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16. ABSTRACT

The California Department of Transportation (Caltrans) is actively working to reduce the occurrence and severity of wrong way driving (WWD) on California's highways. The traditional approach was using radar and/or vision sensors, which is ineffective and costly for large deployment. Thus, the infrastructure-free detection application implemented by Bosch is being considered. The application algorithm has had success with deployment in Europe; thus, it may be a reliable and readily available technology for WWD detection. This project is testing and evaluating Bosch's system for accurate and reliable WWD event detection.

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Evaluation of the Bosch Mobile Device App for Wrong-Way Driver Detection

Anh Duong, Vic Reveles &
Ty Lasky: Principal Investigator

Report Number: CA23-3948
AHMCT Research Report: UCD-ARR-23-06-30-01
Final Report of Contract: 65A0749 Task 3948

April 5, 2023

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

AHMCT conducted this research to determine whether the wrong-way driver (WWD) detection algorithm implemented by Bosch is suitable for the California Department of Transportation's (Caltrans) purposes. To test the algorithm, the Bosch team created a wrong-way driver warning (WDW) application embedded with their wrong way driver detection technology. The WDW application was specially created for testing purposes; thus, it is not available for public use. The Bosch team does not have a standalone wrong-way driver detection application; instead, Bosch's algorithm is integrated into partner applications to make their detection technology available to the public. These partner applications include Sygic, nDrive, Flitsmeister, Radioplayer, Antenne Bayern. Sygic GPS Navigation & Maps is the first application in North America to have implemented Bosch's algorithm, and it is available to download in the US and Canada.

After determining the conditions under which the WDW application would issue alerts, the AHMCT team carried out testing. First, the test ramps were planned out in the Davis and Sacramento areas, with five test ramps in total. The AHMCT team drove on these test ramps while Bosch monitored the AHMCT team live. When the first testing sessions were successful, the Bosch team no longer monitored the AHMCT live feed moving forward. Without the live-monitoring, the alerts were still pushed out as expected. The results show that the algorithm has the capability to detect wrong way drivers in a timely, cost-effective manner.

Problem, Need, and Purpose of Research

Caltrans needs a means to reliably detect wrong way driving behavior that avoids the costs and drawbacks of fixed infrastructure approaches. The WDW algorithm implemented by Bosch has the characteristics Caltrans is looking for to resolve the issue. The purpose of this research is to study how compatible the WDW application is to Caltrans' needs.

Background

The WDW application implemented by Bosch employs a wrong way driving detection algorithm. This algorithm has been implemented in Europe, and the results were successful. AHMCT took interest in this success and collaborated with Bosch to evaluate the algorithm's use in the US. Certain conditions have to be met for the WDW application so that an alert can be issued. Bosch assumptions for wrong way driving behavior are:

- After receiving an alert, the drivers are expected to pull over. In most cases, drivers do not drive in the wrong direction intentionally.
- Drivers are unlikely to enter two different ramps directly one after the other. If someone enters the highway two times in the wrong direction and still has the same ID (driver has not left the hotspot), Bosch will not send out a warning upon entry onto the second ramp.
- Drivers are more likely to be confused about direction when there are not many vehicles around. In other words, wrong way driving situations are more likely to occur when there is little to no traffic.
- Drivers should not be stationary on the ramps for more than ten minutes. The WDW application is limited in how many data points it can collect due to concerns about data privacy protection. The ten-minute limitation can be adjusted according to operational needs.

The AHMCT team needed to understand the WDW application characteristics so that the evaluation could be fair.

Overview of the Work and Methodology

AHMCT coordinated with Bosch to determine the test locations and procedures. Ramps in the Davis and Sacramento areas were selected. After the locations were determined, the routes were planned out to ensure the testing process would run smoothly. In this research, the AHMCT team travelled in the expected (normal) travel direction of the ramps so that no ramp closure was needed. The Bosch team reversed the expected travel direction on the WDW application by reversing the heading of the ramps in the database. Therefore, AHMCT team members would still expect alerts from the WDW application even though they were traveling in the correct direction on the test ramps. The AHMCT team drove on the selected test ramps and expected the WDW application to push out alerts, ideally before the drivers entered the main freeway. The Bosch team sent documentation of the alerts generated by the WDW application the next day in comma separated value (CSV) files so that the AHMCT team could compare the time delay between when the signal was sent in Germany and when the signal was actually received in the US. Caltrans requested that each ramp was trialed ten times in total to ensure the accuracy of the results.

Major Results and Recommendations

From the test results, the WDW application has a 100% rate of sending out alerts at expected locations. The WDW algorithm effectively detects wrong way drivers in a reasonable period of time, with a time delay of up to five seconds in this evaluation. The WDW application is a great alternative for sensors that require physical installation and are expensive to procure and install. Bosch is working with car manufacturers in Europe to implement its technology directly into vehicles. Therefore, the Bosch algorithm can potentially accommodate Caltrans' need of detecting WWDs.

Bosch's WDW algorithm provides alerts to drivers. It is the driver's responsibility to determine and take appropriate corrective actions based on local conditions. Bosch does not recommend a particular action to the drivers for a WWD event; the Bosch system is strictly for identifying WWD behavior and issuing corresponding alerts.

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Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
CHP	California Highway Patrol
CMS	Changeable Message Sign
COTS	Commercial Off–The-Shelf
CSV	Comma Separated Value
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
NMEA	National Marine Electronics Association
OEM	Original Equipment Manufacturer
SDK	Software Development Kit
TMC	Transportation Management Center
WDW	Wrong-way Driver Warning
WWD	Wrong-Way Driving

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Chapter 1: Introduction

Problem

The California Department of Transportation (DOT) (Caltrans) is actively working to reduce the occurrence and severity of wrong way driving (WWD) on California's highways. These efforts include recent research and Caltrans pilot studies to identify WWD causes and the benefits of specific mitigations.[1, 2] Typical systems and methods for identifying WWD behavior are based on radar and/or vision sensors and require fixed installation at key sites. Since these systems require fixed installations and are relatively expensive, they may be prohibitive for widespread deployment. As such, the benefits cannot be fully realized in a timely and cost-effective manner. Caltrans needs a means to reliably detect WWD behavior that avoids the costs and drawbacks of fixed infrastructure approaches.

Objectives

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center evaluated a specific WWD detection system which uses either an in-vehicle system or a smartphone app. AHMCT used a custom-designed smartphone app for this test. The system, developed by Bosch, uses a roadway map network, mobile position tracking using a Global Navigation Satellite System (GNSS) such as the Global Positioning System (GPS), and an intelligent algorithm to detect WWD behavior and issue warnings or alerts as appropriate. AHMCT worked with Bosch to identify ramps for targeted testing and to obtain its smartphone app and evaluate the resulting performance of the Bosch system.

[1] T.A. Lasky, K.S. Yen, and B. Ravani, "Evaluating Wrong-Way Driving Incidents at Highway Exit Ramps and the Effect of Mitigation," *ASCE Journal of Transportation Engineering, Part A: Systems*, vol. 147, no. 12, December 2021

[2] T. Bucko, "Wrong Way Prevention Pilot Projects for Prevention of Wrong Way Collisions on Freeways," California Department of Transportation, 2019.

Scope

The research project scope included the following tasks:

1. Manage project
2. Develop test plan
3. Execute WWD testing
4. Assess feasibility of issuing live warnings
5. Evaluate test results
6. Develop final report

Background

This research and its results focus on Caltrans' stated goal of Safety First. The focus is on evaluating a commercially available WWD detection system. If the results are positive, this system is readily available. As part of the proposed research, AHMCT will discuss with the panel options for widespread deployment in California or nationwide. AHMCT is also working with Caltrans and Bosch to assess the feasibility and merit of issuing live warnings, including providing information to Transportation Management Centers (TMC), California Highway Patrol (CHP), and to the driving public using Changeable Message Signs (CMS). The resulting safety benefits may be substantial.

AHMCT attended preliminary meetings with Bosch and Caltrans in preparation for the research. Bosch conveyed some of the statistics for the European use of their system. In 2021, the system evaluated 1.6 billion driving directions and issued 305 WWD alerts, including on average 10 additional alerts to affected drivers not in the primary vehicle. For these 305 incidents, there was no publicly reported WWD accident. These data provide a strong indication of the effectiveness of the system and its promise for use in California and beyond.

Research Methodology

The AHMCT Research Center obtained Bosch's smartphone app, identified ramps for targeted testing, and evaluated the resulting performance of the Bosch system. The map database for the identified ramps was modified by Bosch to support the testing. WWD is typically associated with drivers incorrectly entering the freeway by way of exit ramps. In this research, AHMCT worked with entrance ramps. Bosch modified the database by reversing the expected direction of travel for each of the test ramps. In this way, AHMCT researchers were able to drive in the real-world correct direction on the on-ramps and flyovers, but the Bosch system would recognize this as WWD behavior and issue a warning. As such, there was no need for special ramp closures to perform testing. Researchers simply drove the test ramps in the normal direction in their test vehicle while carrying the smartphone with the Bosch application installed. AHMCT evaluated the performance of the Bosch system, particularly looking for "false negatives," i.e., driving on a test ramp with no warning being issued. AHMCT did not assess "false positives," i.e., cases where a WWD warning is issued but no WWD event has occurred; such behavior is far too rare and is best assessed from the performance of Bosch's extensive European deployment. False positives were not included in the analysis and are not included in this final report. This report provides AHMCT's final assessment of the Bosch WWD detection system and makes recommendations for future implementation.

AHMCT researchers selected the test ramp set, which consists of five ramps, including three involving the challenging US 50/I-5 interchange. Two ramps are in Davis (Figure 1.1) and three are in Sacramento (Figure 1.2). The ramp names and the approximate starting location (in the normal travel direction) are provided in Table 1.1. In Table 1.1, the source junction and destination junction are Bosch's internal notation for each ramp, while ramp # is used by AHMCT. Table 1.1 provides a mapping.

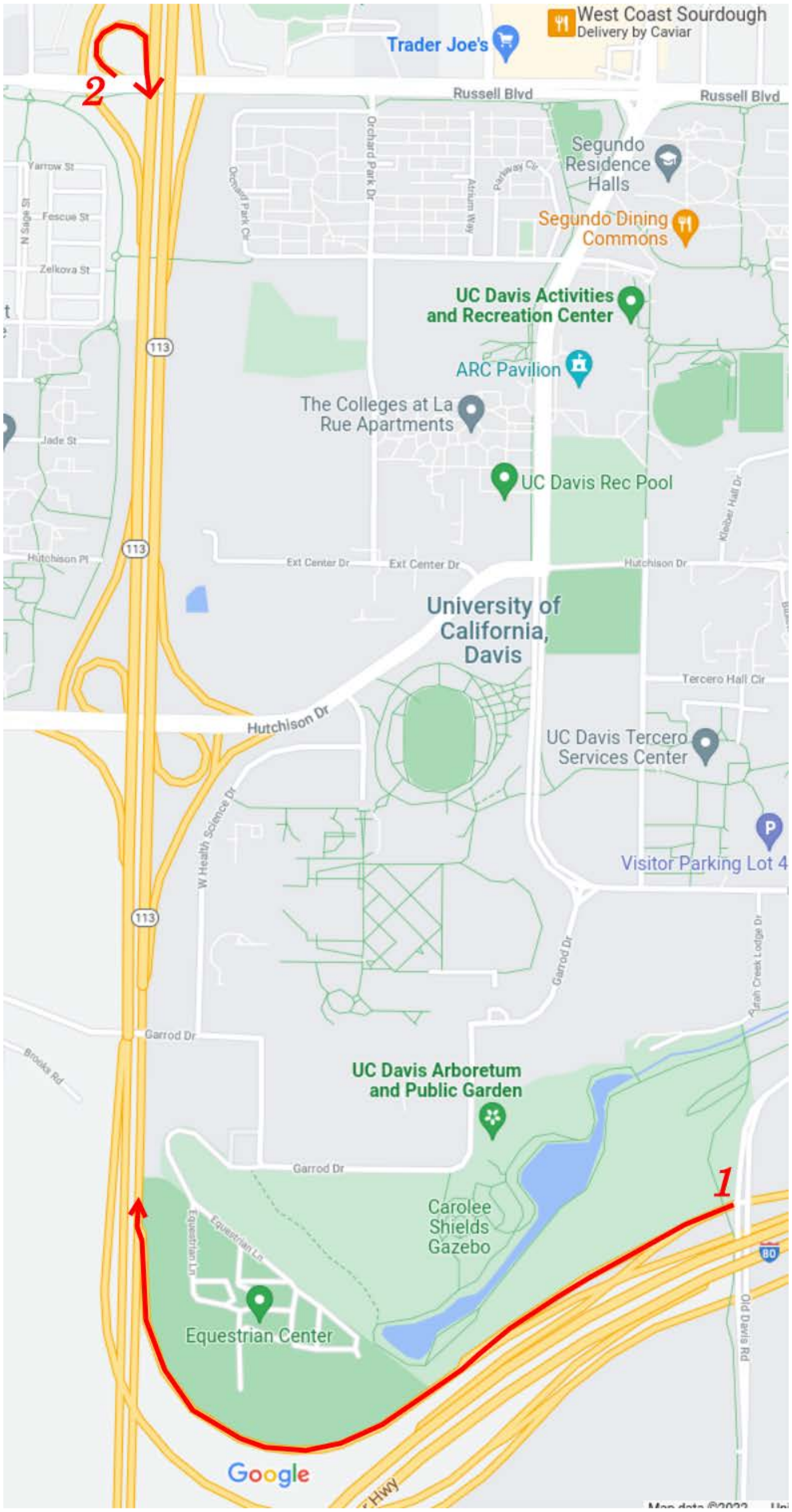

Figure 1.1: Candidate test ramps in Davis

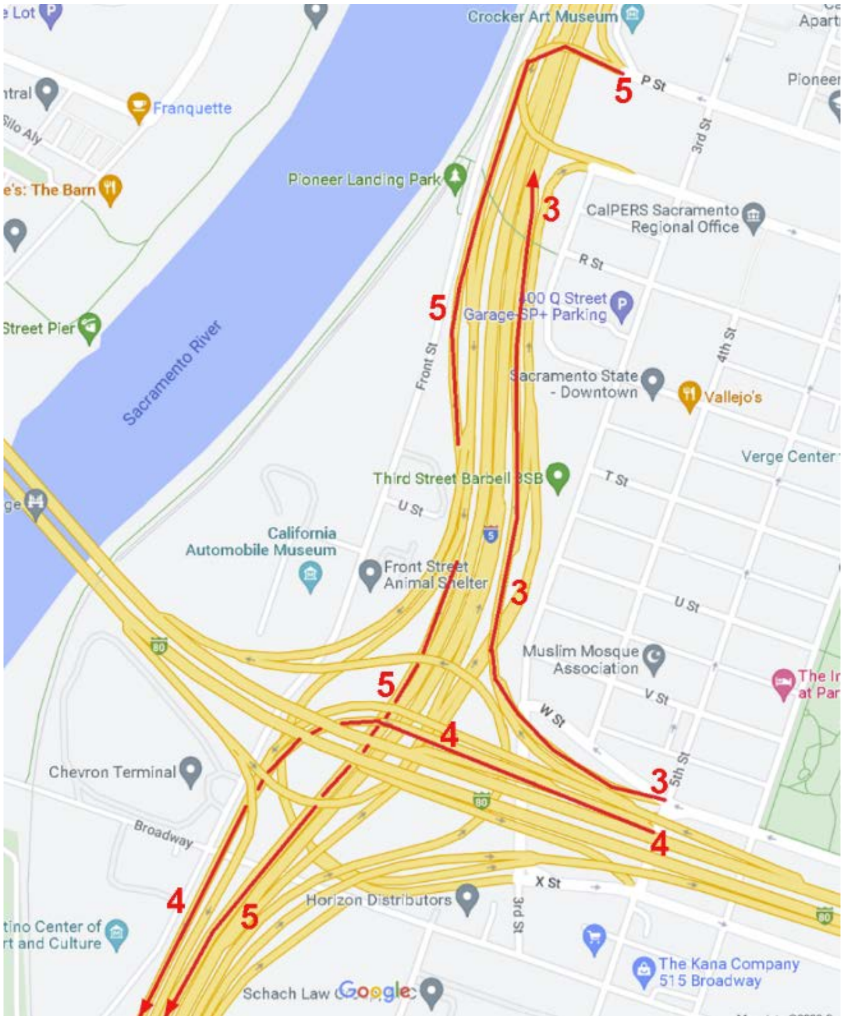

Figure 1.2: Candidate test ramps in Sacramento

Table 1.1: Candidate test ramps including Bosch source and destination junction numbers

#	Ramp	src-junction	dest-junction
	Davis		
1	Old Davis Road to SR 113 NB	70	27
2	Russell Boulevard to SR 113 SB	28	29
	Sacramento		
3	5th Street to I-5 NB	519A	518
4	5th Street to I-5 SB	519A	519A
5	P Street to I-5 SB and to US 50 EB	518	519A

Overview of Research Results and Benefits

The key deliverables of this project include:

- Procedures to achieve a 100% alert receiving rate
- Evaluation of the WDW application characteristics
- Evaluation of the algorithm capability for detecting wrong way drivers
- Potential to implement Bosch’s WWD detection technology in the USA

Chapter 2: Bosch System Overview

The Bosch algorithm was tested via the phone application "Bosch WDW." The application is not available to the public. AHMCT was permitted to download the application by the Bosch team. During this evaluation, the application was not available in the Apple App Store. Thus, the application was downloaded from the Google Play Store. The Google Pixel 6 and the Samsung Galaxy S20 FE were the phone models used in testing.

