



TDOT
Department of
Transportation



Investigation on Wrong way Prevention Technologies and Systems

Research Final Report from The University of Memphis | Dr. Mihalis Golias, Dr. Sabyasachee Mishra, Huan Ngo | May 20, 2021

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16. Abstract <p>Wrong-way driving (WWD) is an event where a vehicle enters a high-speed divided highway from an off-ramp in the direction opposing to the legal traffic flow. Although being less frequent than other crash type, WWD is significantly more fatal and in Tennessee, there are on average 20 WWD annually. Therefore, this report aims to first understand WWD in Tennessee by investigating WWD crash data and second explores Wrong-way Prevention System technologies, investigates, and tests these products. After the results are gathered from testing, these systems are evaluated based on multiple criteria namely accuracy, responsiveness, life cycle cost, live-tracking, and additional features. Based on this evaluation along with the experiences in installing, testing, and operating these products, this report recommends TrafficCalm Wrong-way Prevention System as a solution to WWD. The system detects the WWD vehicle with ultimate accuracy, it is highly responsive and at a reasonable cost that can be deployed at multiple locations.</p>			
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Executive Summary

What was the research need?

Wrong-way driving (WWD) is an event where a vehicle enters a high-speed divided highway from an exit ramp in the direction opposing to the legal traffic flow. This vehicle either collides with an object or other vehicle traveling in the correct direction in the same segment or does not collide at all. Although the frequency of such an event is small compared to other types of traffic accidents, WWD is typically more severe since it usually results in a head on collision. To avoid such event, efforts should be dedicated to both theoretical (i.e., finding common causes and patterns of WWD) and practical (i.e., deploying modern technologies to stop the WWD driver) work. Therefore, this project investigated the Wrong-Way Driving Prevention Systems (WWPS) available on the market to prevent such accidents. WWPS technology is still evolving with different mechanism and there is yet a consensus across many states on what can be the most effective method. Through this project, TDOT can test the standout WWPS and determine what is the most promising product for their situation and need.

What were the research objectives?

The project aimed to achieve the following objectives:

- Understanding what WWPS mechanism are available and comparing them.
- Gathering and analyzing WWD crash data in Tennessee.
- Surveying WWPS available in the market and conducting product testing.
- Evaluating and comparing WWPS performance based on multiple criteria.
- Recommending the most promising product and developing guidelines for deploying.

What was the research approach?

There are four main procedures for this project. First, different wrong-way detection mechanism and existing deployment of WWPS from several States were reviewed and evaluated. Second, based on police reports and ETRIMS crash database, a thorough descriptive analysis of wrong way crashes in Tennessee was conducted. Within these, both the spatial and temporal elements are explored. Third, three selected WWPS were acquired and tested in two phases on both controlled environment and real-world deployment to assess the effectiveness. In the first test conducted in a controlled environment, a test vehicle was driven the wrong way to examine whether the WWPS detects the WWD driver. In the second test, the WWPSs were deployed to real-world exit ramp in Nashville with real traffic and weather conditions for an extended amount of time to determine whether the performance from controlled environment transfer directly to the real world. Finally, results from these tests along with life cycle cost analysis are used to perform a multicriteria evaluation to identify the most effective WWPS out of these three systems.

What were the findings?

We narrow the following main findings:

- Thermal Detection, Radar Detection, and LED-Enhanced Blinking Wrong Way signs are the most effective components of a WWPS.
- In Tennessee, there are on average 20 WWD crashes annually and most of it happens at night and around major cities such as Memphis and Nashville.
- TrafficCalm WWPS has the best general performance out of three WWPS tested.

Implementation at TDOT

For TDOT, TrafficCalm is recommended as the most effective WWPS after considering five main criteria which are accuracy, responsiveness, live-tracking, life-cycle cost, and other relevant elements. TrafficCalm is able to achieve this high performance thanks to the system providing (1) multiple radars and layers of detection to ensure the WWD driver is detected, (2) a live camera showing the feed, (3) multiple logic units, and (4) optional solar panels so that the system can be a standalone and not relying on external electricity or internet connection. Besides these criteria, TrafficCalm also has two advantages over the remaining which are (1) they manufacture and integrate all the components in house with full lifetime technical support and (2) their WWPS were already deployed and operated successfully in several states in across the U.S.

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Glossary of Key Terms and Acronyms

- WWD : Wrong-way Driving
- WWPS : Wrong-way Driving Prevention System
- TDOT : Tennessee Department of Transportation
- DOT : Department of Transportation

Chapter 1 Introduction

1.1 Background

Wrong-way driving (WWD) events occur when a driver enters against the right traffic-flow direction of a divided highway (e.g., freeways). The most frequent WWD incident location is a freeway ramp (Zhou et al., 2012) and according to National Transportation Safety Board (NTSB), 360 wrong-way driving related fatalities occurred annually between 2004 and 2011 in the US (NTSB, 2012). While a small percentage of total crashes (approximately 3%) WWD severity level was much higher than non-WWD crashes (Cooner and Ranft, 2007). Tennessee is one of the top 10 states with the highest number of WWD involved fatalities in the U.S. (Figure 1) (Zhou and Rouholamin, 2014).

