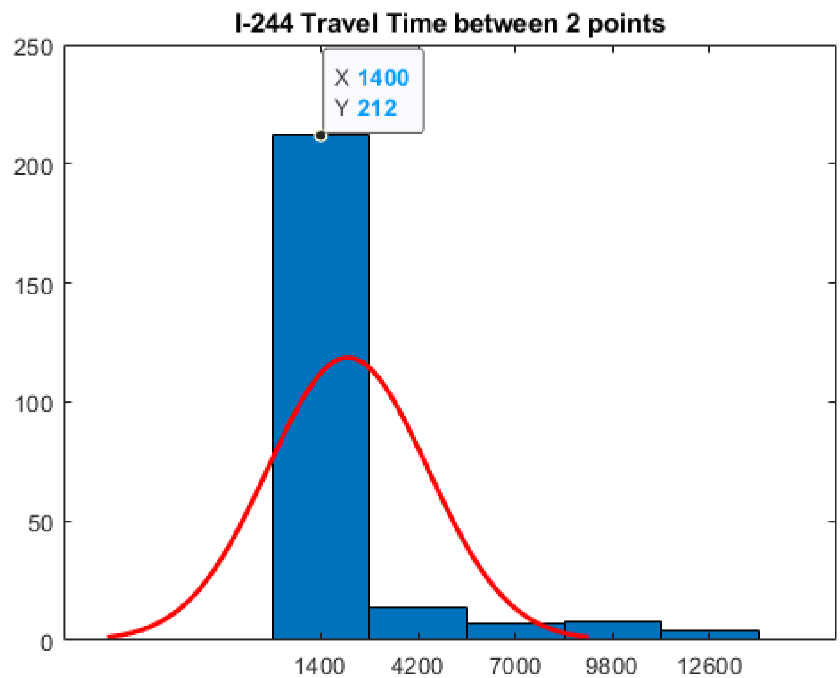


Figure 62. Matched MACs Arrival Time. I-44

d. Mobile Stations

I. 1st Location

- Location: 36.170326, -95.439975
- Time: 10:58 to 11:16 AM
- Travel distance: 3.2 miles
- Expected arrival time: 3 min

Matches to first station: 57
Arrival time: 180 seconds

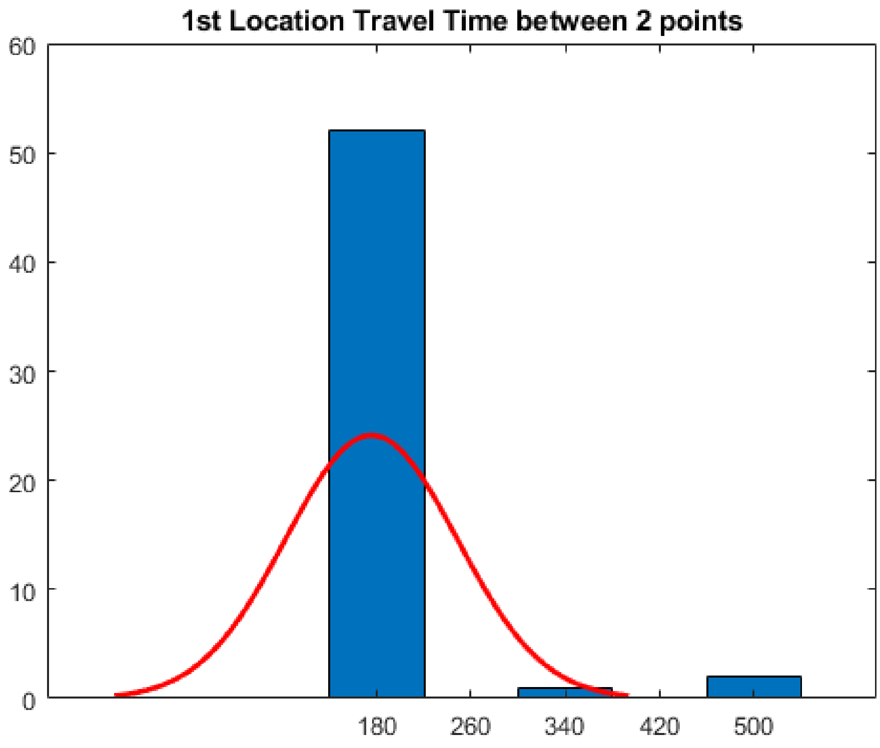


Figure 63. Matched MACs Arrival Time.

II. 2nd Location

- Location: 36.169343, -95.530257
- Time: 11:31 to 11:42 AM
- Travel distance: 8.2 miles
- Expected arrival time: 7 min

Matches to first station: 38
Arrival time: approximately **419.25 seconds,** which is equal to **6.98 minutes**

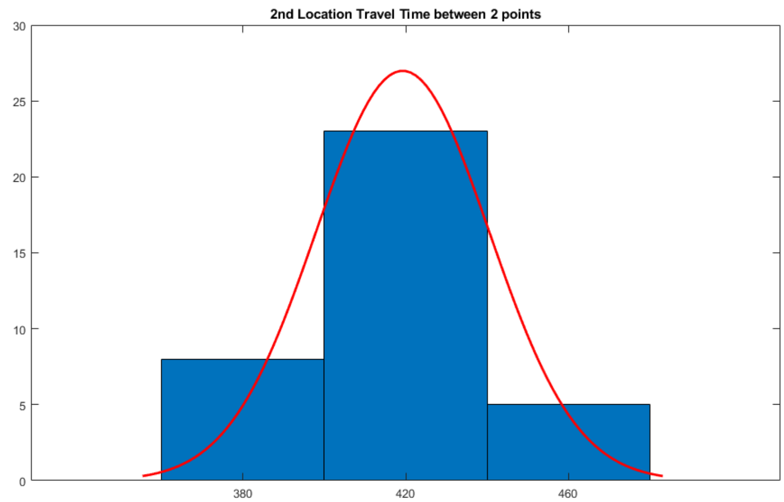


Figure 64. Matched MACs Arrival Time

III. 3rd Location:

- Location: 36.164452, -95.615080
- Time: 12:00 to 12:18 PM
- Travel distance: 13.1 miles
- Expected arrival time: 12 min