After the WDW application was installed, the AHMCT team did not need to modify any settings. Once the application was opened, it was ready to go. Bosch recommended always running the WDW application in front of all other applications, i.e., not in the background.

In the beginning, particularly for validation, the Bosch team monitored and supported Anh and Victor live until the testing procedure went smoothly. After Anh and Victor finished testing, Nikolas emailed Anh data generated from the WDW application the next day in the form of a comma-separated value (CSV) file. Due to the difference in time zones, AHMCT worked in the early morning, and Bosch staff worked at and beyond the end of their workday.

Bosch alert data logs included headings such as fleet ID, trip ID, counter, heading, softpush, speed, latitude, longitude, radius, lifetime, heading relevance, drive ID, unique ID, event, tags, time generated, and bearing. AHMCT mostly focused on latitude, longitude, time generated, and tags to identify and distinguish the alerts. Latitude and longitude identified the exact location where the alert was triggered. The time generated distinguished whether alerts were triggered by Anh or Victor. The tags identified the location of the ramps.

The WDW application has conditions for when it should issue an alert to drivers. For a fair evaluation, these conditions need to be met.

The WDW application activates when the driver enters the red zones or "hotspots." The activation is depicted by a cloud icon on the left corner of the WDW application. Upon entering hotspots, the driver is automatically assigned an ID.

Table 2.1: Ramp identification tags created by the Bosch team

Ramp number	Location	Bosch tags
Davis ramps		
1	Old Davis Road to SR 113 NB	src-junction 70, dest-junction: 27
2	Russell Boulevard to SR 113 SB	src-junction 28, dest-junction: 29
Sacramento ramps		
3	5th Street to I-5 NB	src-junction 519A, dest-junction: 518
4	5th Street to I-5 SB	src-junction 519A, dest-junction: 519A
5	P Street to I-5 SB	src-junction 518, dest-junction: 519A

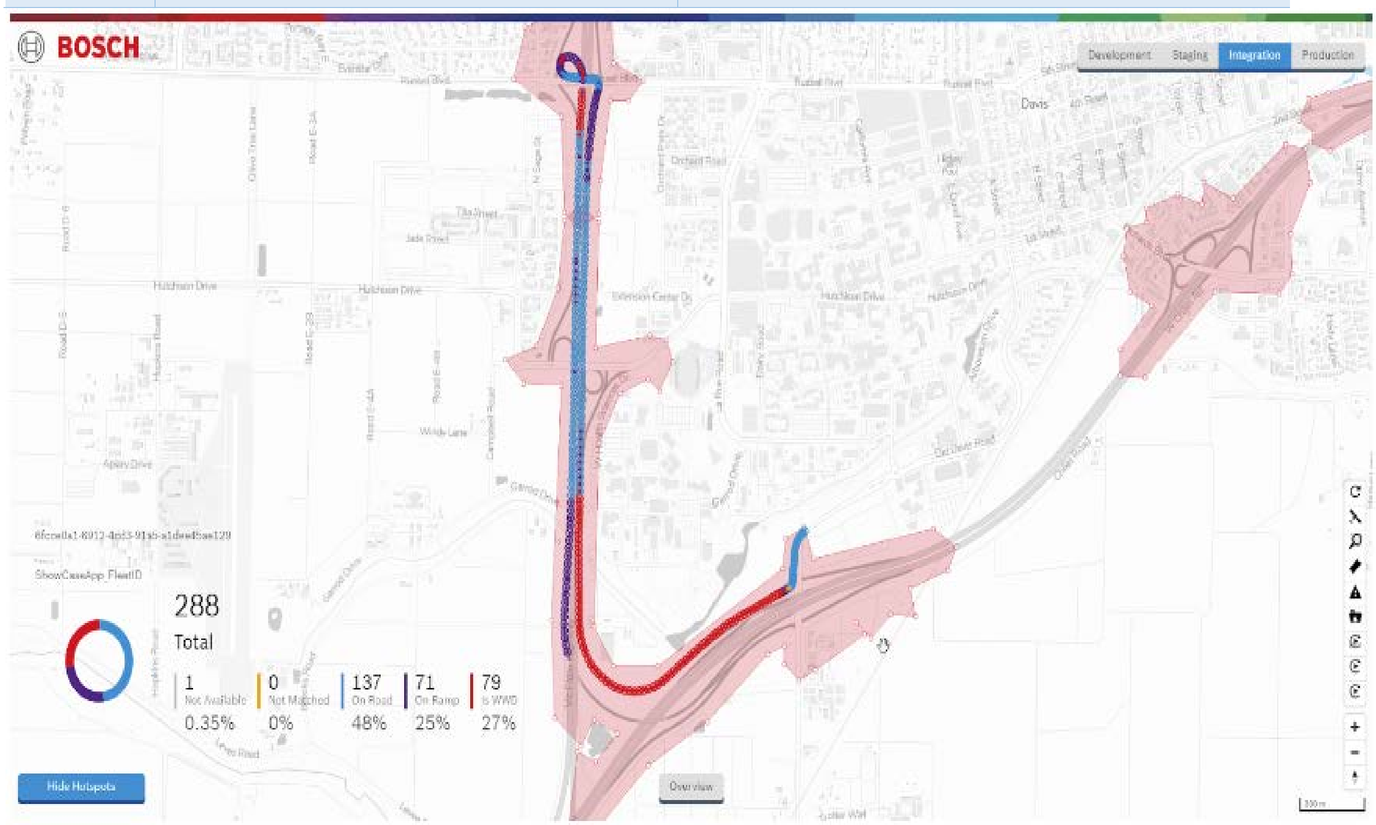

Figure 2.1: Hotspots (in red) surrounding the Davis test ramps

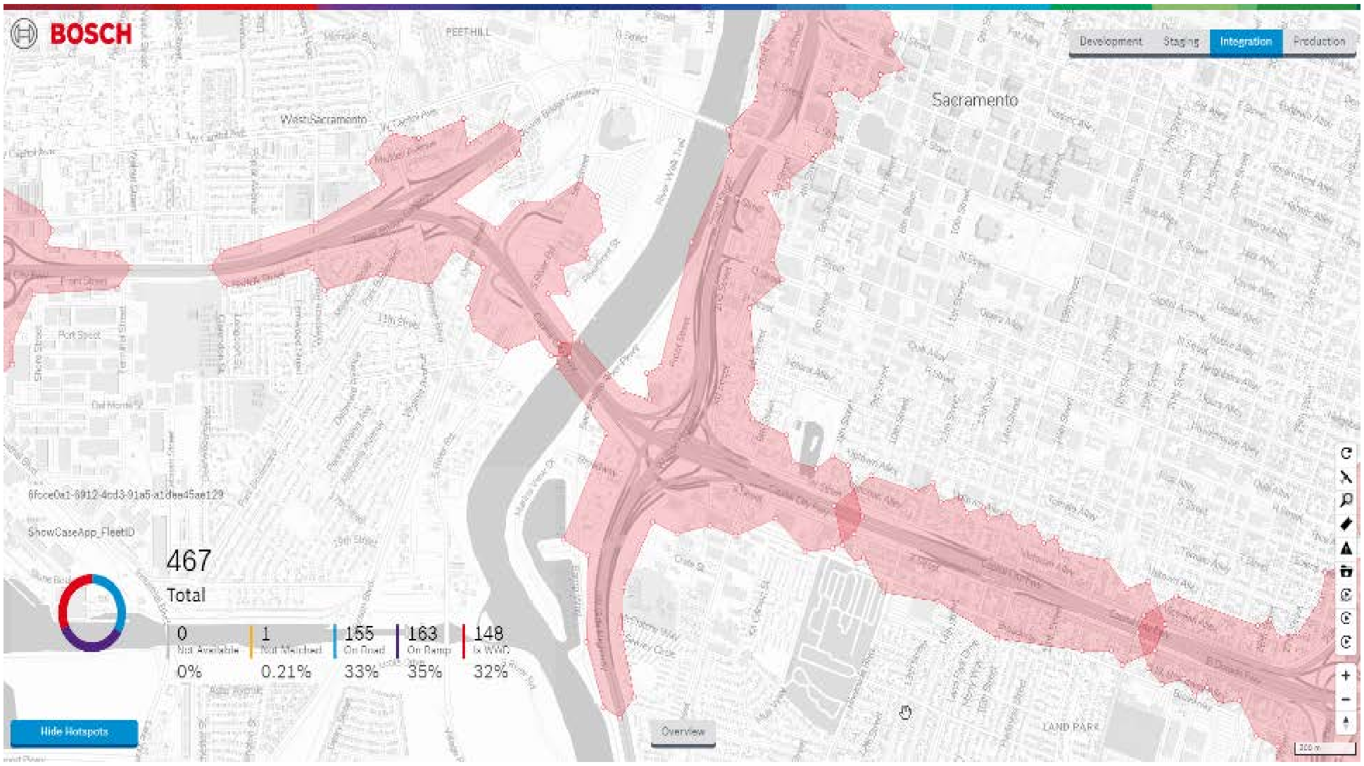

Figure 2.2: Hotspots (in red) surrounding the Sacramento test ramps

Once the driver is assigned an ID by the WDW application, the ID stays the same until the driver exits the red zone completely. Each ID corresponds to one alert. If drivers do not exit the hotspots after receiving the first alert, they will not receive a second alert even when they continue to drive the wrong way. When drivers completely exit the hotspots, the cloud icon disappears, indicating the WDW application has deactivated. Upon re-entering hotspots, the driver will be re-assigned a new ID automatically.

If the driver is stationary in the hotspots for approximately ten minutes (600 locations with 1 Hz sample frequency), the WDW application will stop sending data to Bosch and cancel the trip. Due to concerns about location data privacy in the implementation for smartphone applications, there is a built-in limitation on how many data points the application can collect.

Bosch assumptions for the WDW application are as follows:

- Drivers drive consistently on the road, i.e., do not pull over excessively.
- The drivers do not remain stationary in hotspots for over ten minutes.
- Drivers are less likely to travel in the wrong direction when there is a significant amount of traffic.
- After receiving a WDW alert, drivers are expected to pull over. In most cases, drivers do not drive in the wrong direction intentionally.

- Drivers are unlikely to enter two different hotspots/ramps directly one after the other.
- Drivers are more likely to be confused about direction when there is little to no traffic. Thus, ten minutes should be enough time to access the ramps upon entering the hotspots.

When drivers are stationary in the hotspots for over ten minutes, the cloud icon on the WDW application disappears. The WDW application cancels the trip by default. To re-activate the trip, drivers can:

- Drive away from the hotspot completely and then re-enter the hotspot so that the application can reassign drivers a new ID (non-ideal case).
- Restart the application by removing it from the phone background completely. When the application is turned back on, it automatically assigns drivers a new ID. The counter for the data collection limit also restarts at zero (ideal case).

In this evaluation, the WDW application characteristics were taken into account. On September 16, Anh was unaware of some of these characteristics. Thus, there were four false negatives on ramp 4. However, these false negatives are not taken into consideration because they occurred due to data collection procedures that did not account for the WDW application characteristics. In between each trial, Anh and Victor stopped and waited for the other person to come back to the test route starting point so that any discrepancy during testing could be discussed. Occasionally, it would take more than ten minutes for Anh or Victor to drive back to the starting point because of heavy traffic. As a result, false negatives occurred because the cars had been stationary for more than ten minutes while the WDW application was still running. False negatives only occurred at ramp 4 since the test route starting point was in the hotspot proximity.

On September 26, Anh re-tested on ramp 4 with the characteristics taken into account. Only the results obtained by complying with the Bosch assumptions were used to evaluate the application feasibility. The noted characteristics relate to smartphone privacy considerations and are not inherent to the Bosch algorithm.

Chapter 3:
Test Plan and Execution

First, AHMCT tested the integrity of the equipment before it was used in official testing. The equipment included:

- Two magnetic antennas
- Two SparkFun RTK Surveyors (GPS loggers)
- Two microSD cards
- One Google Pixel 6 phone
- One Samsung Galaxy S20 FE phone

After ensuring the equipment was working properly, Anh and Victor established the testing system shown in Figure 3.1. The magnetic antennas were mounted on top of the vehicles' rooftops. Victor carefully looped the antenna wires back into the front seats and checked that they were not pinched. The antenna wires were connected to the GPS loggers. The smartphones were connected to the GPS loggers via Bluetooth so no wires were needed. The system was setup on two vehicles. Overall, the system consisted of one magnetic antenna, one GPS logger with inserted microSD card, and one smartphone.

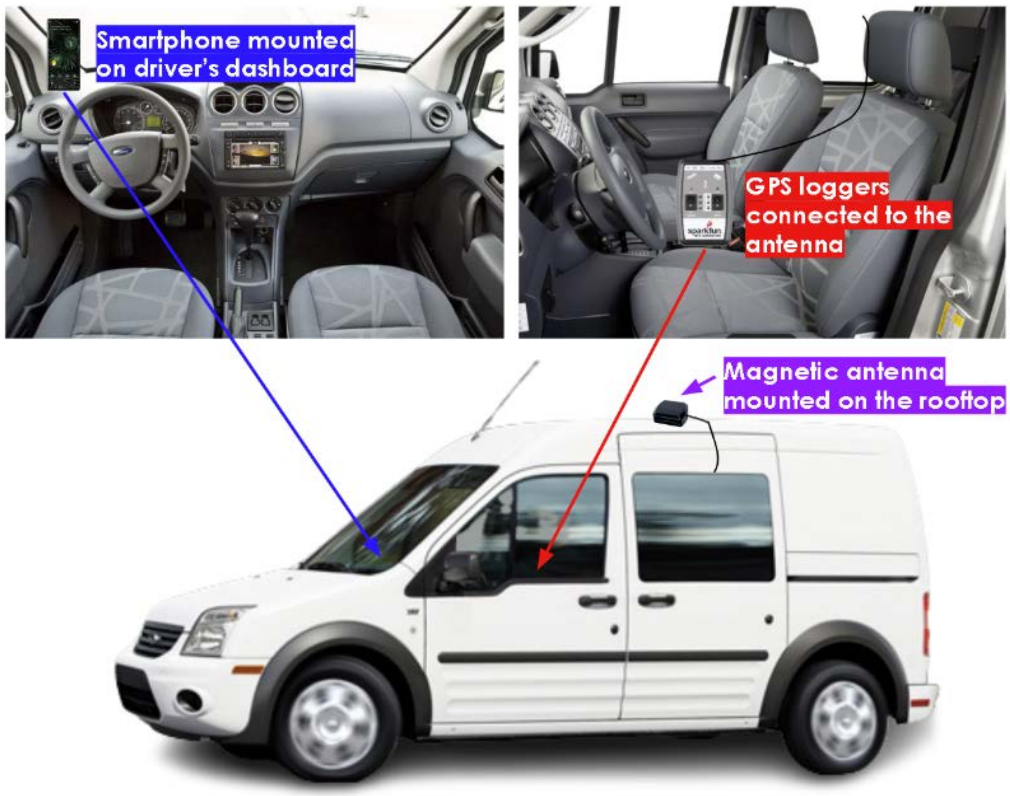

Figure 3.1: Equipment setup

After the setup was completed on both vehicles, Anh and Victor drove out to the planned test ramps.