The leading contributing factors of WWD crashes are traffic violation due to driving under influence, inattention due to fatigue and distractions, impaired judgement due to physical and age-related issues, unfamiliarity with roadways, and any infrastructure deficiencies such as poor lighting, limited line of sight, heavy vegetation (Zhou et al., 2012). A study using the Fatality Analysis Reporting System (FARS) reported that driving under influence was responsible for approximately 60% of WWD crashes (NTSB, 2012). Several studies reported that most WWD crashes occurs on urban areas during weekend nights (Cooner et al. 2004; Zhou et al. 2012; Finley et al., 2014; Kittelson & Associates, Inc. 2015). Young male drivers under influences were overrepresented in WWD crashes on freeways (Tamburri and Theobald 1965; Zhou et al. 2012; Baratian-Ghorghi et al. 2014; Finley et al. 2014), where older drivers were overrepresented in total WWD crashes (NTSB, 2012; Baratian-Ghorghi et al. 2014; Kittelson & Associates, Inc. 2015).

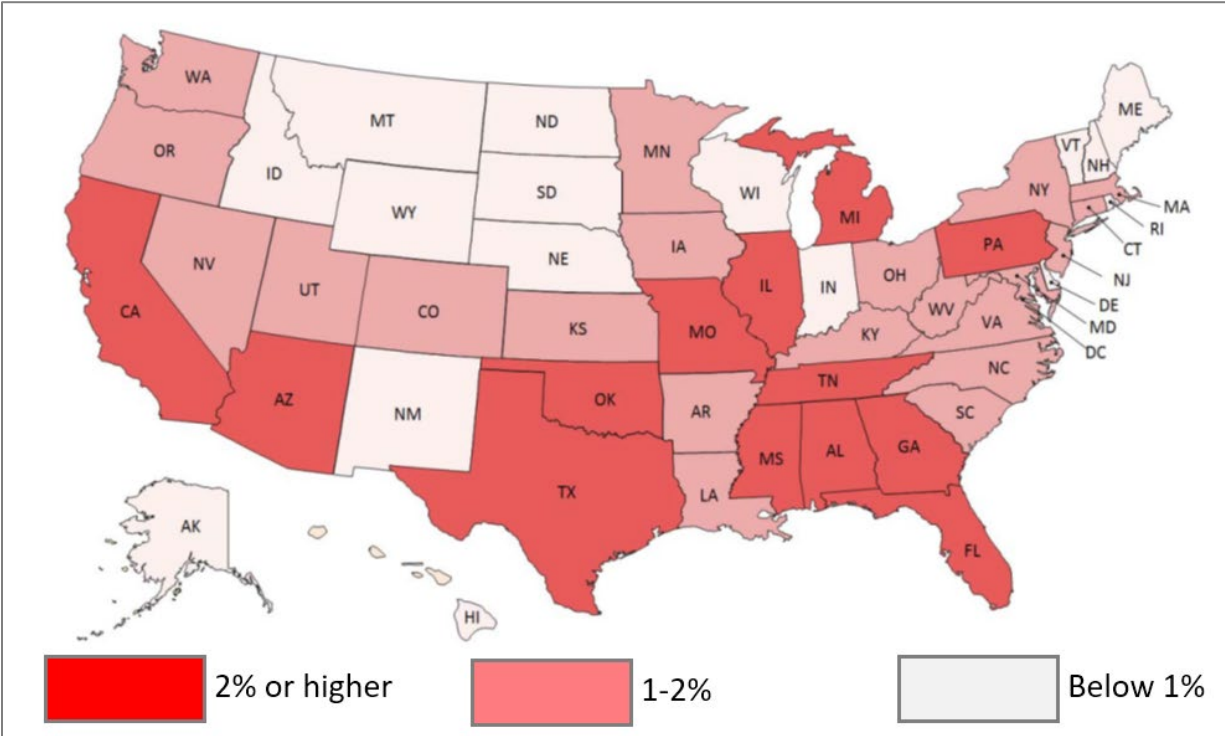


Figure 1-1 WWD Distribution Across States

State transportation agencies have been implementing different types of countermeasures at high-risk WWD crash locations to reduce wrong-way driving and associated crashes. NCHRP Report 881 identified most frequent countermeasures, as “DO NOT ENTER” and “WRONG WAY” signs, flashing red LEDs on the border of “WRONG WAY” signs, wrong-way arrow markings, centerline in the median opening, and stop and yield lines (Finley et al., 2018). Beyond additional warning signs and markings, agencies started to deploy technology supported WWPS, which has been more effective.