Matches to first station: 59
Arrival time: 684.7 seconds, which is equal to **11.4 minutes**

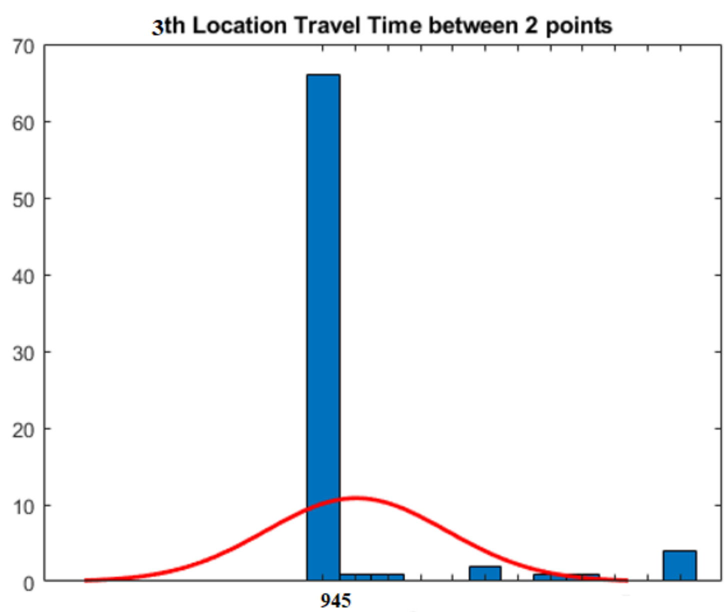


Figure 65. Matched MACs Arrival Time

IV. 4th Location

- Location: 36.162399, -95.768943
- Time: 12:58 to 1:26 PM
- Travel distance: 21.6 miles
- Expected arrival time: 19 min

Matches to first station: 51
Arrival time: 1101.52, which is equal to **18.36 minutes**

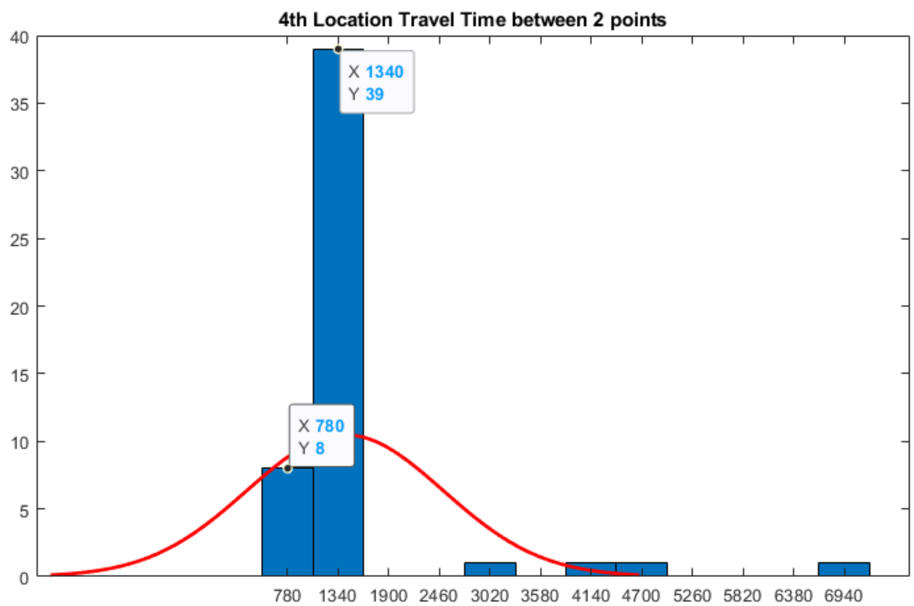


Figure 66. Matched MACs Arrival Time

6-1.6 Origin destination Study:

The main study case of the project is to track the vehicles that is assigned with a class and a MAC address, as the vehicle pass through the main station AVC516, our system that integrates the BT sniffer and the ground sensor will give the vehicle a class value and a unique MAC address. As we mentioned in the last deployment, we added two stations on separate locations at I-44 and I-244 to identify the unique MAC address of vehicles and we used a matching offline algorithm to match only mac addresses between the three locations. We did another offline analysis of the matched MAC addresses with class between the three locations. As mention in the 5th deployment section we matched **172 MACs** on I-244 and **245 MACs** on I-44. The matching between MACs and Class/MACs was 19 on I-244 and 28 on I-44. To visualize the total percentage that the system succeed to capture is **11.04 %** and **11.43%** on both roads. As ODOT is interested in group 4 vehicles, we integrated a breakdown of the real ground truth capture and what that system captured in a total 3 hours of operation.

- The total number of Group-4 captured at AVC516 is **141**
- The total number captured by the sensors is **93**
- Total percentage of sensor captures is **65.96%**
- Total number of MACs assigned to that value is **20** shown at figure 67.
- Total percentage of original captured is **14.18%**
- Total number of matched group-4 between AVC516 and I-44 and I-244 is **8**

Therefore, the total percentage of vehicles group 4 was tracked from AVC516 to the two separate locations is 5.67% in three hours.