Table 3.1: Test ramps

#	Ramp location	Approximate start
	Davis	
1	Old Davis Road to SR 113 NB	38°31'46.15"N, 121°45'25.81"W
2	Russell Boulevard to SR 113 SB	38°32'47.44"N, 121°46'7.68"W
	Sacramento	
3	5th Street to I-5 NB	38°34'4.58"N, 121°30'22.26"W
4	5th Street to I-5 SB	Same as #3
5	P Street to I-5 SB	38°34'35.59"N, 121°30'25.81"W

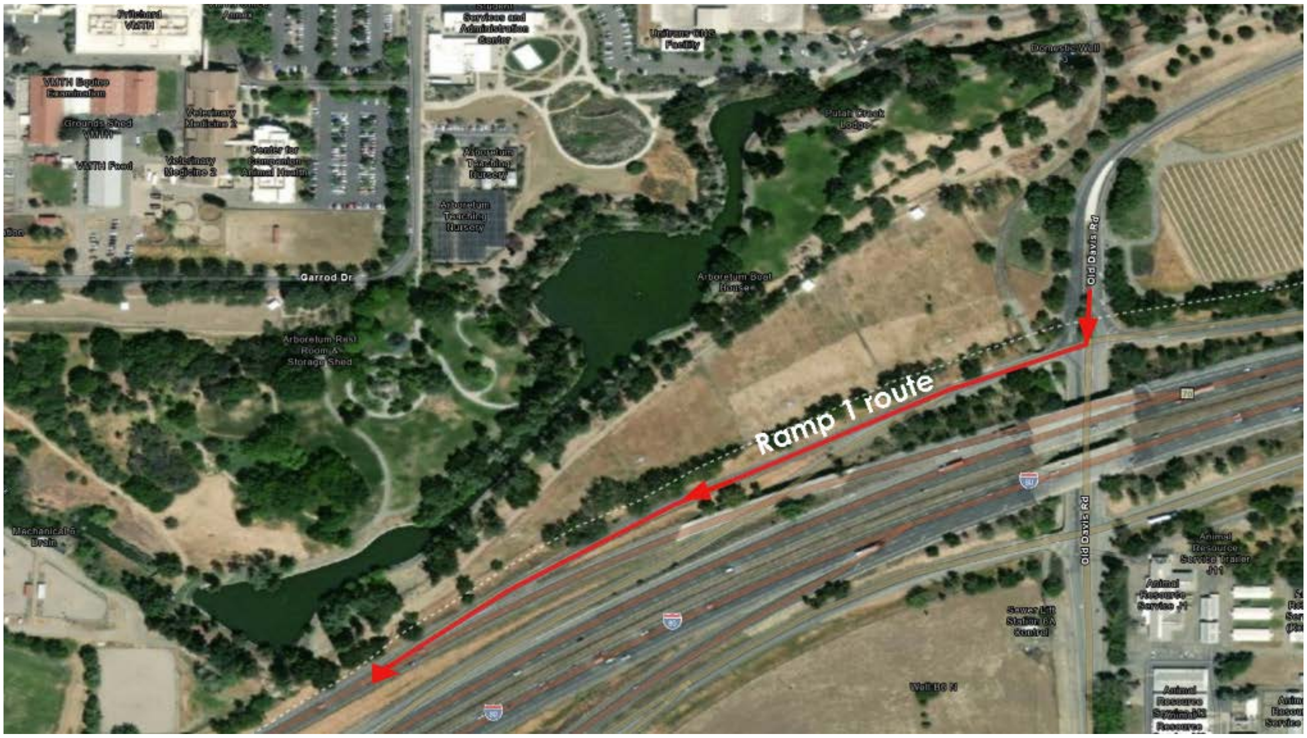

Figure 3.2: Ramp 1 route, alerts were expected to be received along the red outline

Figure 3.3: Ramp 2 route, alerts were expected to be received along the red outline

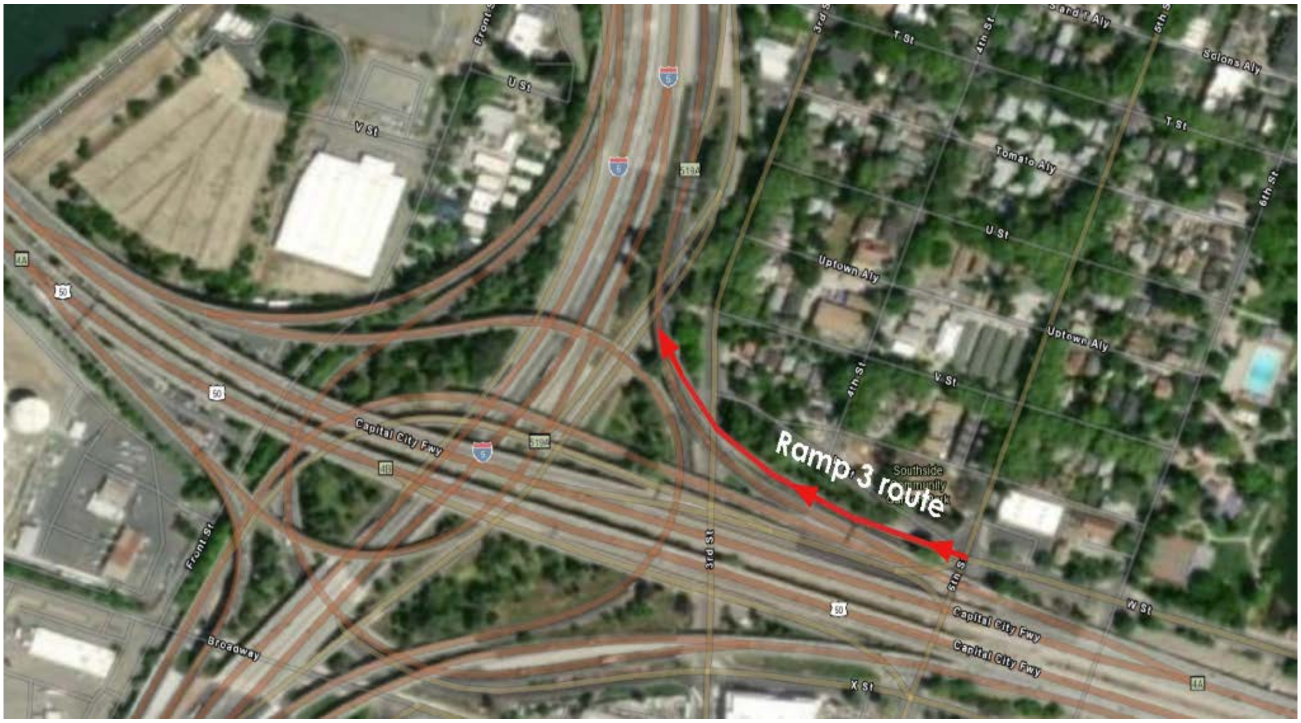

Figure 3.4: Ramp 3 route, alerts were expected to be received along the red outline

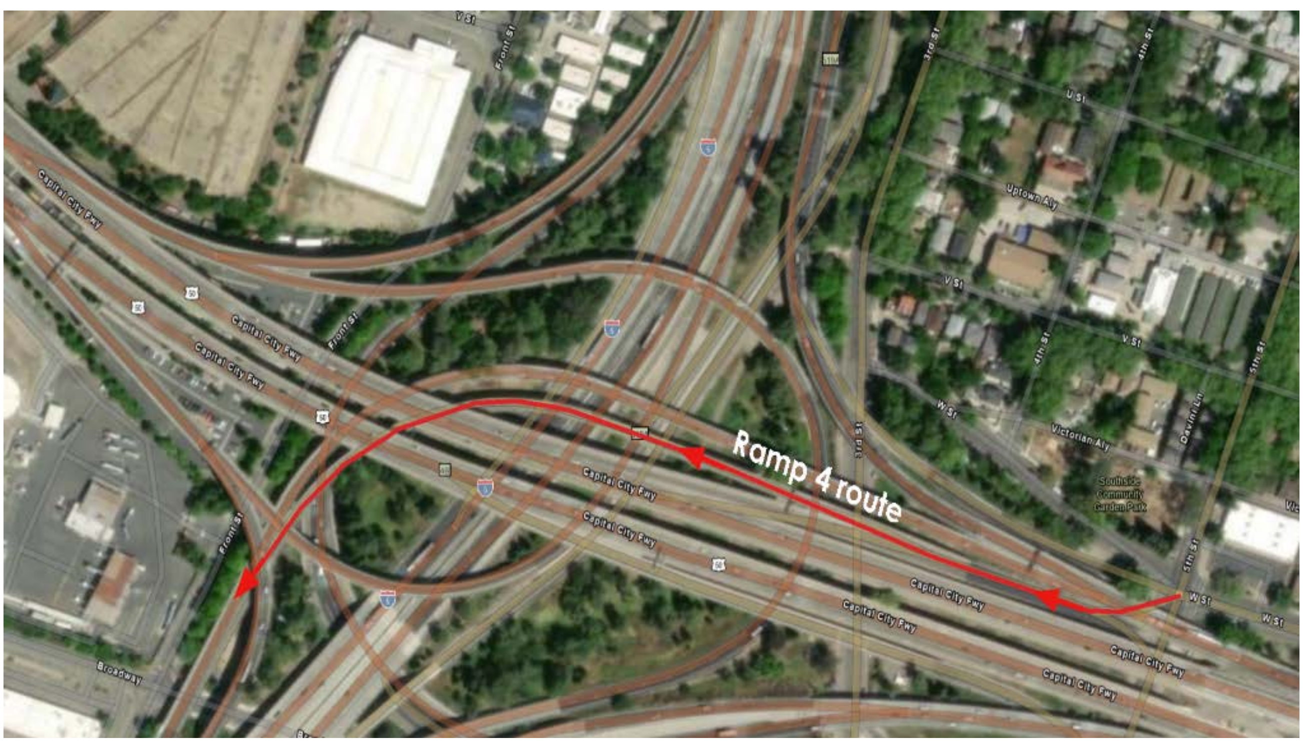

Figure 3.5: Ramp 4 route, alerts were expected to be received along the red outline

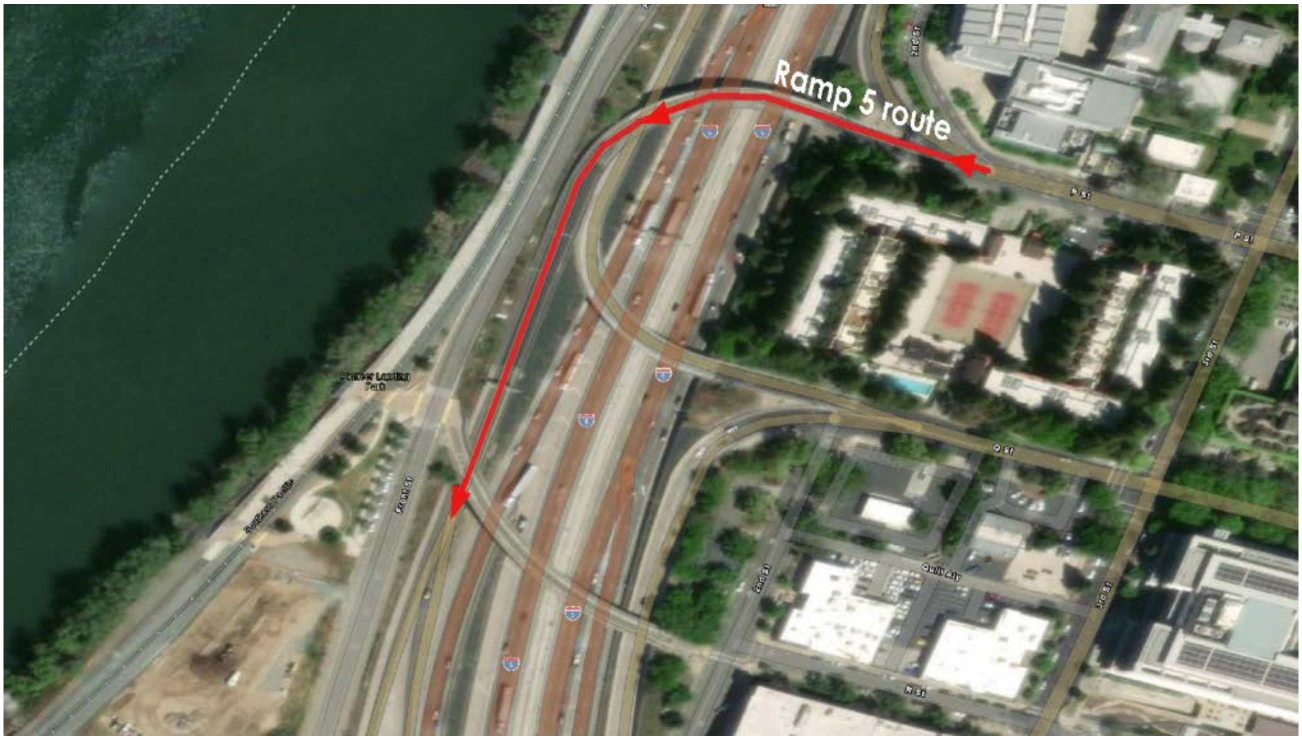

Figure 3.6: Ramp 5 route, alerts were expected to be received along the red outline

Figures 3.2 to 3.6 depict the routes Anh and Victor took during testing. It was expected that the alerts would be received along the routes, ideally before drivers entered the main freeway. For the route depicted in Figure 3.6, the alerts were particularly expected before the ramp split.

When the ramp routes were planned, Anh and Victor coordinated on how to collect data using GPS loggers. First, the application SW Maps was downloaded to access the SparkFun RTK surveyor setting interface. SW Maps was available on the Google Play Store but not available on the Apple App Store when this evaluation occurred.

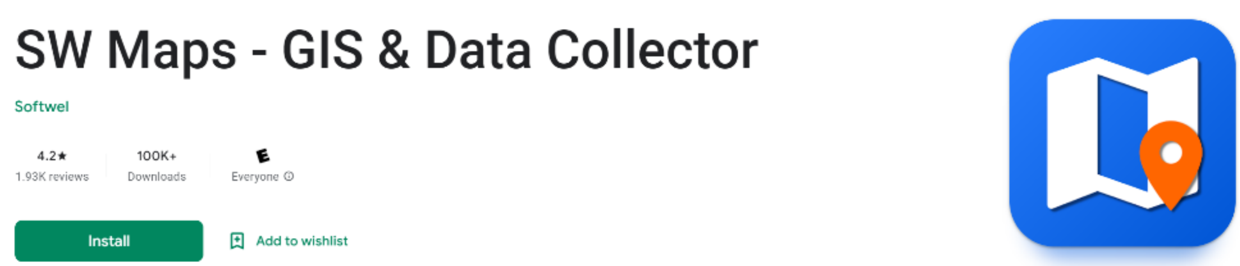

Figure 3.7: SW Maps application in the Google Play Store

The SW Maps application gives the user more setting options than the SparkFun RTK surveyor alone.

Figure 3.8: SparkFun RTK surveyor, also known as the GPS logger

The physical interface of the SparkFun RTK surveyor consisted of a power switch and a setting switch. During testing, the power switch was on, and the setting switch was on rover mode. More settings can be accessed via the SW Maps application.