In this research, the team will identify and investigate different WWPS for implementation in Tennessee. *Three* WWPS will be identified and most suitable three will be *deployed* and *tested*. The primary performance measures will be used to compare the systems are accuracy, user friendliness, cost-effectiveness (life cycle costs), and provision of live tracking of wrong-way drivers. Additional performance such as suitability for night lighting condition, ease of installation, dual functions, maintenance frequency will be considered in the evaluation of WWPS.

1.2 Objectives

The overarching goal of this research project is to determine the effectiveness of different WWPS in reducing WWD crashes in Tennessee. Based on the performance of each system in terms of detection accuracy, user friendliness, low cost, and live tracking of wrong-way drivers, three WWPS will be recommended for Tennessee highways with diverse roadway and traffic characteristics. After reaching each project milestone, the research team will update TDOT project advisory committee and seek feedback on research progress and findings. Specially, the team will seek TDOT’s inputs in selection of WWPS and on-site testing supported by past WWD crash analysis. The specific objectives of this study are to:

- A comprehensive review of the WWPS pilot tested and deployed in different states, effectiveness of each system (in terms of accuracy, user friendliness, life cycle costs, and live tracking provision), deployment and maintenance cost, and deployment challenges.
- Data Collection and Analysis:
 - Collect Data from the Enhanced Tennessee Roadway Information Management System (ETRIMS).
 - Provide descriptive statistics and identify potential contributing factors
- Identification of candidate WWPS through reviewing current practices by all states.
- Life cycle cost analysis: Cost data will be collected from manufacturers and/or system providers of candidate WWPS.
- Selection of top three candidate WWPS for on-site testing considering system performance, cost and WWD crash characteristics in Tennessee.
- On-site implementation and testing of three candidate WWPS, accompanied by surveys to capture user experience.
- Recommendation and guidance of ready-to-implement WWPS TDOT.

1.3 Report organization

The remaining of this report is organized as follow.

- Chapter 2 will first provide an overview of available WWPS in the market, their advantages and disadvantages, and a preliminary alternative analysis between different type of detection mechanism. In addition, historical data from WWD event report in Tennessee are collected and analyzed to identifying common factors leading to a WWD.
- Chapter 3 discusses the methodology used to practically determine the effectiveness of different WWPS which involves surveying and field testing.
- Chapter 4 shows the result of field-testing activities and conducts a lifecycle cost analysis. Based on these two metrics, we perform multicriteria evaluation to compare between top three WWPS.
- Chapter 5 concludes the study and makes recommendation on the most effective WWPS for several deployment scenario.

Chapter 2 Literature Review

2.1 Review of Existing Wrong-way Driving Prevention System

This section discusses different type of technologies being used to prevent wrong-way driving incidents. A WWPS usually consists of three main components, which are detection, warning, and alerting. There is multiple detection mechanism such as (1) Radar, (2) Microwave, (3) Video Detection, and (4) Thermal Detection while warning component is usually in form of a traffic sign (e.g., Wrong-Way R5-1A or Do Not Enter R5-1) with enhanced dynamic LED.

2.1.1 Radar Detection System

A radar detection sensor is mounted on a roadside pole, and typically one radar sensor is used to detect WWD events on multiple lanes. However, to improve accuracy, more than one radar detector can be used. In addition to radar detectors, each system consists of video camera for verification of the WWD incident, communication devices with the traffic management center and LED "WRONG WAY" sign to warn the wrong-way drivers and right-way drivers.

The advantages of the radar detection system are as follows:

- Less than four hours for a complete system installation (Simpson, 2013). As this system is installed on a roadside pole, disruption to traffic flow is minimum.
- Low maintenance need
- Works in any weather and lighting conditions
- Can be powered by solar power

The disadvantages of this system are:

- False alarm rates.
- Sensitivity to large trucks.
- Less effective in heavy traffic scenario (e.g., queues).

2.1.2 Microwave Detection System

Microwave is a type of non-intrusive technology that have been used to detect WWD incidents. Similar to radar sensor, microwave sensor is mounted on a roadside pole facing the travel lanes. Microwave sensors can be programed to detect vehicles on several lanes and can detect vehicle up to 120 ft away. Compared to radar sensor, microwave can detect vehicles that are behind other vehicles and are not directly visible from the microwave sensor location.

The advantages of the microwave detection system are as follows:

- It can detect vehicle that are obstructed by other vehicles
- Insensitive to inclement weather and lighting conditions
- Multi-lane detection capability
- Low maintenance frequency

The disadvantages of this system are:

- External power source is needed to power this system. During the field testing in July 2011 ADOT found that there were three false calls by the microwave detection system.