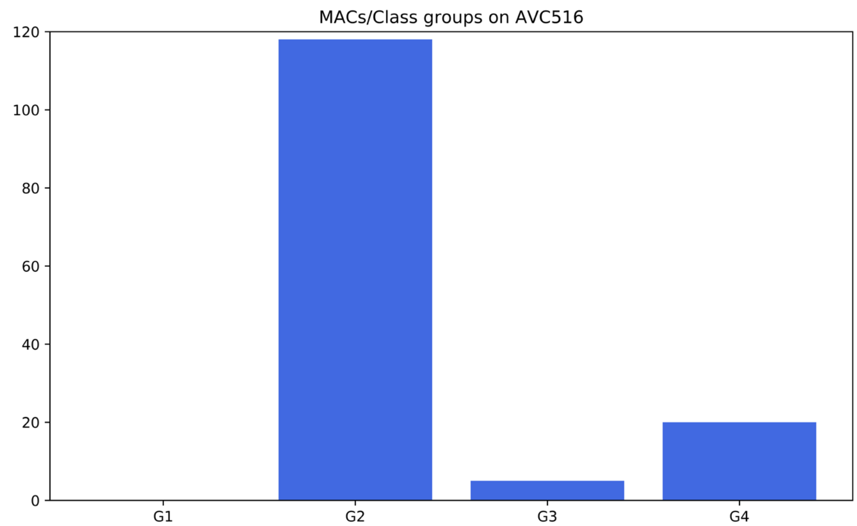


Figure 67. Groups matched vehicles MACs/Class on AVC516

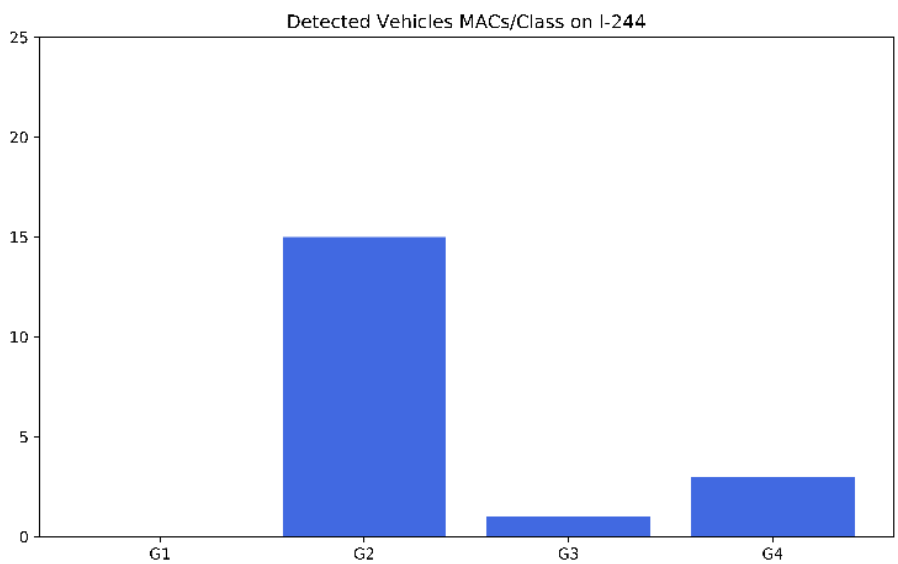


Figure 68. total number of matched vehicles MACs/Class on I244.

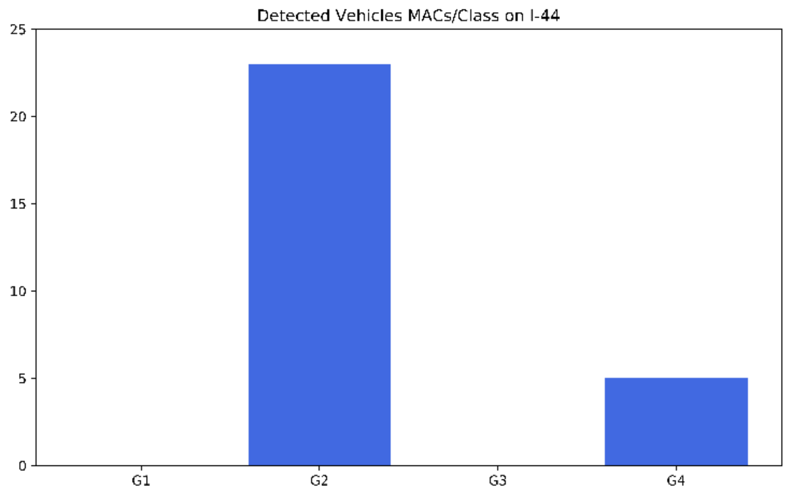


Figure 69. total number of matched vehicles MACs/Class on I44.

To analyze the percentage of vehicles that detected with a MAC/Class to check the quality of the data collected over the three hours, the total amount of Vehicles that assigned with a class and a MAC at the AVC516 are 138. 20.289% detected on I-44 and 13.77% on I-244 with a total of 34.06% of the detected vehicles of all groups. One of the methods to check the difference in the time arrival of each group category as there might be a difference in the period of time arrival between group 2 and 4, despite that the whole number of group 4 that we can visualize is only 8 vehicles in the three hours.

In figure 70&71, the data does not show much useful information for the travel time of each class. The first issue is the lack of data and it can be proved by collecting more information for longer time. Second issue, there are many factors that also can affect the time arrival as road weather condition or any sudden accidents.