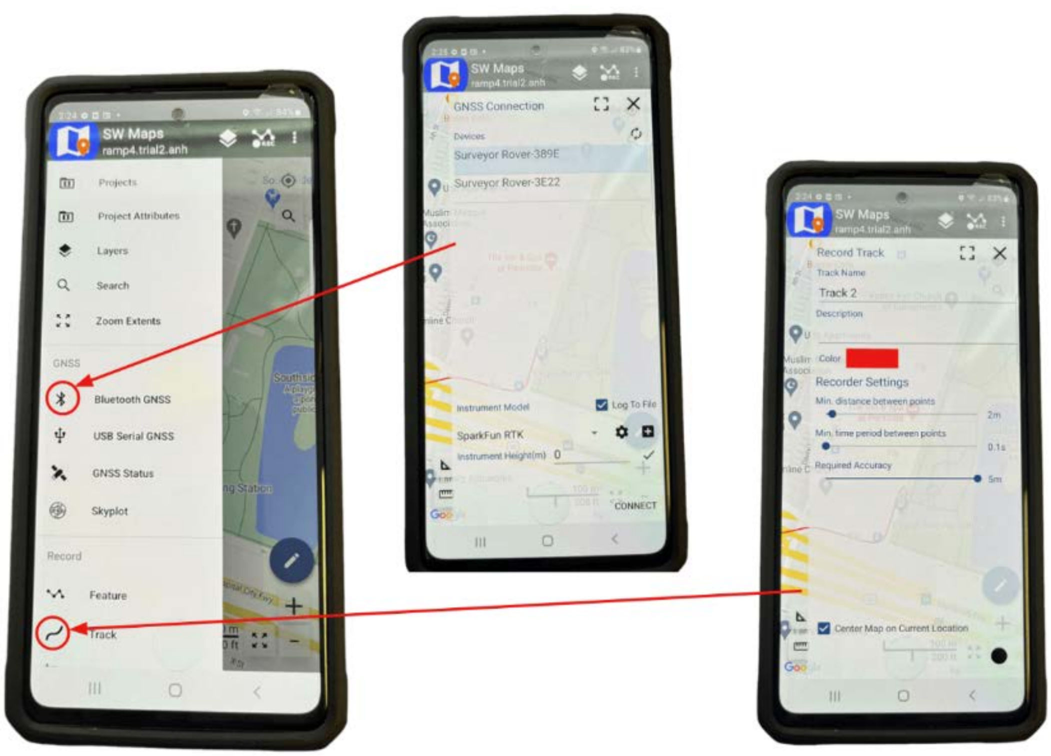

Figure 3.9: SW Maps setting interface

The SW Maps settings to focus on were "Bluetooth GNSS" and "Track." The "Bluetooth GNSS" connected the SparkFun RTK to the smartphone. The "Track" traced the path of travel. The GPS recorder settings were:

- Min. distance between points: 2 meters
- Min. time period between points: 0.1 second
- Required accuracy: 5 meters

After each trial, Anh and Victor shut off and then restarted the GPS loggers so a new log file could be created in between testing. Distinguishing the log files in between trials was crucial since there were ten trials per ramp.

There were five ramps to test, and ten trials for each ramp. There would have been 50 log files if the ramps were tested individually. To reduce the number of log files, the ramps were paired so that one log file would capture two ramps. Pairing the ramps reduced the total number of log files from 50 to 30. With fewer log files to work with, the possibility for errors was reduced.

Table 3.2: Ramp pairing

Location	Ramp(s)	Number of trials
Davis	Ramps 1 and 2	10
Sacramento	Ramp 3	10
Sacramento	Ramps 4 and 5	10

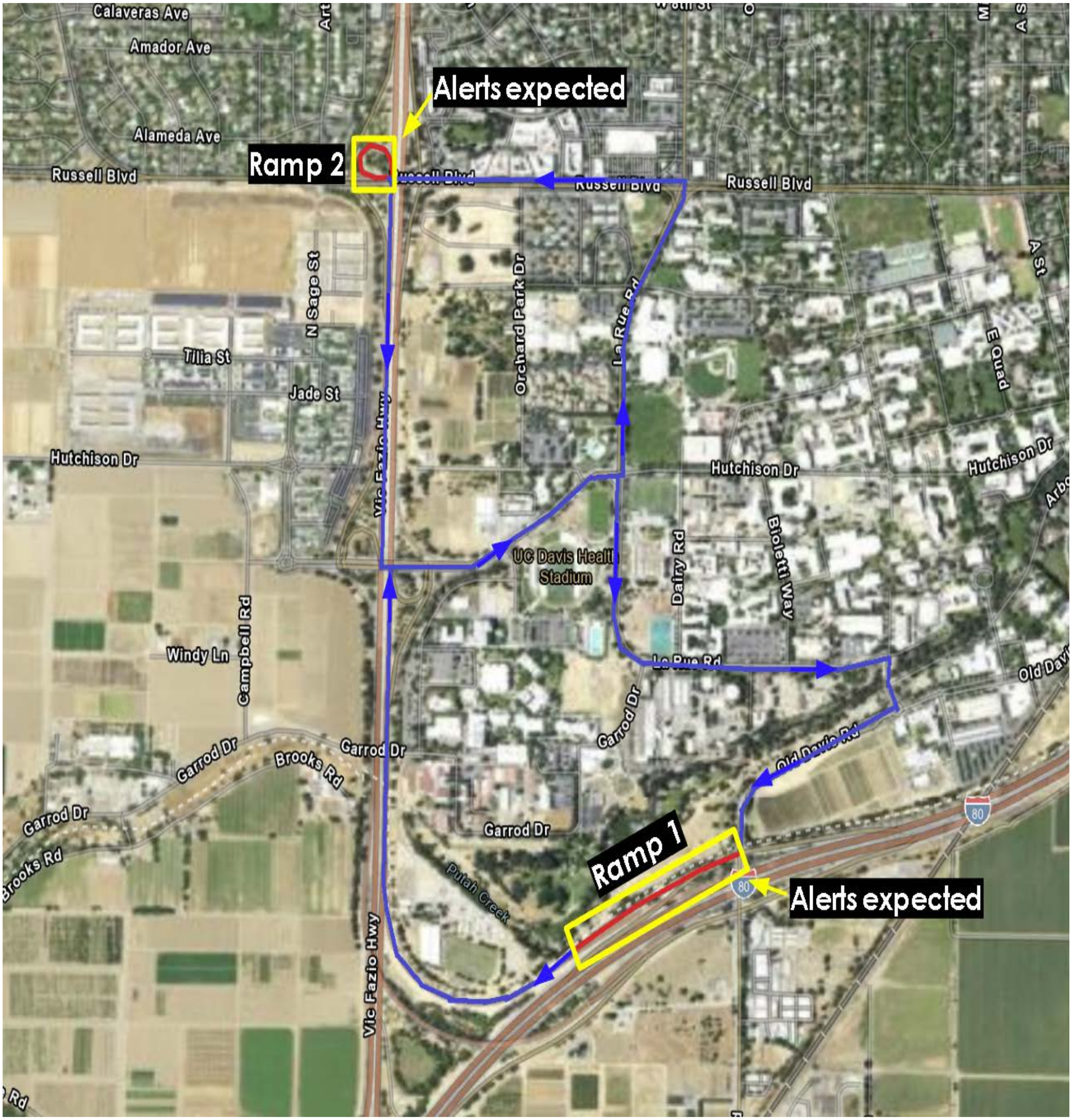

Figure 3.10: Ramps 1 and 2 loop

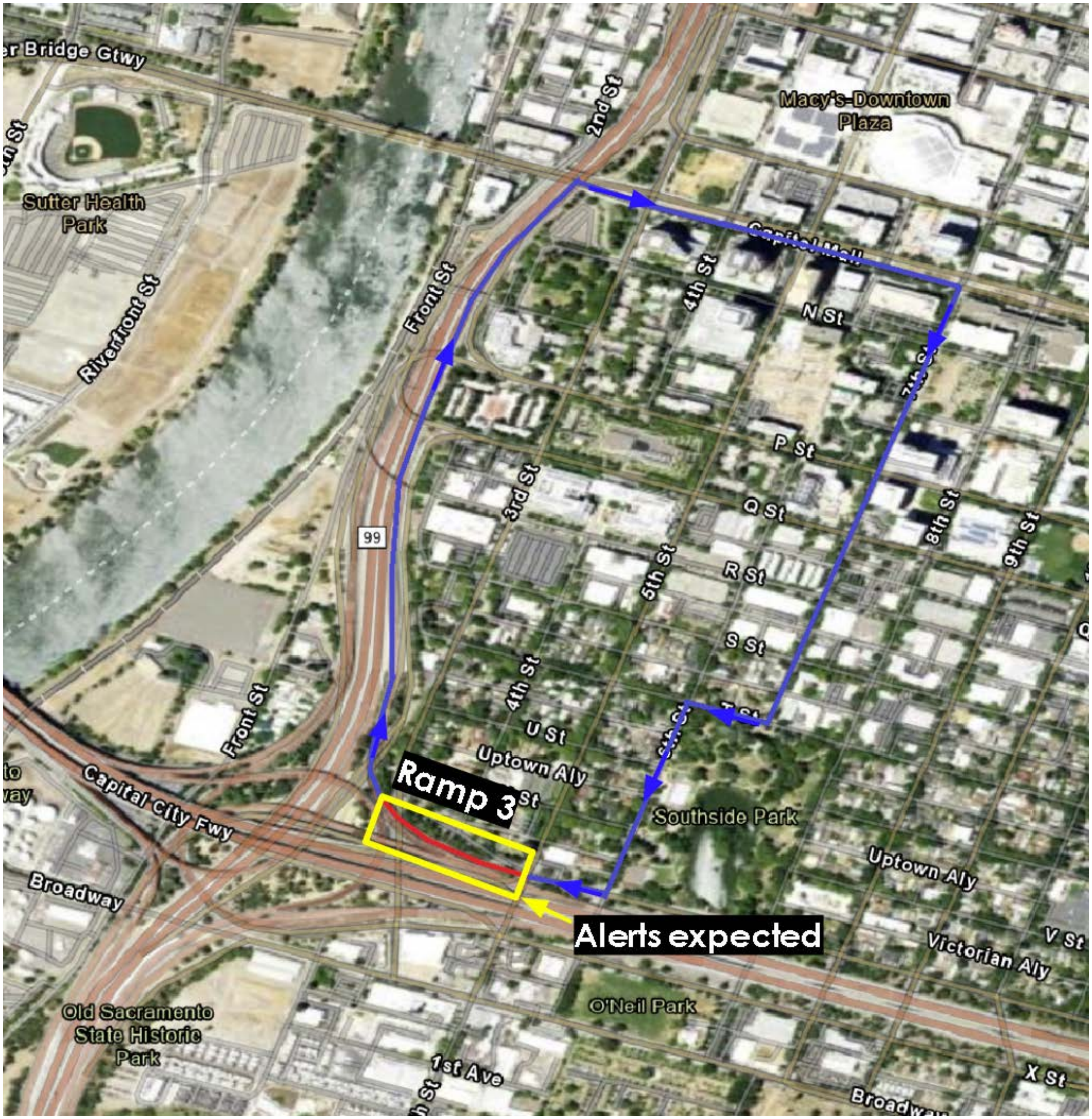

Figure 3.11: Ramp 3 loop

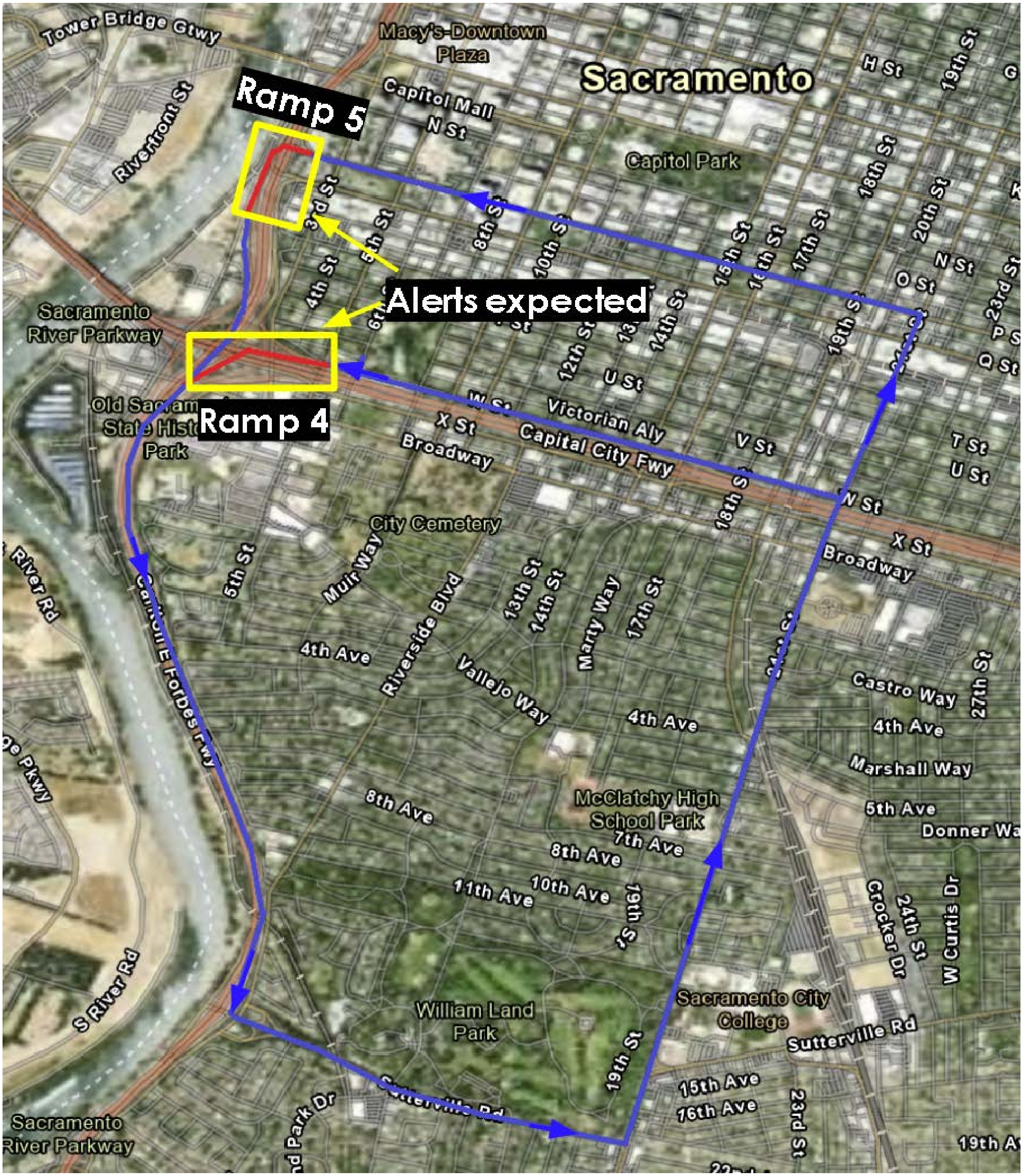

Figure 3.12: Ramps 4 and 5 loop

Anh and Victor followed the procedures outlined below upon starting the loop.

1. Turn on the GPS logger.
2. Connect the GPS logger to the smartphone via Bluetooth.
3. Establish settings on SW Maps, then record track.
4. Turn on WDW application.
5. Run the WDW application in the foreground, and run the SW Maps application in the background.
6. Start driving to the first test ramp.
7. Loop back to the second test ramp (except for ramp 3 since it was tested individually).
8. After driving by all test ramps in the loop, pull over and reset the GPS logger.
9. Repeat the process nine more times for each loop. Each test ramp was traversed ten times.

Table 3.3: AHMCT and Bosch testing timeline

Date	Action	Monitored live
Sep 7, 2022	The Bosch and AHMCT teams had a meeting to discuss the WDW application characteristics.	N/A
Sep 9, 2022	Anh and Victor tested the integrity of the hardware. The equipment worked properly and was ready for testing.	N/A
Sep 12, 2022	Anh and Victor conducted a trial run to test the Bosch algorithm. Anh and Victor travelled in the same vehicle.	Yes
Sep 14, 2022	Bosch deployed the WDW application version 1.43.0.	N/A
Sep 15, 2022	Anh and Victor performed official test runs on the Davis ramps. Anh and Victor travelled in different vehicles.	Yes

Date	Action	Monitored live
Sep 16, 2022	Anh and Victor performed official test runs on the Sacramento ramps. Anh and Victor travelled in different vehicles.	Yes
Sep 26, 2022	Anh performed official test runs on ramp 4 since the characteristics of the WDW application were not followed in previous testing.	No
Oct 18, 2022	Bosch deployed the WDW application version 1.44.0.	N/A
Oct 24, 2022	Anh and Victor performed additional test runs on the Davis ramps. Anh and Victor travelled in different vehicles.	No
Oct 25, 2022	Anh and Victor performed additional test runs on the Sacramento ramps. Anh and Victor travelled in different vehicles.	No

After testing was completed, the AHMCT team translated data collected from the SparkFun RTK surveyor.