2.1.3 Video Detection System

In this system, video camera detects WWD incidents as well as capture and send recorded videos to Traffic Management Center (TMC). Video detection system detects WWD incidents by analyzing movement of the vehicle in a user-defined zone within a fixed field of camera view. Image processing technique are used to identify the WWD incidents.

The advantages of the video detection system are as follows:

- It can be implemented using traditional vehicle detection video cameras
- Can work under different weather conditions.

The disadvantages of this system are:

- Slow vehicle speed and nighttime visibility affect the detection accuracy
- Detection accuracy of this system is about 80 percent in low light condition

2.1.4 Magnetic Detection System

Magnetic detection system uses magnetic sensor technology installed in pavement. This technology detects WWD vehicles by measuring the change in Earth's magnetic field due to the presence of a vehicle. When a change in the magnetic field is detected, the sensors send their data via radio to an access point near the in-pavement sensors. Then, the vehicle's speed and direction are determined by the roadside controller (Simpson, 2013).

Magnetic system can detect a passenger vehicle when vehicle speed is 5 mph or higher. Thus, the detectors should be placed at a distance from the stop line at the end of the ramp. Usually, a minimum distance of 50 feet from the stop line is recommended. Moreover, the detectors should be placed systematically to ensure enough signal strength for WWD incident detection.

The advantages of the magnetic detection system are as follows:

- Performs well in all lighting conditions
- Works in all weather conditions

The disadvantages of this system are:

- The installation and maintenance of this system cause traffic disruption as primary sensors are installed below pavement surface.

2.1.5 Thermal Camera Detection System

Thermal camera can be used to detect WWD incidents. The application of this technology for WWD detection is relatively new, and few DOTs have deployed this system. Arizona Department of Transportation has recently installed this system in a 15 mile stretch of Interstate 17 between the I-10 stack interchange near downtown and the Loop 101 interchange in North Phoenix. This system uses thermal camera to detect the WWD incidents and uses warning signs to warn both right way drivers and wrong way drivers.

The advantages of the thermal detection system are as follows:

- Is easy to install and requires low maintenance

- It can differentiate between the heat signatures of a vehicle, blowing leaves or an animal crossing the road
- It can work at all lighting conditions and be used for other traffic data collection purposes

The disadvantages of this system are:

- The main disadvantage of this system is high capital cost.

2.1.6 LED-Enhanced Warning Components

LED-enhanced “WRONG WAY” sign can be used separately as a low-cost warning system without additional sensors to detect WWD incidents. This sign often has been used with other detection technologies (e.g., radar detection, microwave detection and magnetic detection system). When separate LED enhanced signs are installed, these signs blink continuously facing vehicles entering from the wrong way directions. But when it works as part of other detection system, the signs start blinking only after the detectors detect WWD incident.

In LED enhanced warning system, the standard “WRONG WAY” sign is enhanced by using Light Emitting Diode (LED) around the sign perimeter. Figure 6 shows a LED-enhanced “WRONG WAY” sign installed by Florida Department of Transportation (FDOT).



Figure 2-1 Example of LED-Enhanced Wrong-way Sign

2.1.7 In-Pavement Warning Light

In-pavement warning lights are another kind of wrong way driving warning system that uses Inductive loop detectors or other detection technology to detect the WWD incidents. These detectors activate a series of warning lights imbedded in the pavement to alert the wrong-way drivers that he or she has entered a wrong-way and traveling in the wrong direction.



Figure 2-2 In-Pavement Flashing Light Examples

The advantages of the radar detection system are as follows:

- This system is particularly effective at night because of high visibility to wrong-way drivers.

The disadvantages of this system are:

- During winter, snow accumulation on the road surface can affect the performance of the system. This system causes traffic disruption as installation and maintenance of in-pavement lights require lane closure.

2.1.8 GridSmart 360 Camera

Gridsmart system is a single camera-based system that has been used to count and classify vehicles at intersections. This system can also be used for the detection and verification of wrong-way vehicles. Installation of this system is easy, and it requires less than three. An example deployment of GridSmart 360 Camera is shown in Figure 2-3.



Figure 2-3 GridSmart 360 Camera

The advantages of the radar detection system are as follows:

- User can define zones for WWD detection using the software platform
- Works in all-weather condition
- 360-degree field of view

The disadvantages of this system are:

- This system is being used for vehicle detection and counting at intersections and was not used for wrong-way vehicle detection. Thus, accuracy and efficiency of this system for WWD detection needs to be studied.