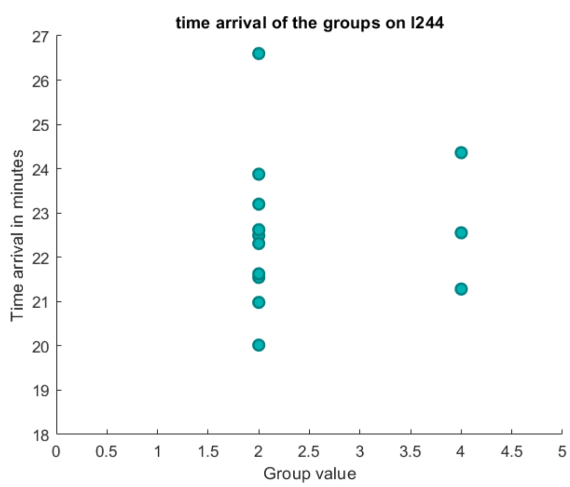


Figure 70. Travel time for each Group at I-244

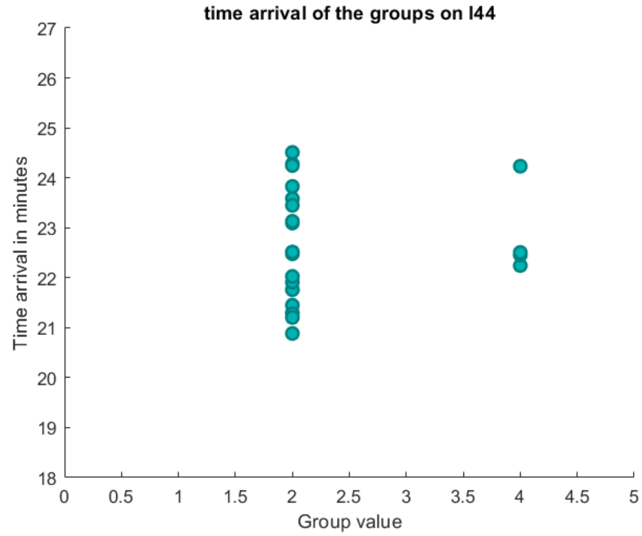


Figure 71. Travel time for each Group at I-44

MACs and MACs/class. This data represents the distribution of vehicle BT IDs (blue distribution) detected during the 3-hour distribution and distribution of BT IDs paired with vehicle classification (red distribution). The bin size used for the distribution calculation was 20-minute bins. The optimal distribution for accurate representation of travel time and origin destination measurements is a uniform for a smaller bin size. The current system needs modification to improve its detection algorithms.

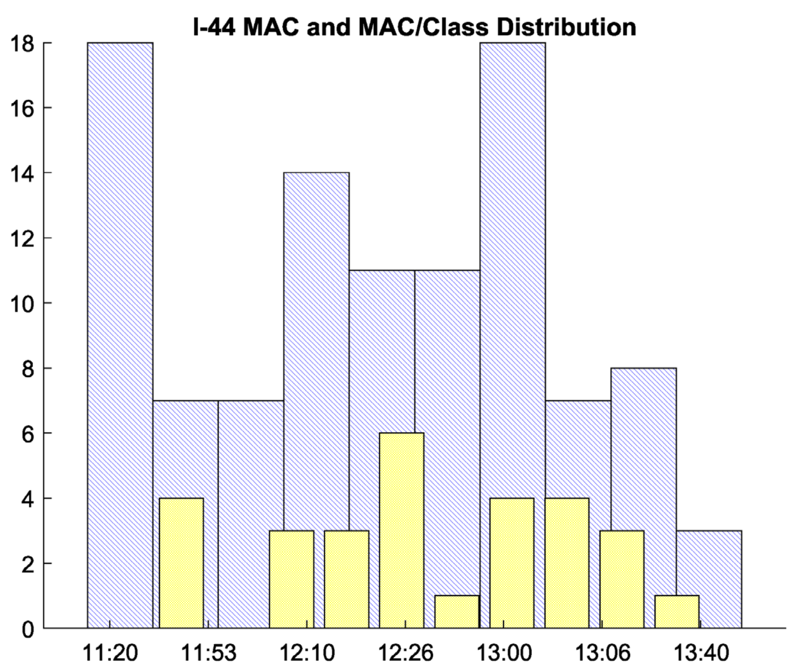


Figure 72. distribution of assigned vehicles MAC/Class vs MACs on I-44.

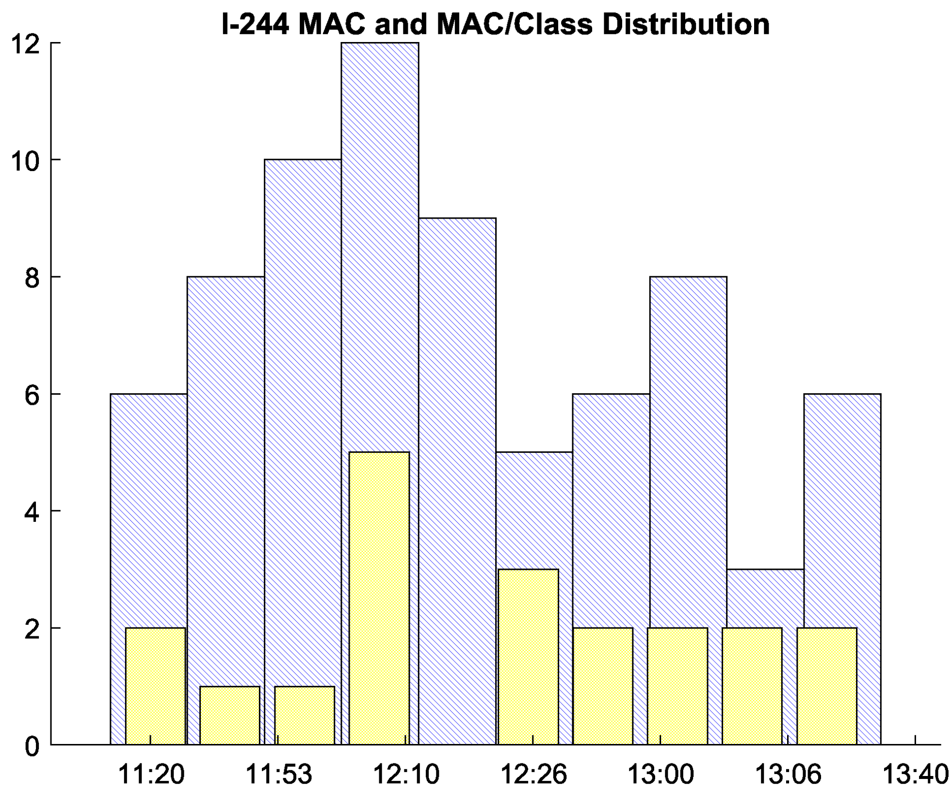


Figure 73. distribution of assigned vehicles MAC/Class vs MACs on I-244

As shown in the data outlook, the system accuracy dropped mostly from the MACs BT detection, that can happen due to many factors, one of them is that the vehicle driver turned off the Bluetooth between the travel time between the two stations, other factor is the speed of scanning of the Ubertooth. The Ubertooth scan with a speed of 100 milli seconds for each channel. The Bluetooth Classic uses 79 channels to transmit data, therefore due to the high speed of the vehicle it can pass before the Sniffer scan all channels, as the vehicle takes almost 0.25 seconds to pass through the antenna.
To test if the Ubertooth can scan all vehicles on the road we added two antennas positioned on the same lane as shown in figure 74, we can see that we are detecting BT MACs from urban areas and it will return with stationary MACs from the houses and stores that are covered by the directional antenna. Therefore, we removed all the MACs that were repeated over the scanning process. The output returned with different MAC addresses from the two antennas which proves that BT scanners doesn't scan all MAC addresses in the 79 channels. As shown in figure 75 Antenna 1 scanned more than antenna 2 scanned, and only they are matched in 942 MACs. Therefore, due to the slow speed of BT scanning we lost **57.61%** of the MACs.