The MicroSD cards were removed from the SparkFun RTK Surveyors. As mentioned before, when the Surveyor was restarted, a new log file was generated. Thus, each log file contained a trial run. The log files are in National Marine Electronics Association (NMEA) 0183 sentences as shown in Figure 3.13.

```
$GNTXT,01,01,01,ESP_RST_POWERON*1D
$GNRMC,223203.25,A,3832.2601249,N,12130.2375354,W,0.329,129.80,260922,,,A,V*1A
$GNGGA,223203.25,3832.2601249,N,12130.2375354,W,1,12,0.52,-0.187,M,-27.532,M,,*5E
$GNGSA,A,3,01,03,04,21,22,26,31,,,,,,1.16,0.52,1.03,1*01
$GNGSA,A,3,74,73,75,65,88,87,71,72,,,,,1.16,0.52,1.03,2*0B
$GNGSA,A,3,12,19,11,21,27,04,10,,,,,,1.16,0.52,1.03,3*08
$GNGSA,A,3,24,28,26,14,33,21,,,,,,,1.16,0.52,1.03,4*09
$GPGSV,3,1,10,01,46,230,48,03,64,322,44,04,38,277,40,16,08,151,41,1*6D
$GPGSV,3,2,10,21,32,208,46,22,35,060,45,26,25,128,38,31,53,056,46,1*69
$GPGSV,3,3,10,32,10,073,22,195,08,302,28,1*5F
$GPGSV,2,1,06,01,46,230,45,03,64,322,47,04,38,277,43,26,25,128,42,6*60
$GPGSV,2,2,06,31,53,056,42,195,08,302,34,6*57
$GPGSV,1,1,02,09,05,266,,25,04,035,,0*6C
$GLGSV,2,1,08,65,21,303,43,71,37,071,42,72,56,355,41,73,38,050,45,1*7D
$GLGSV,2,2,08,74,52,121,41,75,16,174,48,87,28,255,43,88,24,308,44,1*75
$GLGSV,2,1,06,65,21,303,26,71,37,071,40,72,56,355,45,73,38,050,41,3*70
$GLGSV,2,2,06,75,16,174,44,88,24,308,34,3*71
$GLGSV,1,1,02,80,01,021,,86,02,204,,0*7B
$GAGSV,3,1,10,01,19,151,41,04,46,289,47,10,44,258,47,11,36,294,41,2*78
$GAGSV,3,2,10,12,39,223,42,19,59,044,42,21,32,101,38,27,16,047,29,2*7B
$GAGSV,3,3,10,33,07,179,38,36,04,332,27,2*72
$GAGSV,3,1,10,01,19,151,43,04,46,289,39,10,44,258,44,11,36,294,38,7*7B
$GAGSV,3,2,10,12,39,223,42,19,59,044,40,21,32,101,37,27,16,047,30,7*7B
$GAGSV,3,3,10,33,07,179,33,36,04,332,15,7*7D
$GAGSV,1,1,01,09,00,268,,0*40
$GBGSV,2,1,07,11,05,211,29,14,62,328,40,21,28,098,34,24,39,172,42,1*73
$GBGSV,2,2,07,26,57,098,46,28,15,289,41,33,37,306,40,1*49
$GBGSV,1,1,02,11,05,211,41,14,62,328,50,3*79
$GNGST,223203.25,40,2.5,1.8,180,1.0,0.72,2.5*4C
$GNRMC,223203.50,A,3832.2601007,N,12130.2374995,W,0.475,125.49,260922,,,A,V*11
$GNGGA,223203.50,3832.2601007,N,12130.2374995,W,1,12,0.52,-0.194,M,-27.532,M,,*50
$GNGSA,A,3,01,03,04,21,22,26,31,,,,,,1.16,0.52,1.03,1*01
$GNGSA,A,3,74,73,75,65,88,87,71,72,,,,,1.16,0.52,1.03,2*0B
$GNGSA,A,3,12,19,11,21,27,04,10,,,,,,1.16,0.52,1.03,3*08
$GNGSA,A,3,24,28,26,14,33,21,,,,,,,1.16,0.52,1.03,4*09
$GNGST,223203.50,39,2.5,1.8,180,1.0,0.71,2.5*43
$GNRMC,223203.75,A,3832.2600671,N,12130.2374544,W,0.670,130.05,260922,,,A,V*1B
```

Figure 3.13: Sample data results generated by the SparkFun RTK Surveyor

The log files from the Surveyors were translated via GPSBabel.[3] In GPSBabel, NMEA 0183 sentences were converted to Data Logger iBlue 757 CSV (Figure 3.14).

INDEX	RCR	DATE	TIME	VALID	LATITUDE	N/S	LONGITUD	E/W	HEIGHT	SPEED	HEADING	DSTA	DAGE	PDOP	HDOP	VDOP	NSAT (USE	SAT INFO (	DISTANCE
1	T	16/09/202	15:53:40	Unknown	38.56819	N	-121.505	W		0				0	0	0	-1(		0
2	T	16/09/202	15:53:40	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0
3	T	16/09/202	15:53:40	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.00002
4	T	16/09/202	15:53:41	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000042
5	T	16/09/202	15:53:41	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000061
6	T	16/09/202	15:53:41	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000078
7	T	16/09/202	15:53:41	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000095
8	T	16/09/202	15:53:42	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.00011
9	T	16/09/202	15:53:42	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000121
10	T	16/09/202	15:53:42	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000131
11	T	16/09/202	15:53:42	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000141
12	T	16/09/202	15:53:43	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000151
13	T	16/09/202	15:53:43	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000157
14	T	16/09/202	15:53:43	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000164

Figure 3.14: Converted data results in Data Logger iBlue 757 CSV format

Data Logger iBlue 757 CSV key headings included date, time, latitude, longitude, and speed. Heading information might have been helpful, but the course direction was not included in the translation. Thus, NMEA 0183 sentences were converted to universal CSV (Figure 3.15).

[3] GPSBabel (http://www.gpsbabel.org/)

No	Latitude	Longitude	Altitude	Speed	Course	FIX	HDOP	VDOP	PDOP	Satellites	Date	Time
1	38.56819	-121.505		0.01	0						########	53:40.3
2	38.56819	-121.505	4.4	0.01	0	3d	0.5	0.82	0.96	12	########	53:40.5
3	38.56819	-121.505	4.3	0	0	3d	0.5	0.82	0.96	12	########	53:40.7
4	38.56819	-121.505	4.3	0	0	3d	0.5	0.82	0.96	12	########	8:53:41
5	38.56819	-121.505	4.3	0	0	3d	0.5	0.82	0.96	12	########	53:41.2
6	38.56819	-121.505	4.3	0	0	3d	0.5	0.82	0.96	12	########	53:41.5
7	38.56819	-121.505	4.3	0	0	3d	0.5	0.82	0.96	12	########	53:41.8
8	38.56819	-121.505	4.2	0.01	0	3d	0.5	0.82	0.96	12	########	8:53:42
9	38.56818	-121.505	4.2	0.01	0	3d	0.5	0.82	0.96	12	########	53:42.3
10	38.56818	-121.505	4.2	0.01	0	3d	0.5	0.82	0.96	12	########	53:42.5
11	38.56818	-121.505	4.2	0	0	3d	0.5	0.82	0.96	12	########	53:42.7
12	38.56818	-121.505	4.1	0.01	0	3d	0.5	0.82	0.96	12	########	8:53:43
13	38.56818	-121.505	4.1	0	0	3d	0.5	0.82	0.96	12	########	53:43.2
14	38.56818	-121.505	4.1	0.01	0	3d	0.5	0.82	0.96	12	########	53:43.5
15	38.56818	-121.505	4.1	0.01	0	3d	0.5	0.82	0.96	12	########	53:43.8

Figure 3.15: Converted data results in universal CSV format

The universal CSV key headings included the course. The course provided travel direction in degrees. The universal CSV translated information was not as useful as Data Logger iBlue 757 CSV translated information for the WDW analysis. Thus, the "Course" column was extracted and pasted into the converted Data Logger iBlue 757 file (Figure 3.16) as "Course" (all the way to the right). The "Course" for the first data was zero since the drivers had not yet moved. As the drivers started driving, "Course" had values greater than zero.

INDEX	RCR	DATE	TIME	VALID	LATITUDE	N/S	LONGITUDE	E/W	HEIGHT	SPEED	HEADING	DSTA	DAGE	PDOP	HDOP	VDOP	NSAT (USE	SAT INFO (	DISTANCE	Course
1	T	16/09/202	15:53:40	Unknown	38.56819	N	-121.505	W		0				0	0	0	-1(		0	0
2	T	16/09/202	15:53:40	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0	0
3	T	16/09/202	15:53:40	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.00002	0
4	T	16/09/202	15:53:41	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000042	0
5	T	16/09/202	15:53:41	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000061	0
6	T	16/09/202	15:53:41	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000078	0
7	T	16/09/202	15:53:41	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000095	0
8	T	16/09/202	15:53:42	3d	38.56819	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.00011	0
9	T	16/09/202	15:53:42	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000121	0
10	T	16/09/202	15:53:42	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000131	0
11	T	16/09/202	15:53:42	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000141	0
12	T	16/09/202	15:53:43	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000151	0
13	T	16/09/202	15:53:43	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000157	0
14	T	16/09/202	15:53:43	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000164	0
15	T	16/09/202	15:53:43	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000169	0
16	T	16/09/202	15:53:44	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000175	0
17	T	16/09/202	15:53:44	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.00018	0
18	T	16/09/202	15:53:44	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000185	0
19	T	16/09/202	15:53:44	3d	38.56818	N	-121.505	W	4	0				0.96	0.5	0.82	12(		0.000195	0

Figure 3.16: Converted data results in Data Logger iBlue 757 CSV format with the added course column

The data translation was repeated 30 times. The translated data files were input into custom Python analysis code. Python extracted data points that were nearest to the Bosch alerts. This process is further explained below.

A review was conducted to find compatible Python codes for the analysis. The Python codes below were adjusted to compare Surveyor data to WDW data:

- Ahmed, Rahil. "Finding nearest pair of latitude and longitude match using Python." *Medium*, May 22nd 2020, (https://medium.com/analytics-vidhya/finding-nearest-pair-of-latitude-and-longitude-match-using-python-ce50d62af546)
- Wilhelm, Florian. "GPS data analysis with Python." GitHub, July 7th, 2016, (https://github.com/FlorianWilhelm/gps_data_with_python/tree/master/notebooks)

The code extracted Surveyor data points that were close to the Bosch alerts. This process saved time as the original data files contained approximately 5,000 data points. After extraction, the data points were input into ArcGIS Pro.

Figure 3.17: Sample GPS logger results compared to WDW alerts on ArcGIS Pro

Latitude, longitude, UTC time, and date were used to identify and match the drivers' paths with the corresponding WDW alerts. Bosch recommended that Anh and Victor drive two minutes (or more) apart so the data files could be more easily distinguished.

Chapter 4:
Evaluation of Test Results

Main Evaluation

Figures 4.1 to 4.10 show the driving paths recorded by the Surveyor GPS loggers and the alerts generated by the WDW application. The data points closest to the WDW alerts (red dots) are selected for comparison in Table 4.1.

Ramp 1 – Old Davis Road to SR 113 NB

Figure 4.1: Ramp 1 Trial 1 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.2: Ramp 1 Trial 2 driving path (purple arrows) and received Bosch alert (red dot)

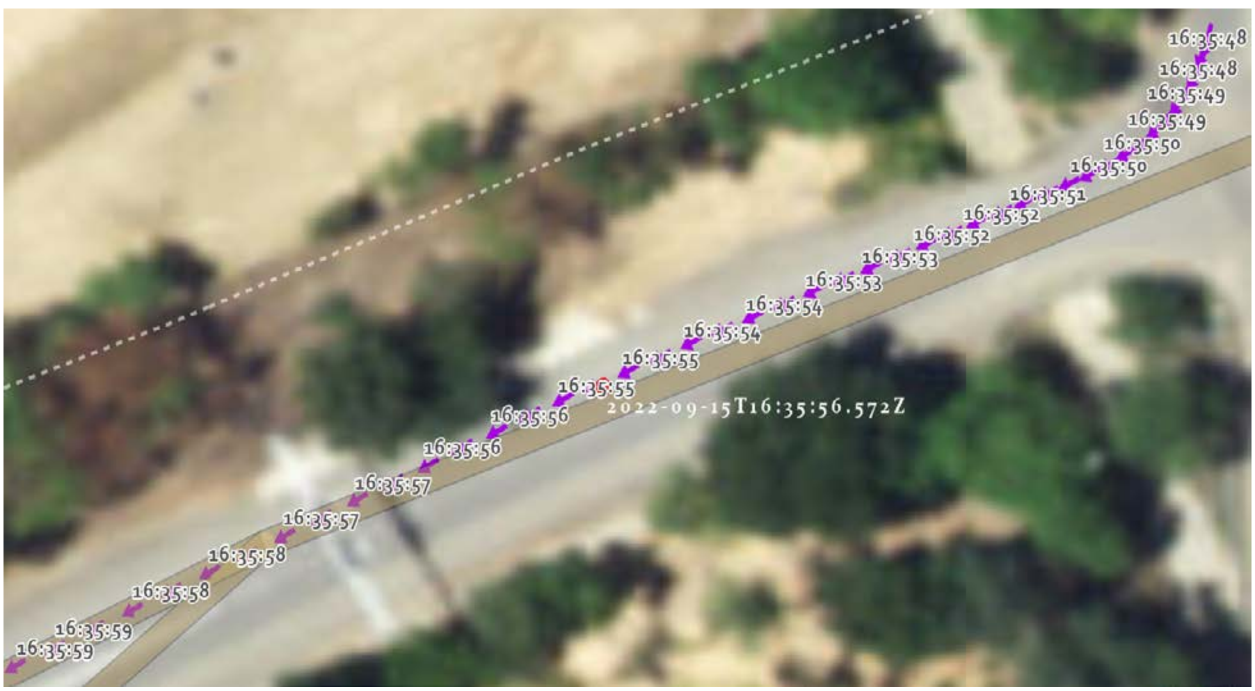

Figure 4.3: Ramp 1 Trial 3 driving path (purple arrows) and received Bosch alert (red dot)

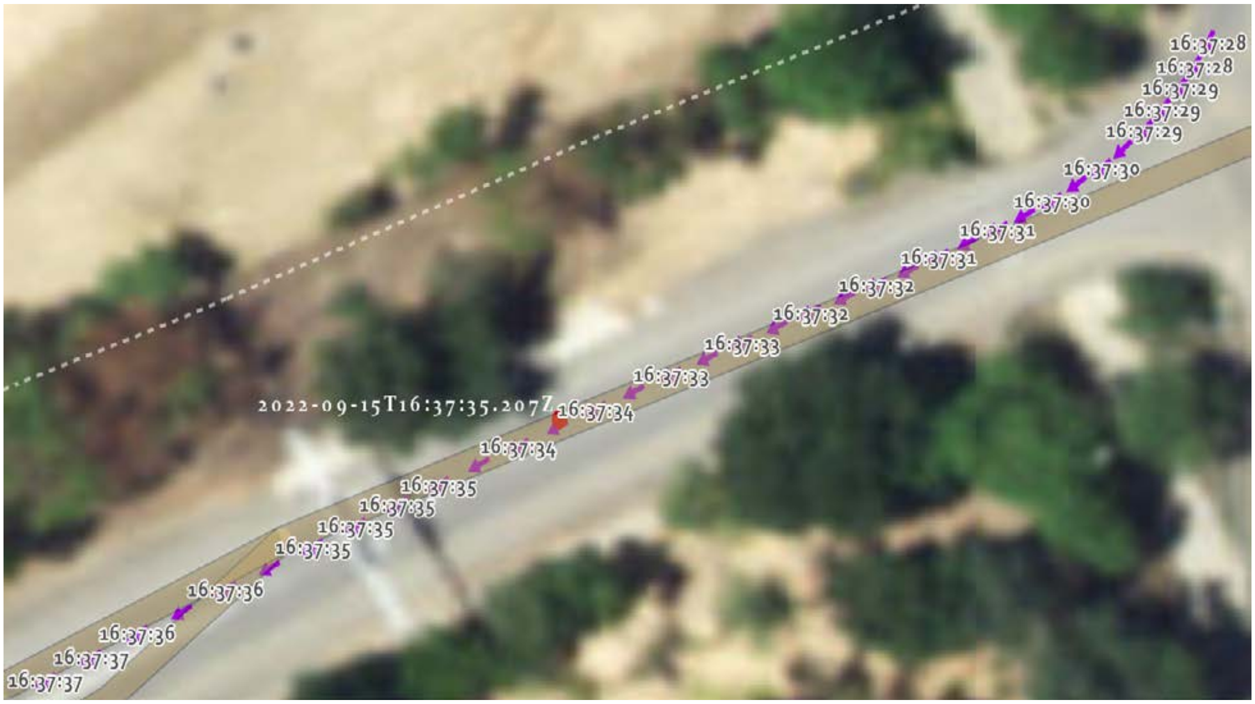

Figure 4.4: Ramp 1 Trial 4 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.5: Ramp 1 Trial 5 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.6: Ramp 1 Trial 6 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.7: Ramp 1 Trial 7 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.8: Ramp 1 Trial 8 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.9: Ramp 1 Trial 9 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.10: Ramp 1 Trial 10 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.11: 10 Bosch alerts received on ramp 1

Table 4.1: Ramp 1 test results comparison

Trial #	Time stamp of the GPS logger at the position of the vehicle where WWD was detected	Time stamp when Bosch issued WWD alert	Time difference between the two time stamps*
1	16:16:26	16:16:27.617	1 sec
2	16:17:29	16:17:30.606	1 sec
3	16:35:55	16:35:56.572	1 sec
4	16:37:34	16:37:35.207	1 sec
5	16:58:56	16:58:57.534	1 sec
6	17:00:26	17:00:27.408	1 sec
7	15:53:19	15:53:20.602	1 sec

Trial #	Time stamp of the GPS logger at the position of the vehicle where WWD was detected	Time stamp when Bosch issued WWD alert	Time difference between the two time stamps*
8	15:56:12	15:56:13.536	1 sec
9	16:17:56	16:17:57.444	1 sec
10	16:20:35	16:20:36.412	1 sec

***The time difference is the result of the process of the driver driving on the test ramps, the Bosch WDW application sending data via mobile network to the Bosch server, and the Bosch server calculating and issuing WWD alerts.**

Ramp 2 – Russell Boulevard to SR 113 SB

Figures 4.12 to 4.21 show the driving paths recorded by the Surveyor GPS loggers and the alerts generated from the WDW application. The data points closest to the WWD alerts (in red) are selected for comparison in Table 4.2.