2.1.9 Summary of WWPS

We summarize all the WWPS listed above in several aspects such as installation time, components, and accuracy in TABLE I below:

TABLE I. Summary of the Existing Technologies for Wrong-way Vehicle Detection

Attributes	Radar Detection system	Thermal Camera system	Video Detection system	In Pavement Warning Light system with Loop Detectors	LED-Enhanced Sign	Microwave Detection System	Magnetic Detection System	GridSmart 360 Camera System
Installation time	<4 hrs.	<4 hrs.	<4 hrs.	>4 hrs.	<4 hrs.	<4 hrs.	>4 hrs.	<3hrs.
Components	<ul style="list-style-type: none"> • Radar (1 to 3 units) • Video Camera • Cellular modem • LED-enhanced Sign • Software package for detection and notification 	<ul style="list-style-type: none"> • Thermal Camera censor • Cabinet and controller • LED-enhanced Sign • Software package detection and notification 	<ul style="list-style-type: none"> • One or more video cameras • A computer for digitizing and analyzing the imagery, and • Software for interpreting the images and converting them into traffic flow data • Signage and warning facility 	<ul style="list-style-type: none"> • Warning light imbedded in the pavement • Inductive Loop Detectors (ILDs) 	<ul style="list-style-type: none"> • Light emitting diode (LED) around the perimeter of the standard sign 	<ul style="list-style-type: none"> • Microwave detector (1 unit) • Video camera (2 units) • Cabinet and controller for satellite communication • LED enhanced sign • A data recorder • Software System for detection and notification 	<ul style="list-style-type: none"> • Magneto-resistive sensors • a transmitter • a video camera • Cabinet and controller • LED-enhanced sign 	<ul style="list-style-type: none"> • Bell shaped Camera • GS Processor • GS client software • LED-Enhanced Signing
Estimated Cost	<\$5,000 per system (with 1 radar)	>\$25,000 per system (with 1 thermal camera)	>\$10,000 per system (with 2 video cameras)	Average \$17,000 for each system	\$ 1600-\$ 1900 per Sign (with Solar Power)	< \$5000 per system	\$5,000-\$10,000	System cost was not found
Maintenance Need	Low	Low	High	Moderate	Low	Moderate	Moderate to Low	Low
Accuracy	70% with 2 radar	80%	100% in day 83% in night	100%	30% reduction in WWD	100 % (based on testing by United Civil Group)	100 % (based on testing)	Accuracy is high for traditional use. Accuracy of WWD detection is yet to be determined.
Night Operation¹	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Non-Intrusive	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Dual Function²	Yes	Yes	Yes	No	No	No	Yes	Yes

1. It works during night regardless of headlight illumination.

2. Detector can operate in a dual function capacity. Example: daily ramp vehicle counts as well as detection of a wrong-way vehicle

2.2 Data Analysis of Wrong-way Driving in Tennessee

2.2.1 Data Collection

The TDOT crash data is made available via the Enhanced Tennessee Roadway Information Management System (ETRIMS). By performing a query request for crash data, we downloaded the crash data as data points in shapefile format. The raw data contained all types of crashes ranging from 2011 – 2018 and was post-processed to identify Wrong-Way Driving Crashes. FHWA defines a Wrong-Way Driving Crash event as follows:

"Traffic safety and highway design literature has historically defined a wrong-way driving (WWD) crash as one in which a vehicle traveling in a direction opposing the legal flow of traffic on a high-speed divided highway or access ramp. This vehicle either collides with an object or other vehicle traveling in the correct direction in the same segment or does not collide at all. This definition typically concerns only controlled-access highways (freeways) and associated entrance and exit ramps and excludes crashes that result from median crossover encroachments."

Altogether, 154 WWD crash events occurred from 2011 – 2018. For each crash event, several factors are recorded, which includes:

- Time of Crash: In Month/Date/Year and Hour: Minutes format
- Severity: Number of fatalities, incapacitated, injury, and vehicles involved
- Coordinates of crash locations
- Location characteristics: Nearest facility type; roadway features and function; County
- Manner of Collision i.e., head-on, angle, rear-end, etc.
- Injury Type i.e., Fatal, Property Damage, Suspected Minor Injury, etc.
- Weather and Lighting Condition i.e., clear, rain, dark-not-lighted, daylight, etc.

The raw ETRIMS crash data is available in a panel format where each row is an observation of 1 crash event, and each column (or field) represents a crash characteristic (e.g., type of crash). Based on the definition of FHWA about WWD Crash, we selected WWD crash events from the raw ETRIMS data applying the following filtering logic. To be considered as a WWD crash, the following criteria must be met concurrently:

1. The "RELATIONTO" field must either be "NON_JUNCTION" or "ENTRENCE/EXIT RAMP RELATED" or "ACCEL/DECEL LANE"
2. The "TDOTLOC" field must either be: "Along Roadway" or "Ramp"
3. The "FUNC_CLASS" must either be: "U/Interstate" or "R / Interstate" or "U / FWY OR EXP"

2.2.2 Data Analysis

The objective of the data analysis was to investigate the statistical characteristics of WWD crashes such as when and where they occurred and what are the main contributing factors. We divided the analysis into six sub-sections: Annual Trend; Spatial Distribution; Temporal Distribution; Crash Characteristics; and Environment Condition.