Figure 74. Antennas setup "300 feet of detection"

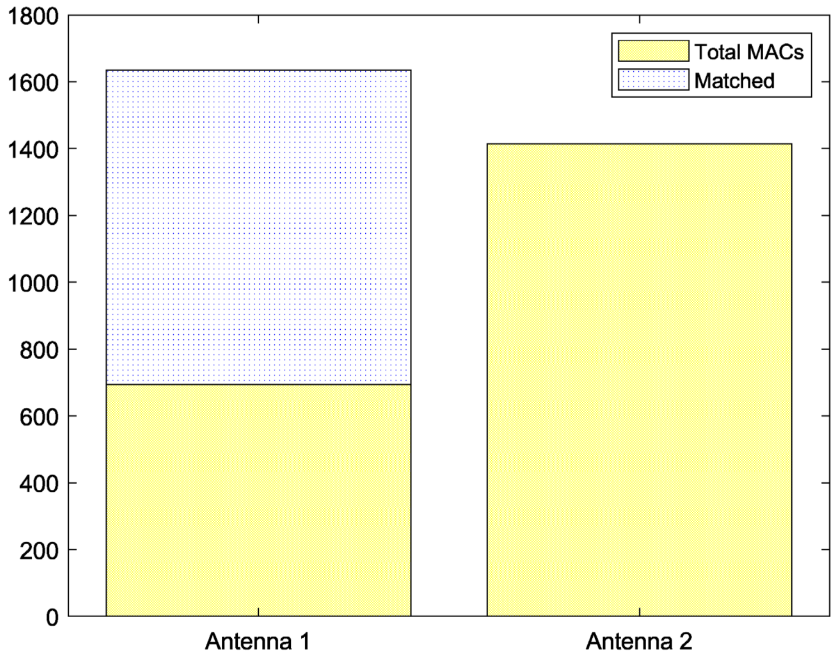


Figure 75. Bar Chart of the matched counts between antennas

7. Vehicle BTA and Class Association

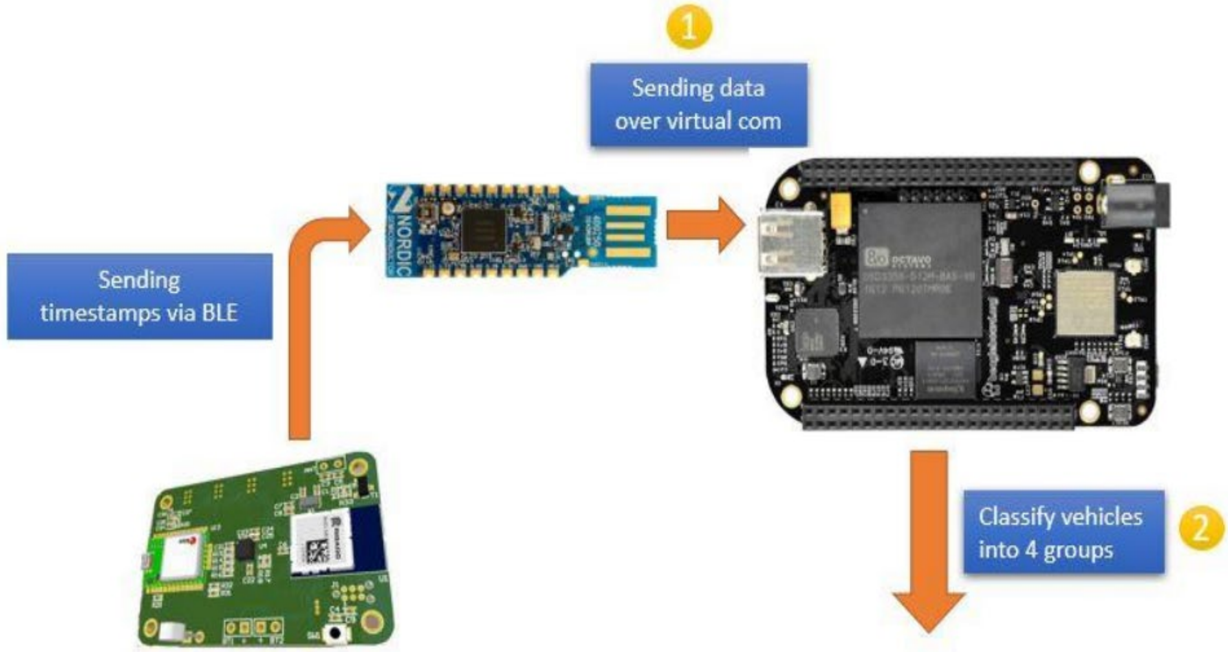
Providing reliable route choices per vehicle class data requires precise vehicle classification and highly accurate BTA-to-vehicle class attachment. Assigning a MAC address to the corresponding vehicle class can be accomplished by matching reported sensor timestamps to MAC detection timestamps. However, received MAC timestamps provide no indication of vehicle travel lane or direction. Thus, temporal analysis will not be sufficient for achieving highly accurate MAC/vehicle class assignment. To overcome this issue and to provide a more reliable solution, unidirectional antennas were used in favor of omnidirectional antennas. Using multiple unidirectional antennas limits DZ for each antenna on specific highway segments and adds a spatial dimension to temporal data. It is important to note that utilizing two antennas establishes a precedence for incorporating two DZ. Hence, two iVCCs were installed between DZ. Given that a vehicle enters the first DZ (DZ1), MAC will initially be captured by the first antenna. After that, two sensors will detect the vehicle and report timestamps to the AP for classifying the vehicle. Next, the vehicle will enter DZ2, wherein the vehicle MAC will be captured and saved in the MAC database. This process will, in turn, trigger the assignment algorithm.