Figure 4.12: Ramp 2 Trial 1 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.13: Ramp 2 Trial 2 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.14: Ramp 2 Trial 3 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.15: Ramp 2 Trial 4 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.16: Ramp 2 Trial 5 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.17: Ramp 2 Trial 6 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.18: Ramp 2 Trial 7 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.19: Ramp 2 Trial 8 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.20: Ramp 2 Trial 9 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.21: Ramp 2 Trial 10 driving path (purple arrows) and received Bosch alert (red dot)

Figure 4.22: 10 Bosch alerts received on ramp 2

Table 4.2: Ramp 2 test results comparison

Trial #	Time stamp of the GPS logger at the position of the vehicle where WWD was detected	Time stamp when Bosch issued WWD alert	Time difference between the two time stamps*
1	16:25:08	16:25:09.555	1 sec
2	16:26:53	16:26:58.230	5 sec
3	16:45:20	16:45:21.139	1 sec
4	16:45:27	16:45:29.861	2 sec
5	17:09:18	17:09:23.144	5 sec
6	17:09:43	17:09:44.740	1 sec
7	16:02:10	16:02:11.314	1 sec
8	16:06:00	16:06:04.072	4 sec
9	16:26:59	16:27:03.054	4 sec
10	16:28:59	16:29:01.405	2 sec

***The time difference is the result of the process of the driver driving on the test ramps, the Bosch WDW application sending data via mobile network to the Bosch server, and the Bosch server calculating and issuing WWD alerts.**

Ramp 3 – 5th Street to I-5 NB

Figures 4.23 to 4.32 show the driving paths recorded by the Surveyor GPS loggers and the alerts generated from the WDW application. The data points closest to the WWD alerts (in red) are selected for comparison in Table 4.3.

Figure 4.23: Ramp 3 Trial 1 driving path (orange arrows) and received Bosch alert (red dot)

Figure 4.24: Ramp 3 Trial 2 driving path (orange arrows) and received Bosch alert (red dot)

Figure 4.25: Ramp 3 Trial 3 driving path (orange arrows) and received Bosch alert (red dot)

Figure 4.26: Ramp 3 Trial 4 driving path (orange arrows) and received Bosch alert (red dot)

Figure 4.27: Ramp 3 Trial 5 driving path (orange arrows) and received Bosch alert (red dot)

Figure 4.28: Ramp 3 Trial 6 driving path (orange arrows) and received Bosch alert (red dot)

Figure 4.29: Ramp 3 Trial 7 driving path (orange arrows) and received Bosch alert (red dot)

Figure 4.30: Ramp 3 Trial 8 driving path (orange arrows) and received Bosch alert (red dot)

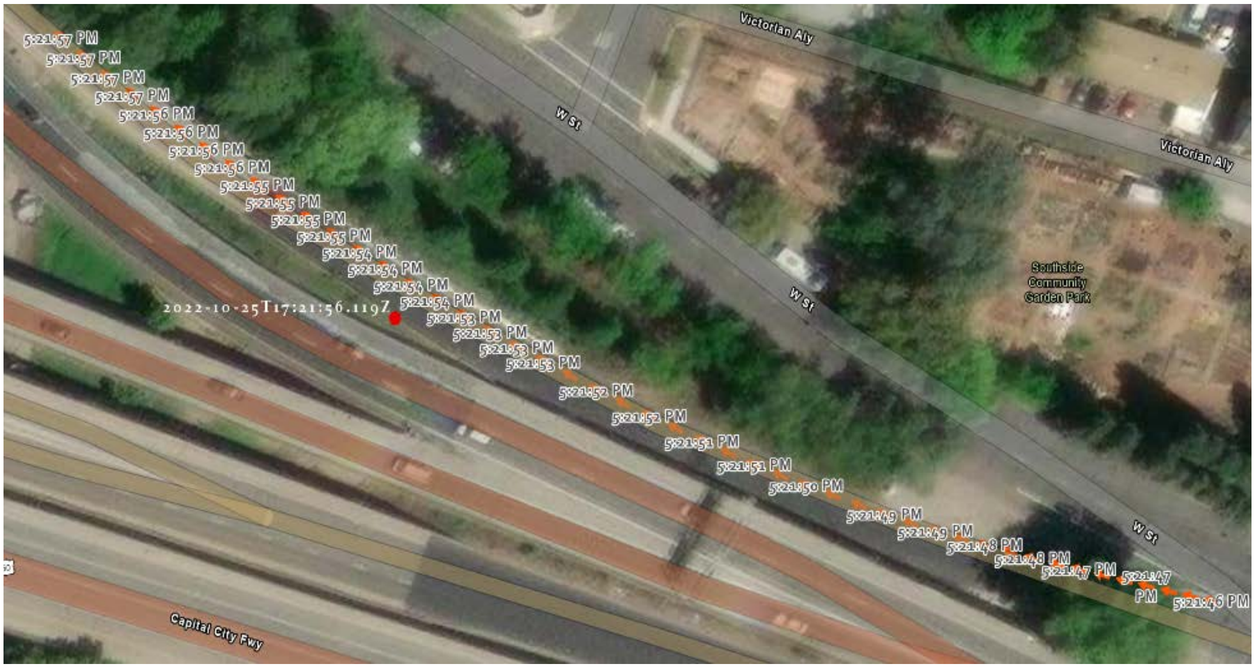

Figure 4.31: Ramp 3 Trial 9 driving path (orange arrows) and received Bosch alert (red dot)

Figure 4.32: Ramp 3 Trial 10 driving path (orange arrows) and received Bosch alert (red dot)

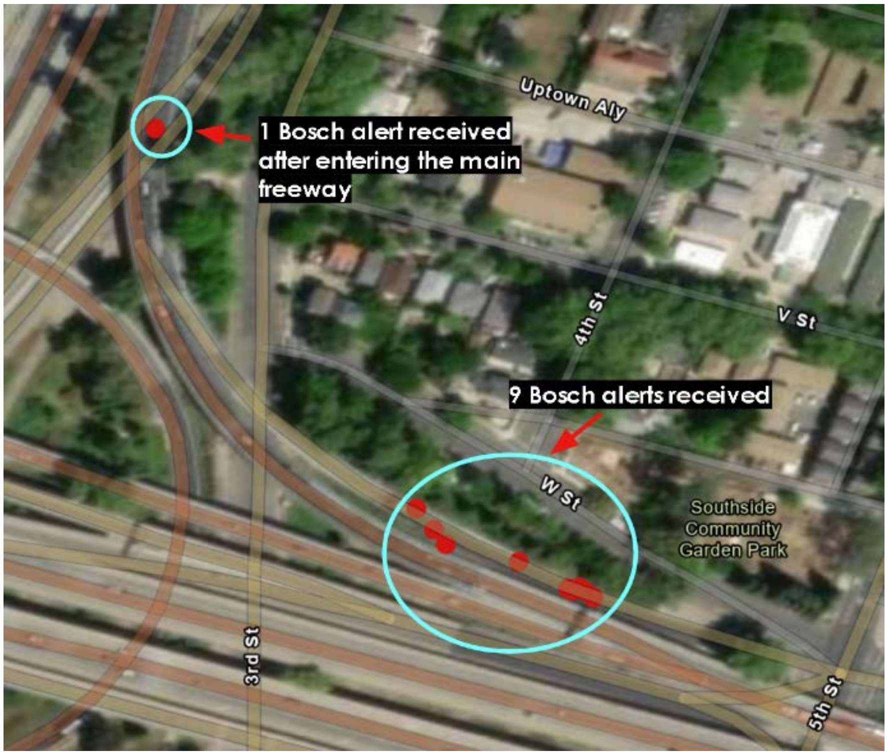

Figure 4.33: 10 Bosch alerts received on ramp 3

Table 4.3: Ramp 3 test results comparison

Trial #	Time stamp of the GPS logger at the position of the vehicle where WWD was detected	Time stamp when Bosch issued WWD alert	Time difference between the two time stamps*
1	15:07:00	15:07:01.086	1 sec
2	15:08:58	15:08:58.765	Less than 1 sec
3	15:24:01	15:24:01.663	Less than 1 sec
4	15:26:24	15:26:27.758	3 sec
5	15:38:00	15:38:01.104	1 sec
6	15:40:24	15:40:28.755	4 sec
7	16:26:24	16:26:25.892	1 sec
8	17:11:28	17:11:28.711	Less than 1 sec

Trial #	Time stamp of the GPS logger at the position of the vehicle where WWD was detected	Time stamp when Bosch issued WWD alert	Time difference between the two time stamps*
9	17:21:54	17:21:56.119	2 sec
10	17:24:21	17:24:21.645	Less than 1 sec

***The time difference is the result of the process of the driver driving on the test ramps, the Bosch WDW application sending data via mobile network to the Bosch server, and the Bosch server calculating and issuing WWD alerts.**

Ramp 4 – 5th Street to I-5 SB

Figures 4.34 to 4.43 show the driving paths recorded by the Surveyor GPS loggers and the alerts generated from the WDW application. The data points closest to the WWD alerts (in red) are selected for comparison in Table 4.4.

Figure 4.34: Ramp 4 Trial 1 driving path (pink arrows) and received Bosch alert (red dot)

Figure 4.35: Ramp 4 Trial 2 driving path (pink arrows) and received Bosch alert (red dot)

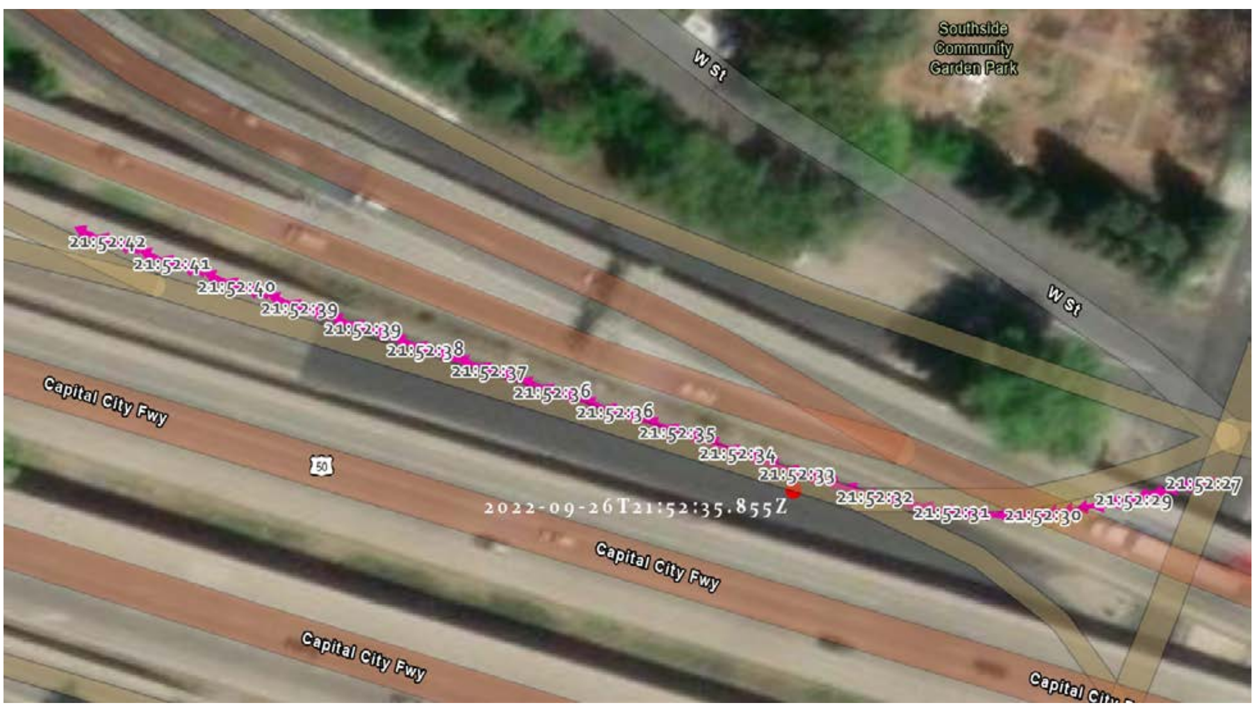

Figure 4.36: Ramp 4 Trial 3 driving path (pink arrows) and received Bosch alert (red dot)

Figure 4.37: Ramp 4 Trial 4 driving path (pink arrows) and received Bosch alert (red dot)

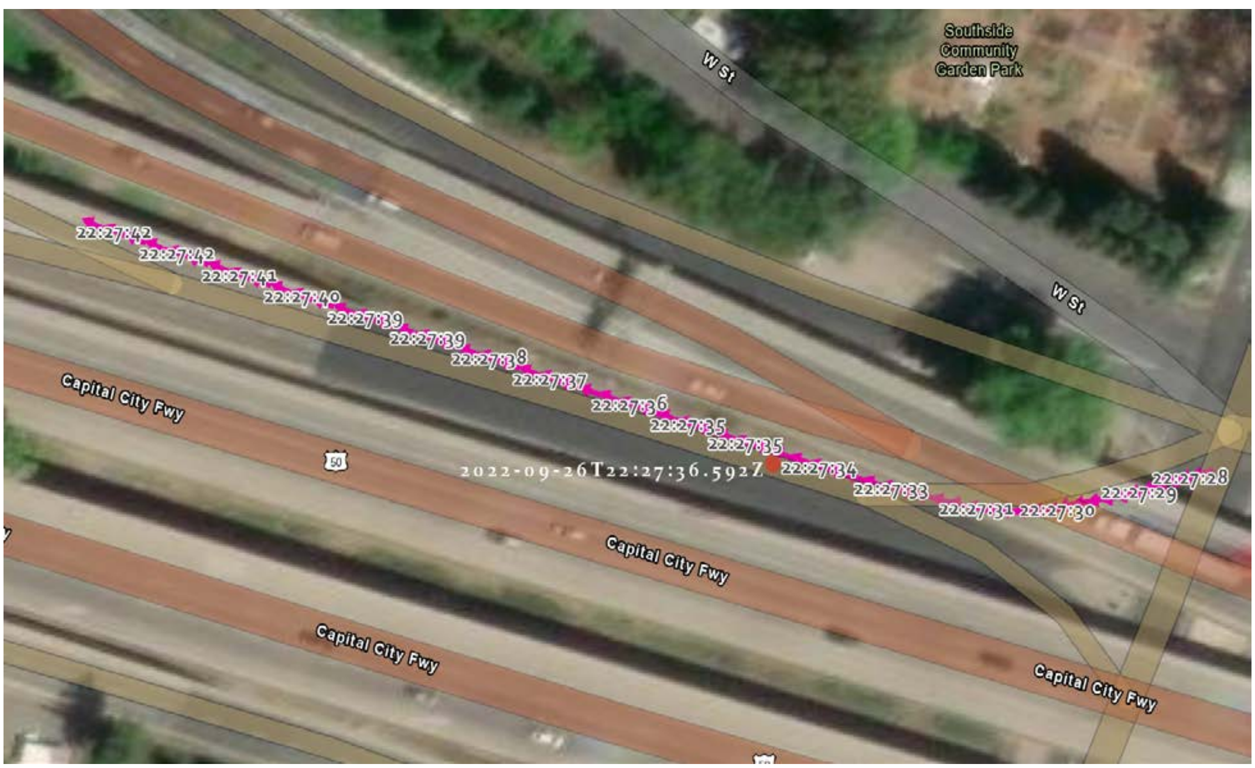

Figure 4.38: Ramp 4 Trial 5 driving path (pink arrows) and received Bosch alert (red dot)