Annual Trend

TABLE II shows the number of WWD crashes and associated fatalities, injuries, incapacitated injuries by year between 2011 to 2018. The average number of annual WWD crashes was around 21 from 2011-2018 with the exception of the year 2015 when there are only 9 WWD crashes. The total number of fatalities, injuries, incapacitated injuries, and WWD crash events are 29, 215, 69, and 154 respectively.

TABLE II. WWD Crash by Year and Severity

Year	Fatalities	Injury	Incapacitated Injury	Other types of injury	Number of vehicles involved	Number of events
2011	1	32	7	25	41	21
2012	8	29	6	23	49	21
2013	9	18	4	14	38	20
2014	3	23	12	10	40	20
2015	2	13	5	8	20	9
2016	2	31	9	22	43	22
2017	2	35	17	18	42	21
2018	2	34	9	25	40	20
Total	29	215	69	145	191	154

Spatial Distribution

While there are several WWD crash clusters noticeable in a “birdeye” view of the entire Tennessee State highway system, it is hard to visualize the WWD crash density. Therefore, we aggregated WWD crashes that are close to each other to a single data point that bares the value representing the number of WWD crashes adjacent to that data point. Figure 2-4 shows the WWD crash location and density throughout the Tennessee State from 2011 – 2018. Each dot represents a data point where WWD crashes are aggregated to and the color of the dot represents the crash density where brighter color expresses higher density and vice versa. It is easy to see that the top 4 regions experiencing the highest WWD crash density are Memphis, Nashville, Knoxville, and Chattanooga (in decreasing order). In Memphis, most crashes happened on the Interstate 40 that runs around the Northern side of Memphis and Interstate 240 that runs around the Southern side. For Interstate 40, WWD crashes occurred at junctions (interchange) between I-40 and important routes such as I-69, Jackson Avenue, Sam Cooper Blvd. In Nashville, the majority of WWD crashes occurred in two locations, which are the I-40 segment at the City Center and the Belt-loops Interstate 24. In Knoxville and Chattanooga, WWD crashes happened in the city center too. For the entire TN highway system, the majority of WWD crashes happened on I-40 connecting Memphis-Nashville-Knoxville and distribute evenly.

In addition to exact spatial distribution, we analyzed the counties where WWD crashes happened the most, which is shown in TABLE III. As expected, most crashes happened in Shelby, Davidson, Knox, and Hamilton in respective order. These counties have large metropolitan areas such as Memphis, Nashville, Knoxville, and Chattanooga, and the traffic volume is considerably higher than other areas within the Tennessee State.

TABLE III. Top 10 County with most WWD Crashes

County	Number of WWD crashes			
	Rural Interstate	Urban Freeway/ Expressway	Urban Interstate	Total WWD Crash
SHELBY	0	8	25	33
DAVIDSON	9	7	11	27
KNOX	0	2	17	19
HAMILTON	0	0	9	9
PUTNAM	6	1	0	7
CUMBERLAND	0	0	5	5
WILLIAMSON	1	0	4	5
ROBERTSON	3	0	1	4
RUTHERFORD	0	0	4	4
WASHINGTON	0	0	4	4

Temporal Distribution

We plotted a heatmap representing the number of WWD crashes by time of the day and Day of the week as shown in Figure 2-5. **Error! Reference source not found.** This map helps to identify the critical period where WWD crashes are most likely to happen. From Figure 2-5, most crashes occurred between the period 12 AM to 5 AM in terms of the hour of the day and Monday and Sunday in terms of the day of the week. However, from the day of the week perspective, we should understand as drivers tend to go out late in the evening on either Saturday or Sunday and thus returning home earlier in the morning the day after when the crashes occurred. The most frequent time is 2 AM on Sunday, with seven WWD crashes recorded.