7-1. Vehicle BTA and Class association

1. Software implementation for parsing data received by the BLE dongle and then classifying the detected vehicle is based on received timestamps. Software development occurs in two parts:

   1) read data received by the dongle through a virtual COM
   2) parse it.
   3) Extract information from part one and execute the classification algorithm.

   Figure 76 shows an overview of the system data flow.



Group	FHWA-S_F
G1	F_1
G2	F_2—F_3
G3	F_4—F_7
G4	F_8—F_{13}

Figure 76. Overview of data flow inside the system.

7-1.1 Data Pairing

A BLE dongle enables REECE to communicate with sensors. Accordingly, the dongle will receive timestamps from sensors before forwarding them to REECE. The algorithm flow diagram is shown below in Figure 77. Examples of data sent from iVCCs are shown in Figure 78.

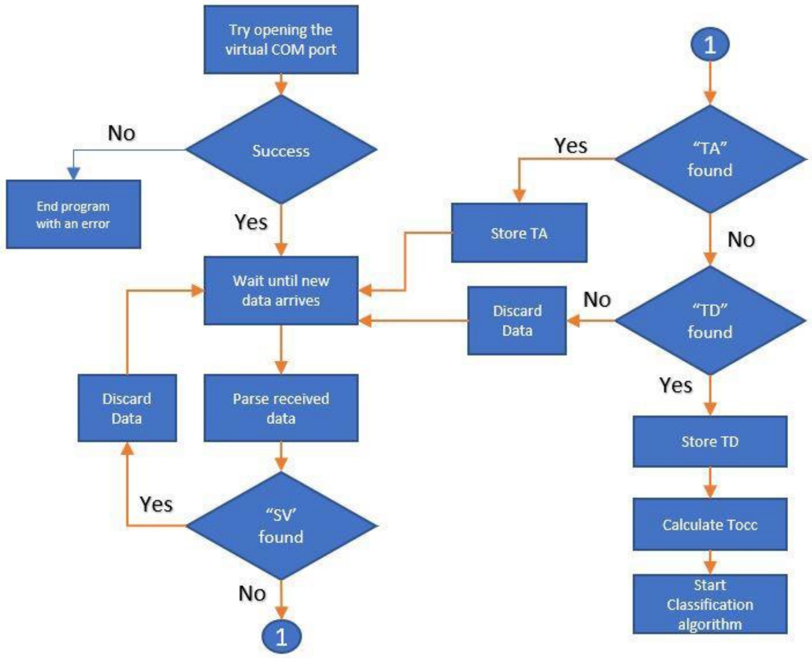


Figure 77. Flow diagram of parsing algorithm.

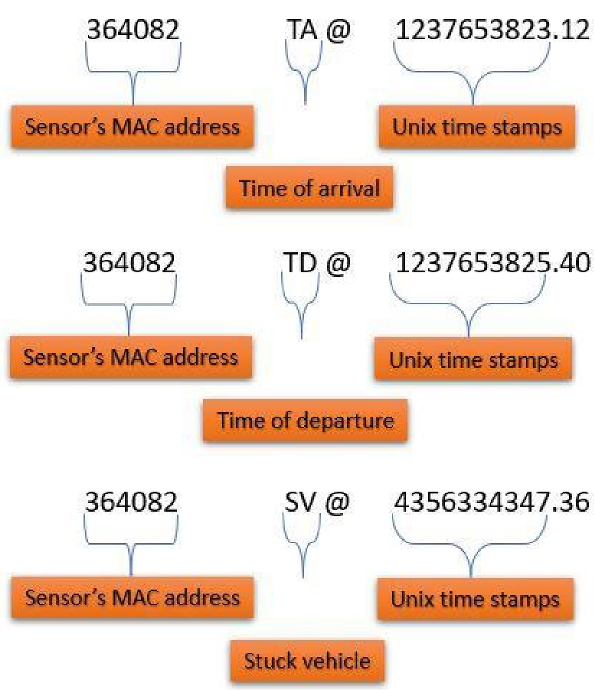


Figure 78. Examples of timestamps sent by the sensor.

Unix timestamps are a method for measuring time in seconds. The first timestamp counter of this type was initiated at Unix epoch on January 1, 1970, at

Universal Time Coordinated (UTC). Each timestamp represents the difference between a date and the Unix epoch. The full parsing algorithm is described in Appendix A.

7-1.2 Classification

Length-based classification is used for classifying detected vehicles into one of four groups. The method relies on two sensors in each lane, which are positioned at a predefined distance. Each sensor reports both arrival and departure time of the vehicle. After parsing collected data, vehicle velocity between sensor nodes NA and NB can be calculated using the following formula:

$$\bar{v}_i \approx \frac{2 \times d^{(N_A \rightarrow N_B)}}{T_A^{(N_B)} - T_A^{(N_A)} + T_D^{(N_B)} - T_D^{(N_A)}}$$

where d is the distance between the two nodes.
Calculated velocity will be used in accordance with the difference between T_A and T_D (T_{occc}) for calculating vehicle magnetic length (**VML**):

$$\overline{VML} = \bar{v} \times T_{OCC}^{(N_i)} = \bar{v} \times \frac{T_D^{(N_A)} - T_A^{(N_A)} + T_D^{(N_B)} - T_A^{(N_B)}}{2}$$