Figure 4.39: Ramp 4 Trial 6 driving path (pink arrows) and received Bosch alert (red dot)

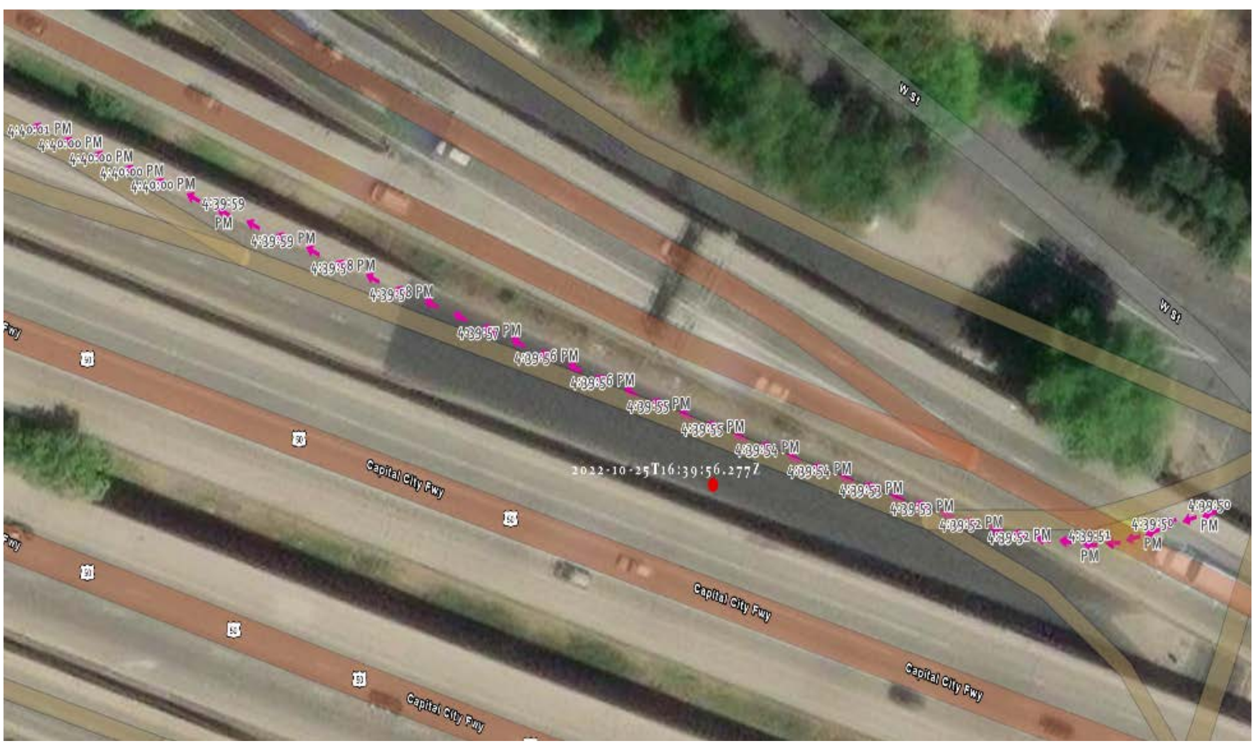

Figure 4.40: Ramp 4 Trial 7 driving path (pink arrows) and received Bosch alert (red dot)

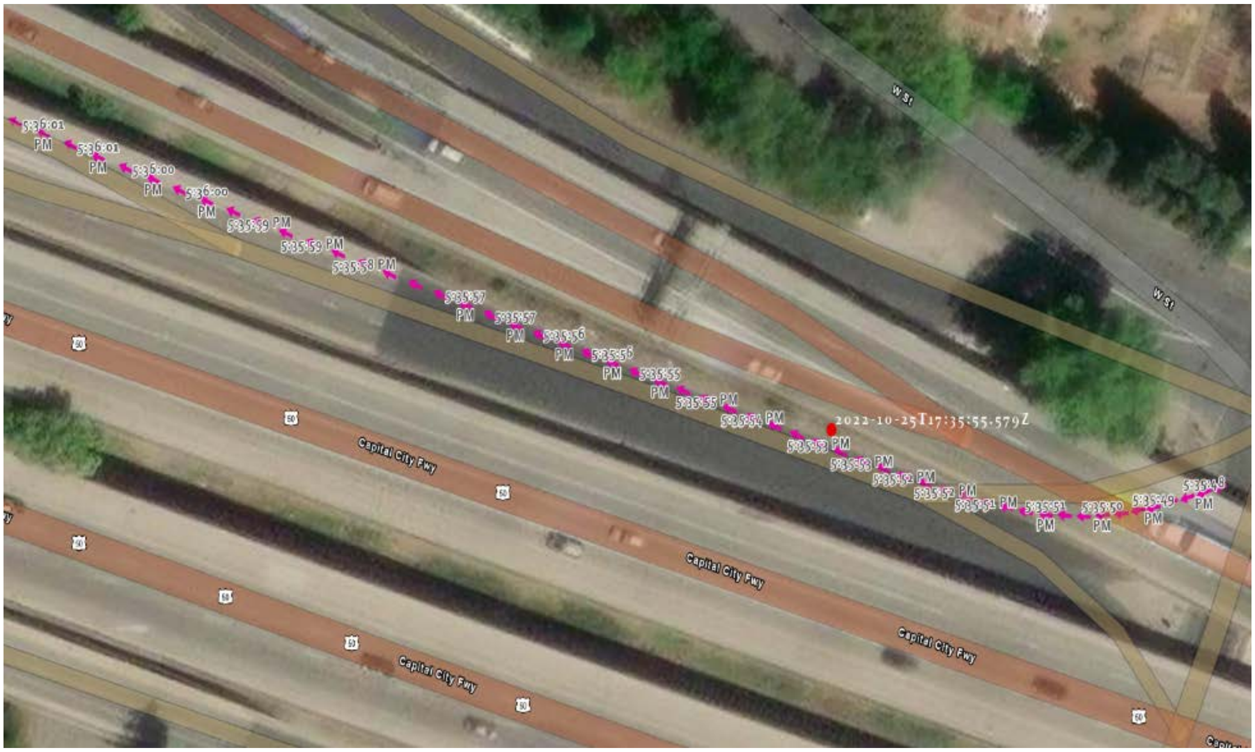

Figure 4.41: Ramp 4 Trial 8 driving path (pink arrows) and received Bosch alert (red dot)

Figure 4.42: Ramp 4 Trial 9 driving path (pink arrows) and received Bosch alert (red dot)

Figure 4.43: Ramp 4 Trial 10 driving path (pink arrows) and received Bosch alert (red dot)

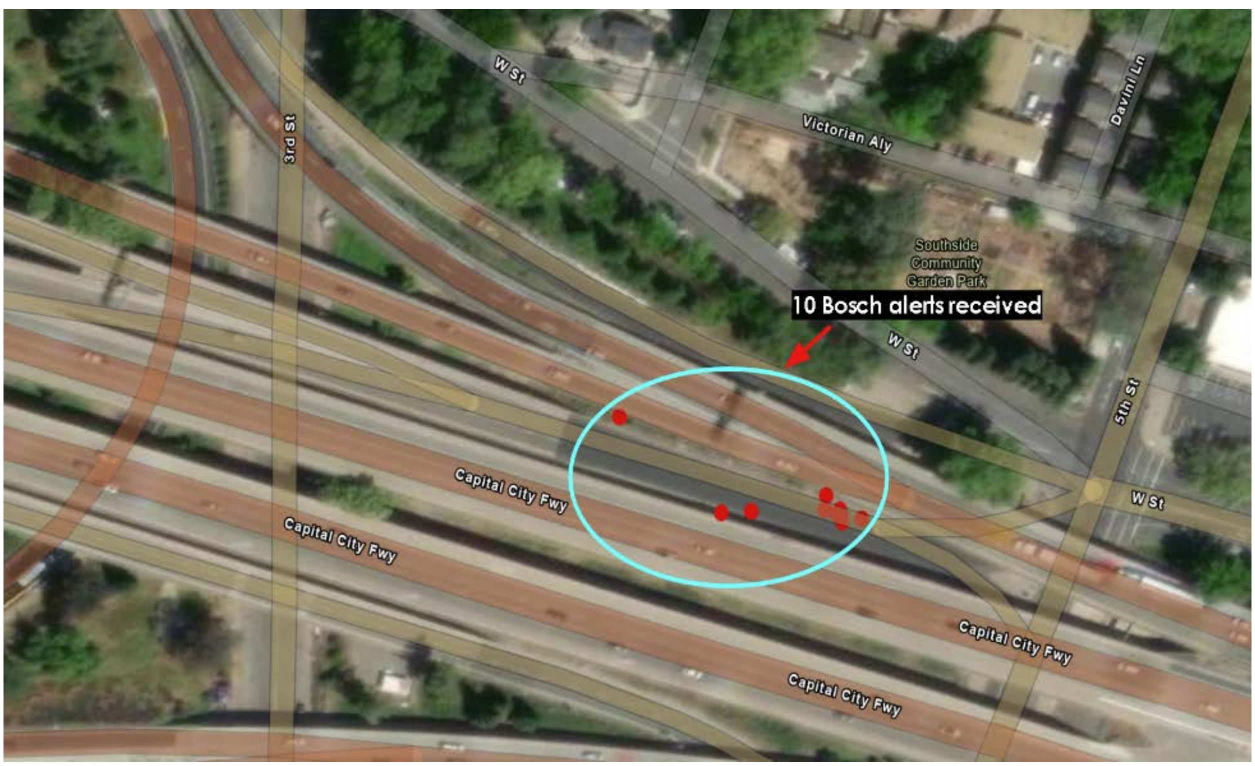

Figure 4.44: 10 Bosch alerts received on ramp 4

Table 4.4: Ramp 4 test results comparison

Trial #	Time stamp of the GPS logger at the position of the vehicle where WWD was detected	Time stamp when Bosch issued WWD alert	Time difference between the two time stamps*
1	21:15:19	21:15:21.102	2 sec
2	21:35:04	21:35:06.578	2 sec
3	21:52:33	21:52:35.855	2 sec
4	22:10:04	22:10:06.957	2 sec
5	22:27:34	22:27:36.592	2 sec
6	22:39:35	22:39:36.539	1 sec
7	16:39:55	16:39:56.277	1 sec
8	17:35:53	17:35:55.579	2 sec
9	18:11:20	18:11:22.090	2 sec
10	18:13:17	18:13:18.807	1 sec

***The time difference is the result of the process of the driver driving on the test ramps, the Bosch WDW application sending data via mobile network to the Bosch server, and the Bosch server calculating and issuing WWD alerts.**

Ramp 5 – P Street to I-5 SB

Figures 4.45 to 4.54 show the driving paths recorded by the Surveyor GPS loggers and the alerts generated from the WDW application. The data points closest to the WWD alerts (in red) are selected for comparison in Table 4.5.

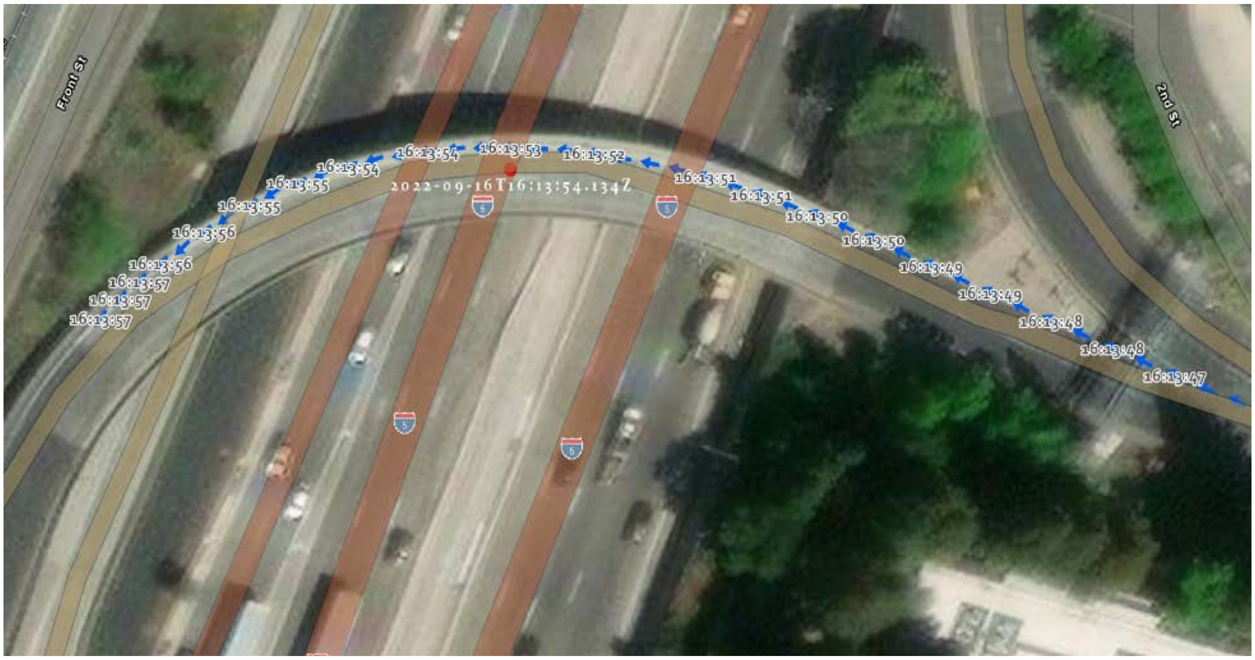

Figure 4.45: Ramp 5 Trial 1 driving path (blue arrows) and received Bosch alert (red dot)

Figure 4.46: Ramp 5 Trial 2 driving path (blue arrows) and received Bosch alert (red dot)

Figure 4.47: Ramp 5 Trial 3 driving path (blue arrows) and received Bosch alert (red dot)

Figure 4.48: Ramp 5 Trial 4 driving path (blue arrows) and received Bosch alert (red dot)

Figure 4.49: Ramp 5 Trial 5 driving path (blue arrows) and received Bosch alert (red dot)

Figure 4.50: Ramp 5 Trial 6 driving path (blue arrows) and received Bosch alert (red dot)

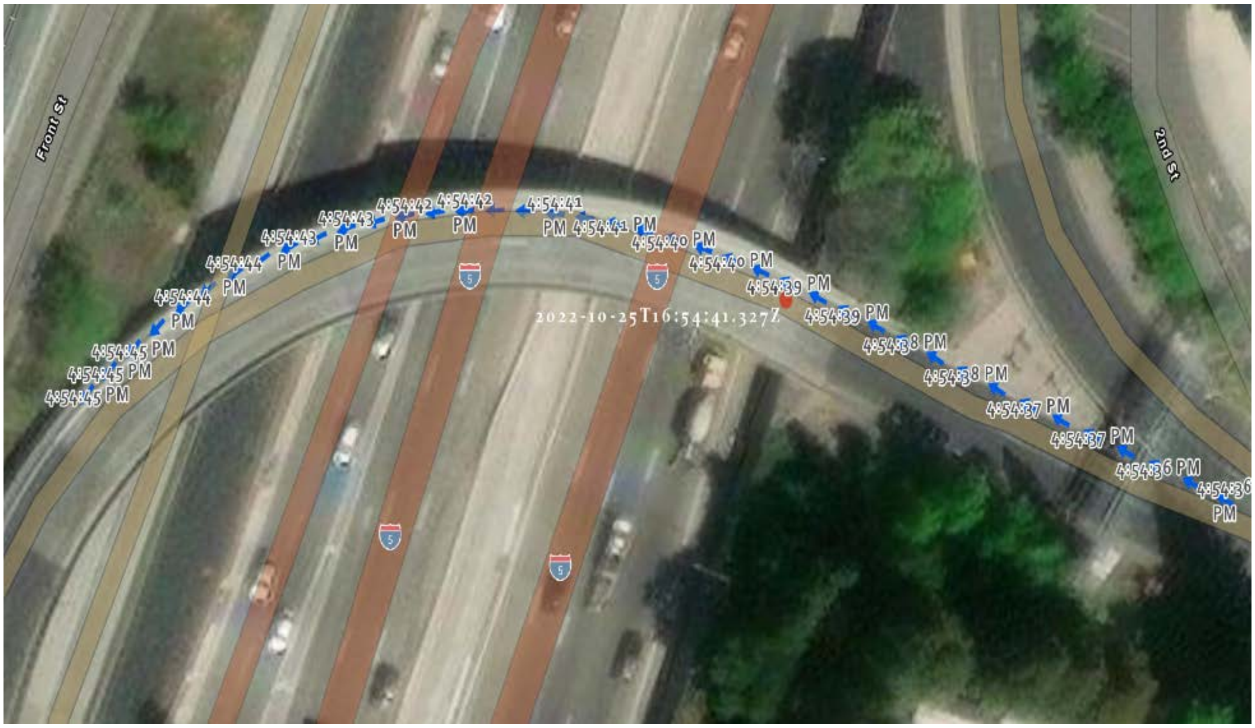

Figure 4.51: Ramp 5 Trial 7 driving path (blue arrows) and received Bosch alert (red dot)