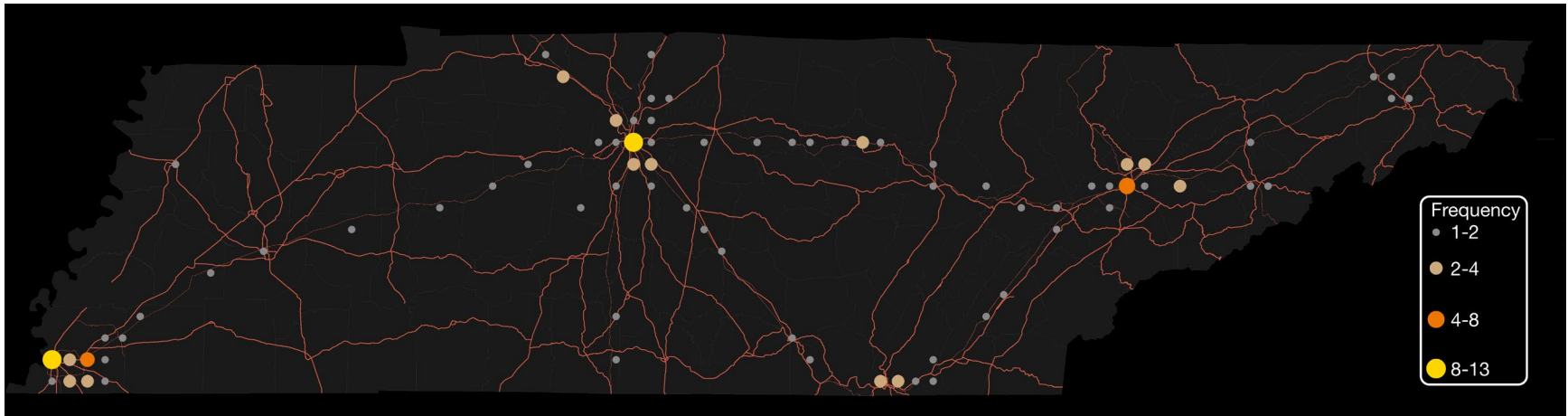


Figure 2-4 WWD Crash Density in Tennessee

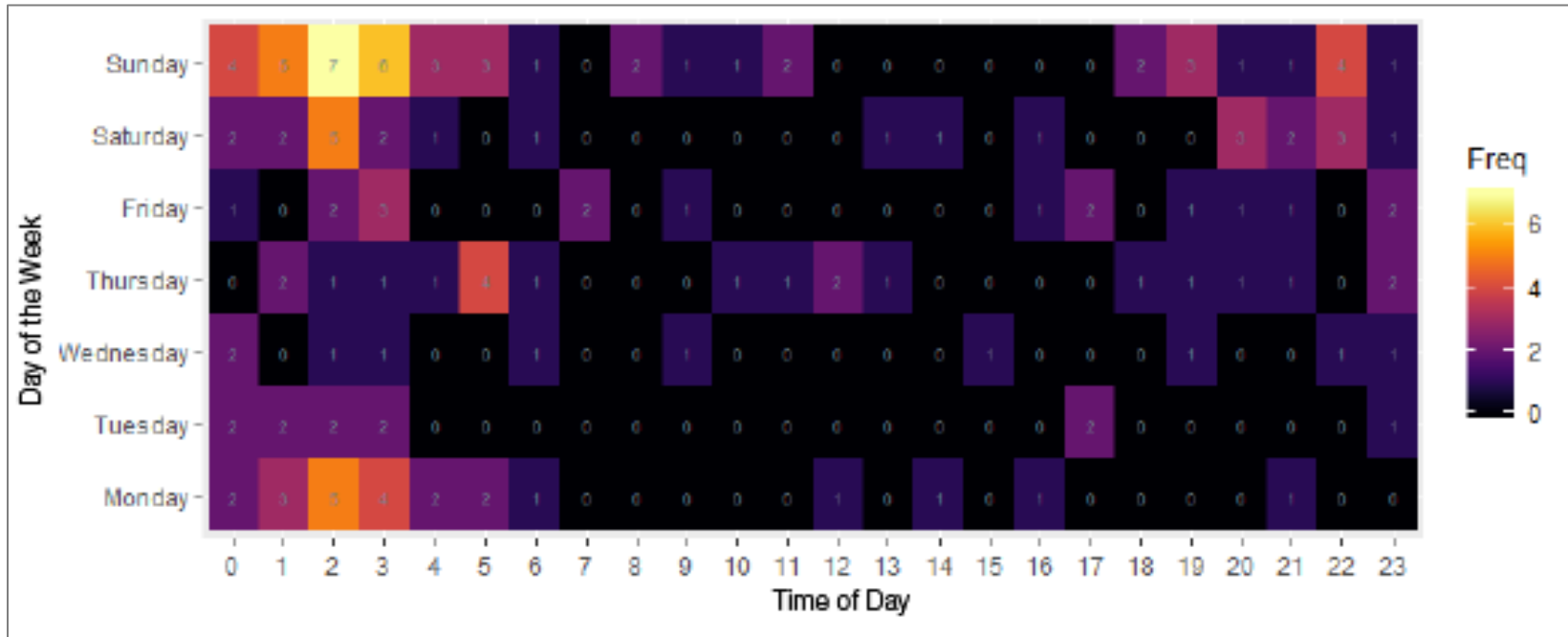


Figure 2-5 Heatmap of WWD Crash Frequency

Crash Characteristics

Unlike other types of crash, WWD crashes share distinctive characteristics, and the study of crash manner can help us to understand the leading contributing factors. TABLE IV shows the number of WWD crashes by collision type and injury type. The majority of WWD crashes are characterized by a Head-on collision and the crash severities are almost equally likely to be Fatal, Serious Injury, or Minor Injury. The Head-on type WWD crash happens where there is a vehicle driving in the correct direction being exposed to a WWD vehicle (there are at least two vehicles in a WWD crash). Another likely scenario is “No Collision with Vehicle,” where the WWD vehicle crashes into a random obstacle (barrier, tree) and no other vehicle is involved.

TABLE IV. WWD Crash by Collision and Injury Type

Collision Type	Fatal	Property Damage (over)	Prop Damage (under)	Suspected Minor Injury	Suspected Serious Injury	Total
Head-on	21	4	0	24	29	78
No collision with vehicle	0	14	1	11	0	26
Angle	1	9	1	6	3	20
Sideswipe, opposite direction	1	9	1	7	1	19
Rear-end	1	7	0	1	0	9
Sideswipe, same direction	0	2	0	0	0	2

Environment Condition

We examined the weather and lighting conditions, as well as the characteristics of the locations for all WWD, crashes in TN. TABLE V shows the top 5 most frequent combinations of weather and lightning condition in which WWD crashes occurred. The majority of WWD crashes (81%) happened on a clear day, where Dark-Not Lighted, Dark-Lighted and Daylight conditions represent 39%, 30%, and 20% of WWD crashes respectively.

TABLE V. Weather and Lighting Condition

Weather	Lighting	Frequency
Clear	Dark-Not Lighted	55
	Dark-Lighted	42
	Daylight	28
Rain	Dark-Lighted	9
Cloudy	Dark-Not Lighted	5

We also studied the location's environmental settings that WWD crashes are likely to occur. TABLE VI shows the top 10 environmental settings that WWD crashes are most likely to occur. Most of the crashes happened not on the ramp but on the highway itself. This can be explained as the vehicle turned into the wrong ramp, finished traveling the ramp, and entered the highway in the wrong direction where the collision happened.