VML is the disturbance in the Earth’s magnetic field caused by the vehicle’s metal mass. The classification algorithm uses calculated VML to classify the vehicle to one of several predefined groups, as described in Figure 79 and 80. Following is the code used to implement the classification algorithm.

```
def ClssifyVehicle(SensorIndex):
    if SensorIndex == 1:
      lane = "L1"
    elif SensorIndex == 3:
       lane = "L2"

    Vi = ((2.0 * distance) ) / ((TA[SensorIndex] - TA[SensorIndex - 1]) + (TD[SensorIndex]
         - TD[SensorIndex - 1]))

    Lm = (Vi / 2 ) * (Tocc[SensorIndex] + Tocc[SensorIndex - 1])

    if (Lm < 2.984):
       print("G1" + " " + str(TA[SensorIndex - 1]) + " " + str(TD[SensorIndex]) + " "
           + str(Vi) + " " + str(Lm) + " " + lane)
       sys.stdout.flush()

    elif (Lm > 2.984 and Lm < 10.971):
       print("G2" + " " + str(TA[SensorIndex - 1]) + " " + str(TD[SensorIndex]) + " "
           + str(Vi) + " " + str(Lm) + " " + lane)
       sys.stdout.flush()

    elif (Lm > 10.971 and Lm < 14.727):
       print("G3" + " " + str(TA[SensorIndex - 1]) + " " + str(TD[SensorIndex]) + " "
           + str(Vi) + " " + str(Lm) + " " + lane)
       sys.stdout.flush()


    elif (Lm > 14.727):
       print("G4" + " " + str(TA[SensorIndex - 1]) + " " + str(TD[SensorIndex]) + " "
          + str(Vi) + " " + str(Lm) + " " + lane)
       sys.stdout.flush()
```

Figure 79. Detailed vehicle classes description.

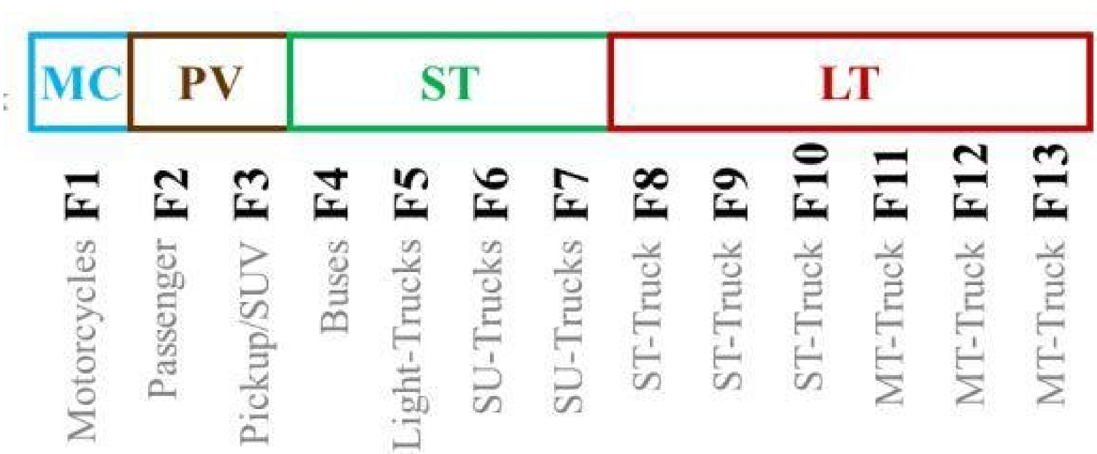


Figure 80. Group Classification.

7-2. BTA/ Vehicle Assignment Algorithm

The second part of the algorithm focuses on finding the lane in which the BTA was detected. Each sensor resides on a lane, with two sensors on each lane. All sensors report timestamps to the AP, which, in turn, aids in classifying the vehicle. Next, database sensors (DB) will store the following: TA1 (i.e., time of arrival for the first sensor on each lane); TD2 (i.e., time of departure for the second sensor on each lane); and vehicle class. The algorithm commences by filtering the database established in the previous step, and then compares each record of the sensor database to records in MAC DB, selecting only BTA that fall within a specific time threshold before TA1 and after TD2. The two highest RSSI values will be assigned to vehicles on Lane 1 and Lane 2, respectively. Figure 80 shows the flow diagram of the algorithm.

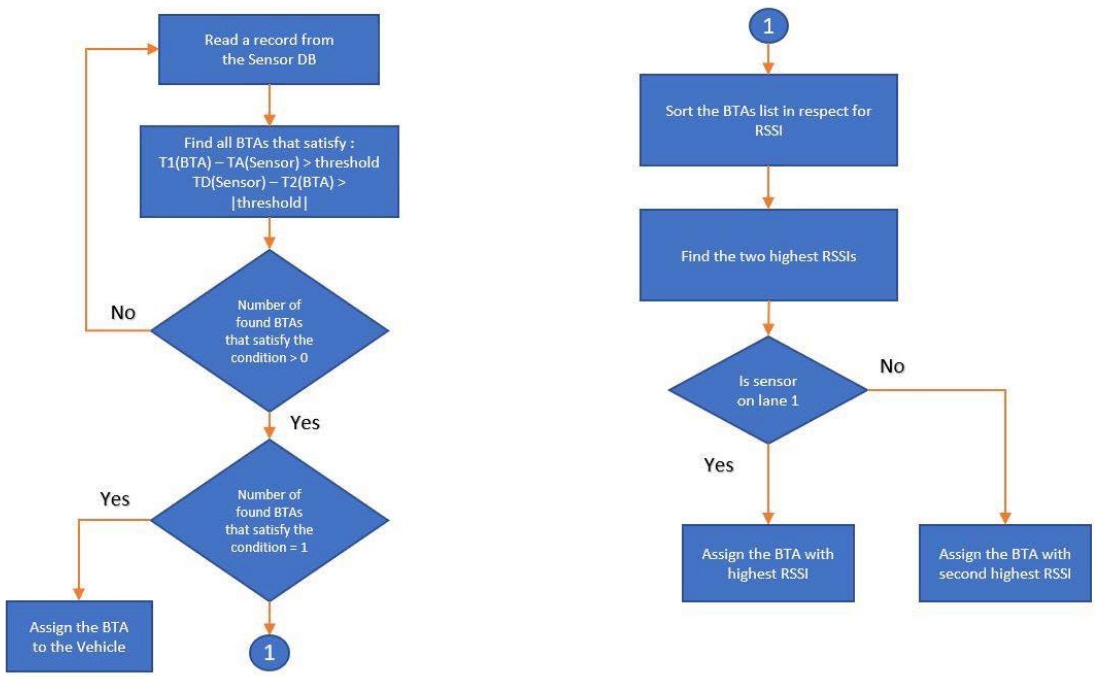


Figure 81. Flow diagram of the BTA/vehicle assignment algorithm.