Figure 4.52: Ramp 5 Trial 8 driving path (blue arrows) and received Bosch alert (red dot)

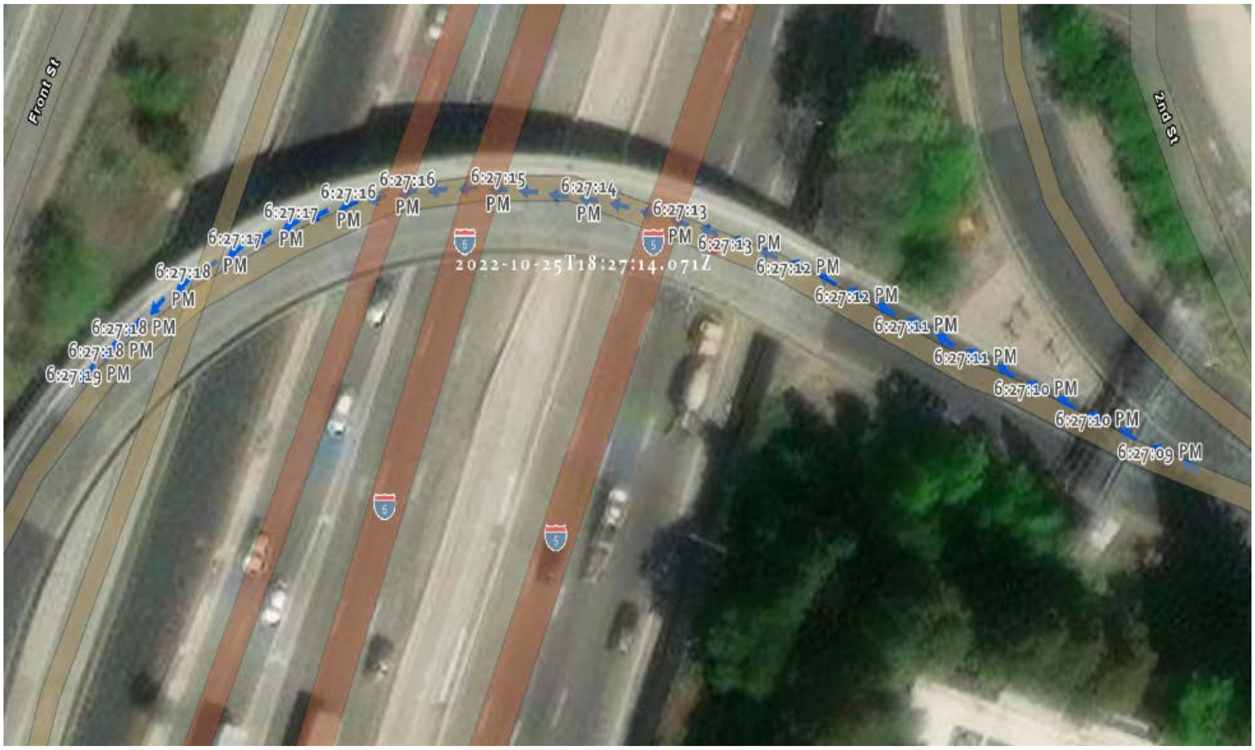

Figure 4.53: Ramp 5 Trial 9 driving path (blue arrows) and received Bosch alert (red dot)

Figure 4.54: Ramp 5 Trial 10 driving path (blue arrows) and received Bosch alert (red dot)

Figure 4.55: 10 Bosch alerts received on ramp 5

Table 4.5: Ramp 5 test results comparison

Trial #	Time stamp of the GPS logger at the position of the vehicle where WWD was detected	Time stamp when Bosch issued WWD alert	Time difference between the two time stamps*
1	16:13:53	16:13:54.134	1 sec
2	16:17:55	16:17:56.733	1 sec
3	16:48:49	16:48:50.011	1 sec
4	16:51:24	16:51:26.356	2 sec
5	17:28:43	17:28:44.338	1 sec
6	17:30:27	17:30:30.445	3 sec

Trial #	Time stamp of the GPS logger at the position of the vehicle where WWD was detected	Time stamp when Bosch issued WWD alert	Time difference between the two time stamps*
7	16:54:39	16:54:41.327	2 sec
8	17:50:31	17:50:31.989	Less than 1 sec
9	18:27:13	18:27:14.071	1 sec
10	18:28:50	18:28:50.974	Less than 1 sec

***The time difference is the result of the process of the driver driving on the test ramps, the Bosch WDW application sending data via mobile network to the Bosch server, and the Bosch server calculating and issuing WWD alerts.**

Feasibility of Issuing Live Warnings

The results from the main evaluation show that Bosch alerts were not received at the same exact coordinates/locations where the wrong way movement was detected. The driver can receive alerts anywhere along the Bosch-defined detection zone.

There were time delays from when the WDW server issued alerts to when the drivers received alerts. These time delays are the result of the data transfer process (Figure 4.56). The WDW application forwards the vehicular data (i.e. vehicle's coordinates) to the Bosch server. The Bosch server processes the vehicular data, then issues a WDW alert when the vehicle is in the Bosch test zone. The latency in this report is from when Bosch issued an alert to when AHMCT drivers received an alert.

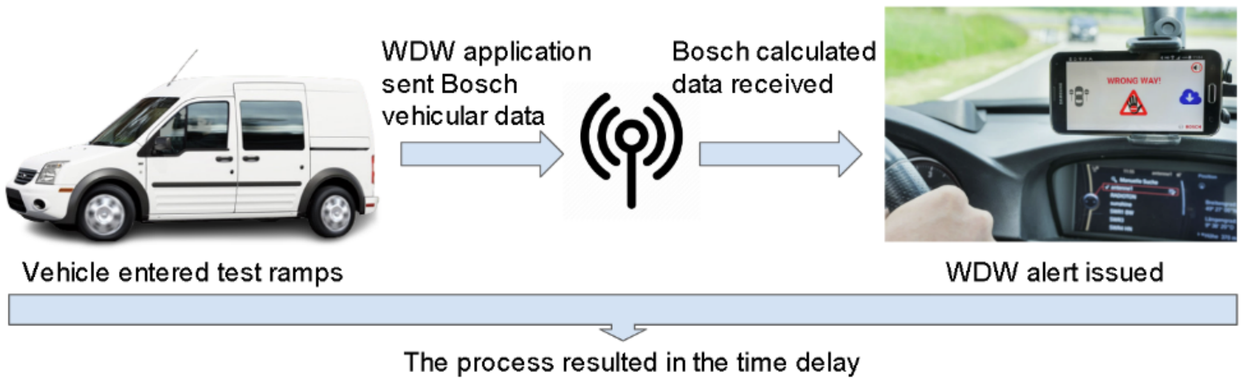

Figure 4.56: The data transfer process to receive WDW alerts[4]

Time delay results are shown and highlighted in Table 4.6.

Table 4.6: Results of time delay from all ramps

Trial #	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5
1	1 sec	1 sec	1 sec	2 sec	1 sec
2	1 sec	5 sec	Less than 1 sec	2 sec	1 sec
3	1 sec	1 sec	Less than 1 sec	2 sec	1 sec
4	1 sec	2 sec	3 sec	2 sec	2 sec
5	1 sec	5 sec	1 sec	2 sec	1 sec
6	1 sec	1 sec	4 sec	1 sec	3 sec
7	1 sec	1 sec	1 sec	1 sec	2 sec
8	1 sec	4 sec	Less than 1 sec	2 sec	Less than 1 sec
9	1 sec	4 sec	2 sec	2 sec	1 sec

[4] "WDW alert issued" image from Bosch deploys new wrong-way driver alert system in 13 European countries – Automotive Today (automotive-today.ro)

Trial #	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5
10	1 sec	2 sec	Less than 1 sec	1 sec	Less than 1 sec

In this research, five ramps were tested with ten trials for each ramp, and all alerts were received as expected. The success rate for receiving alerts was100% across all 50 trials. Taking the latency into consideration, the success rate for receiving alerts within 3 seconds was 90%.

It is ideal that all alerts be received **before** drivers enter the main freeway or **before** the ramp split, but there was one alert received **after** the driver entered the main freeway (Figure 4.33). The success rate for receiving alerts **before** the driver entered the main freeway/ramp split was 98%.

Table 4.7: Overall results

	Success rate
Success rate for receiving alerts	100%
Success rate for receiving alerts within 3 seconds	90%
Success rate for receiving alerts before the driver entered the main freeway or ramp split	98%

Chapter 5: Conclusions and Future Research

Key contributions of this research project included:

1. Determining the procedures necessary for achieving a 100% success rate for receiving alerts.

WDW application characteristics must be followed for the algorithm to work flawlessly every time. Drivers have to meet the assumptions made by the Bosch team:

- Drivers enter the red zone and get assigned an ID. Drivers must exit the red zone to get assigned a new ID. Drivers will not receive further WDW alerts if their ID stays the same.
- Drivers should pull over after the first alert since a second alert will not be issued.
- Drivers should not be stationary within a hotspot for more than 10 minutes as the application has a limitation on how many data points it can collect. However, this is only the case for the WDW application and can be configured by Bosch. Bosch's OEM installations have a much higher threshold.
- Drivers are unlikely to enter two ramps/hotspots directly one after the other. If this is the case, i.e., someone drives on two ramps consecutively in the wrong direction with the same ID, the driver will receive a WDW alert on the first ramp but not on the second ramp. If the driver drives in the right direction on the first ramp but drives in the wrong direction on the second ramp, the driver will receive a WDW alert on the second ramp.
- If the application cancels the trip due to the driver being stationary for more than 10 minutes, the driver can re-activate the application by:
    - Driving away and then re-entering the hotspot so that the application can reassign a new trip ID.
    - Restarting the application by removing it from the phone background completely. When the application is turned back on, it automatically assigns drivers a new trip ID. The counter for the data collection limit also restarts at zero.

2. Evaluating the capability of the WDW application algorithm

The WDW application algorithm worked flawlessly in every test when the procedures were followed correctly. In addition, for this evaluation, the drivers were driving in the correct direction, so no ramp closures were required to carry out testing. The Bosch team "flipped" the driving direction of the drivers to trigger an alert. In the data logs received from Bosch, the driving directions followed the drivers' driving path on the ramps. The "flip" was not reflected in the data logs. If a driver actually drove in the wrong direction, the algorithm would have identified that the heading was wrong and triggered an alert. ***The algorithm has the capability to detect wrong way drivers.***

3. Evaluating the feasibility of issuing live warnings

In this evaluation, each of the five ramps was tested ten times for a total of 50 tests. When the WDW application characteristics were taken into account to eliminate the erroneous results for ramp 4, the drivers received an alert for every single event, i.e., there were no false negatives.

Bosch monitored the AHMCT team live on September 15 and 16 to ensure the testing process ran smoothly. However, Bosch did not live-monitor the AHMCT team moving forward. Results after September 26 were not live-monitored by Bosch, but alerts were pushed out exactly as expected.

Table 5.1: Testing timeline for official results

Date	Ramp tested	Days apart from the first testing date
Sep 15, 2022	Ramps 1 and 2	N/A
Sep 16, 2022	Ramps 3, 4, and 5	1 day
Sep 26, 2022	Ramp 4	11 days
Oct 24, 2022	Ramps 1 and 2	39 days
Oct 25, 2022	Ramps 3, 4, and 5	40 days

The testing process spanned 40 days. Although testing dates were far apart, the WDW application sent out alerts consistently. ***The Bosch system is reliable over time.***

The success rate for receiving an alert is 100%. The success rate for receiving an alert within 3 seconds is 90%. The success rate for receiving an alert before the drivers entered the main freeway or a ramp split is 98%.

The WDW application fulfilled the purpose of issuing live alerts when activated inside a vehicle heading in the wrong direction. From planned steps to actual testing process, there was a misunderstanding of the WDW application characteristics, leading to the re-test on September 26. When the conditions to receive an alert were met, the Bosch algorithm worked perfectly.

The results from the test that did not follow the WDW application characteristics were not considered in this evaluation. ***There were no false negatives (WWD behavior but no WDW alert) among the results***. False positives (no WWD behavior but a WDW alert is issued) were not within the scope of this study. That said, no false positives were observed. This finding was expected since Bosch's self-determined false positive rate is extremely low.

The WDW algorithm is ready for deployment as it has a 100% rate of issuing a wrong way driver alert. The application interface is convenient as the end user does not need to adjust any settings.

In conclusion, the WDW algorithm is reliable for issuing WWD alerts. Instead of typical systems and methods like radar and/or vision sensors, which require fixed installation and are costly, the WDW application can be installed on smartphones and tablets. In this evaluation, the process to set up the Bosch system took less than five minutes. The user downloaded the application then opened it, and that was it. The benefits of utilizing the WDW algorithm are:

- Fast installation on smartphones and tablets
- No setup process
- 100% success rate of issuing a WWD alert
- Cost effective

As mentioned previously, the WDW application characteristics must be followed. There is more "wiggle room" to change an application's characteristics than to change a physical installation, especially in a large deployment.

4. Bosch current and future deployment

In this evaluation, Bosch triggered alerts according to the WDW application characteristics listed above. In a live system integrated into a vehicle, an OEM automaker could decide how the warning sequence should look. For example, an automaker could continue tracking the driving direction and trigger further warnings. The purpose of the Bosch demonstration of the WDW application was to prove its WWD detection functionality. The WDW application does not consider how the integrated live system interacts with the driver. The integrated live system is within the domain for discussion when a customer is interested in the Bosch algorithm. ***The purpose of this evaluation was to test the effectiveness***

of sharing the detected WWD signal with the road operators via the WDW application. The algorithm can change to accommodate interested customers.

The application Bosch provided AHMCT for testing is a special application for demonstration purposes. The core of this application is the Software Development Kit (SDK) used in production, which Bosch provides to all application partners. This SDK is available for Android and iOS, and the demo application is available only on Android. In Europe, Bosch's SDK is currently integrated into more than 30 partner applications, which leads to more than 12 million daily observed trips on highway ramps for more than two million unique users. Typical partner applications are navigation apps and radio apps. Bosch does not have its own wrong way driver warning application.

Besides the usage of the wrong way driver warning within partner applications, Bosch is partnering with manufacturers to integrate the service directly into vehicles. The benefits of having direct warning systems integrated into vehicles are reduced delays in communication and driver alerts via the vehicular display and/or audio. Modern vehicles have external antennas for mobile network and satellite navigation, which is beneficial for warning drivers that they are driving the wrong way as quickly as possible. In Europe, Volkswagen has deployed the Bosch wrong way driver warning system in their vehicles, particularly the model "Skoda."

In this evaluation, Bosch created a WDW application so that the AHMCT team could evaluate the algorithm's WWD detection quality. Bosch's algorithm is only available to the public through partner applications, such as Sygic, nDrive, Flitsmeister, Radioplayer, Antenne Bayern, etc. Sygic is the first application in North America to implement Bosch's algorithm, and it is ready to download from app stores in the United States and Canada. The future vision is to implement the algorithm directly into vehicles across North America.