7-3. Privacy

Because of the unique data gathered by the sensors, collecting and analyzing BTA introduces privacy concerns. These legitimate fears should be addressed by researchers so that the organization can offer BT users assurance that their data will not be shared or used in any way to threaten their privacy. Protocols were followed for the research discussed in this report, adhering to the conduct of protecting driver privacy, as follows:

1- BTA is in no way connected to the person using the BT device.

2- Only the lower half—LAP—of the BTA was collected.
3- BTA databases were cleared each time 20,000 records were recorded.

References

(1) "Smart City Priority Areas. " Smart City Priority Areas, The Information and Communications Technology Council, 2019, www.ictc-ctic.ca/wp-content/uploads/2019/2019/08/ICTC_smart-city-Priority-Areas_Brief_ENG-8.19.19.pdf

(2) Harrison, C., Eckman, B., Hamilton, R., Hartswick, P.,Kalagnanam, J., Paraszczak, J., &Williams, P. (2010). Foundations for Smarter Cities. IBM Journal of Research and Development, 54(4).

(3) Washburn, D., Sindhu, U., Balaouras, S., Dines, R. A., Hayes, N. M., & Nelson, L. E. (2010). Helping CIOs Understand "Smart City" Initiatives: Defining the Smart City, Its Drivers, and the Role of the CIO. Cambridge, MA: Forrester Research, Inc.

(4) Giffinger, R., Fertner, C., Kramar, H., Kalasek, R., Pichler-Milanović, N., & Meijers, E. (2007). Smart Cities: Ranking of European Medium-Sized Cities. Vienna, Austria: Centre of Regional Science (SRF), Vienna University of Technology. Available from http://www.smartcities.eu/download/smart_cities_final_report.pdf

(5) Chourabi, H., Nam, N., Walker, S., Gil-Garcia, J.Ramon., Mellouli, S., Nahon, K., Pardo,T., & Jochen Scholl, H. 2012 45th Hawaii International Conference on System Sciences, Understanding Smart Cities: An Integrative Framework

(6) Gartner. (2014, March 19). Gartner says the Internet of Things will transform the data center. Retrieved from http://www.gartner.com/newsroom/id/2684616

(7) J. Gantz and D. Reinsel, "The digital universe in 2020: Big data, bigger digital shadows, and biggest growth in the far east," IDC iView: IDC Anal. Future, vol. 2007, pp. 1–16, Dec. 2012

(8) https://www.statista.com/statistics/764026/number-of-iot-devices-in-use-worldwide/

(9) Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., Ayyash, M., IEEE COMMUNICATIONS SURVEYS &AMP TUTORIALS · JANUARY 2015 Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications

(10) Atzori, L., Iera, A., Morabito, G., The International Journal of Computer and Telecommunications Networking (October 2010) The Internet of Things: A Survey

(11) D. S. Kim, J. D. Porter, S. Park, A. Saeedi, A. Mohseni, N. Bathaee, and M. Nelson, Bluetooth Data Collection System for Planning and Arterial Management.

(12) W. Wang, J. Attanucci, and N. Wilson, "Bus Passenger Origin-Destination Estimation and Related Analyses Using Automated Data Collection Systems," J. Public Transp., vol. 14, no. 4, pp. 131–150, Dec. 2011

(13) Large Truck Origin Destination Monitoring | Freight Planning, New Jersey, 2008
(14) Blogg, M., Semler, C., Hingorani, M., Troutbeck, R. Australasian Transport Research Forum 2010 Proceedings 29 September – 1 October 2010, Travel Time and Origin-Destination Data Collection using Bluetooth MAC Address Readers.
(15) Y. Wang, B. N. Araghi, Y. Malinovskiy, J. Corey, and T. Cheng, “Error Assessment for Emerging Traffic Data Collection Devices: WSDOT Research Report,” Seattle, Washington, 2014
(16) Calabrese, Francesco, Giusy Di Lorenzo, Liang Liu, and Carlo Ratti. “Estimating Origin-Destination Flows Using Mobile Phone Location Data.” IEEE Pervasive Computing 10, no. 4 (April 2011): 36–44.
(17) G. Schiffer, R., Tools of the Trade Conference on Transportation Planning for Small and Medium-sized Communities (September 2016), Alternate Methodologies for Origin-Destination Data Collection, retrieved from http://www.trbtoolsofthetrade.org/files/theme/C2-4-presentation.pdf
(18) Electronic Frontier Foundation, https://www.eff.org/pages/automated-license-plate- readers-alpr
(19) License Plate Matching Techniques, https://www.fhwa.dot.gov/ohim/handbook/chap4.pdf
(20) Carpenter, C., Fowler, M., J. Adler, T. Journal of the Transportation Research Board (January 2012) Generating Route-Specific Origin–Destination Tables Using Bluetooth Technology
(21) Stephanie Box (December 2011) Arterial Roadway traffic Data Collection Using Bluetooth Technology [22] Vinagre Díaz, J., González, A., Wilby, M., IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS, VOL. 17, NO. 1, JANUARY 2016, Bluetooth Traffic Monitoring Systems for Travel Time Estimation on Freeways
(22) Murphy, P., Welsh, E., Frantz, J. P. 2002. Using Bluetooth for short-term ad hoc connections between moving vehicles: a feasibility study. Vehicular Technology Conference. IEEE 55th Vehicular Technology Conference. VTC Spring 2002 (Cat. No.02CH37367), 1, 414-418. doi:10.1109/VTC.2002.1002746
(23) Khliefat, I. and Shatnawi, I. (2017) An Optimization of Bluetooth Sensor Locations for Origin Destination in an Urban Network. Journal of Transportation Technologies, 7, 367- 375.
(24) J.C.Haartsen,“The Bluetooth radio system,”IEEEPers. Commun.Mag., vol. 7, no. 1, pp. 28–36, Feb. 2000.
(25) https://macaddresschanger.com/what-is-bluetooth-address-BD_ADDR