TABLE VI. Top 5 Environmental Settings of WWD Crashes

In Relation To	TDOT Location	Function Class	Occurred on	Frequency
NON_JUNCTION	Along Roadway	U / INTERSTATE	On Roadway	52
NON_JUNCTION	Along Roadway	R / INTERSTATE	On Roadway	26
ENTRANCE/EXIT RAMP RELATED	Ramp	U / INTERSTATE	On Roadway	16
NON_JUNCTION	Along Roadway	U / FWY OR EXP	On Roadway	12
ENTRANCE/EXIT RAMP RELATED	Ramp	R / INTERSTATE	On Roadway	8

Chapter 3 Methodology

3.1 Identification of WWPS for Testing

We designed a Wrong Way Prevention Technologies Survey to collect the detailed information from a variety of Wrong-Way driving prevention technologies available in the market. From this information, a screening analysis and alternative analysis was conducted to narrow down the top 5 technologies for consideration. The survey was designed and executed using Qualtrics. For accessing the survey, the reader can copy and paste the link provided in Appendix A of this report.

The survey was issued out to several companies (selected based on-line search and literature review) on December 9th and closed on December 24th of 2019. We received a total of 15 responses, but only 12 of which provides full answers to all 19 questions. TABLE VII shows the 12 full response by company name, participant name and email, and the technology of interest. In the case where a company has more than one technology to offer, they (i.e., TAPCO) were asked to complete the survey multiple times for each technology.

TABLE VII. List of Survey Respondents by Company Name

Participant No.	Company Name	Technology
1	Stantec	Edge Computing and AI
2	FLIR Intelligent Transportation Systems	Thermal Camera Detection System
3	Image Sensing Systems	Video Camera Detection System
4	Navtech Radar Ltd	Radar Detection System
5	Wavetronix LLC	Radar Detection System
6	MS Sedco INC	Radar Detection System
7	Southwest Research Institute	Connected Vehicle Basic Safety Message
8	M.H. Corbin, LLC	Based on DOT's resource at hand
9	TAPCO	Thermal Camera Detection System
10	TAPCO	Thermal and Radar
11	TAPCO	Magnetic Detection System
12	TraffiCalm Systems, LLC.	Radar Detection System

System Components and Cost

The participants was requested to provide the number of Detection, Verification, and Warning components in their product package. Figure 3-1 shows the number of components of each technology, color-coded by component type.

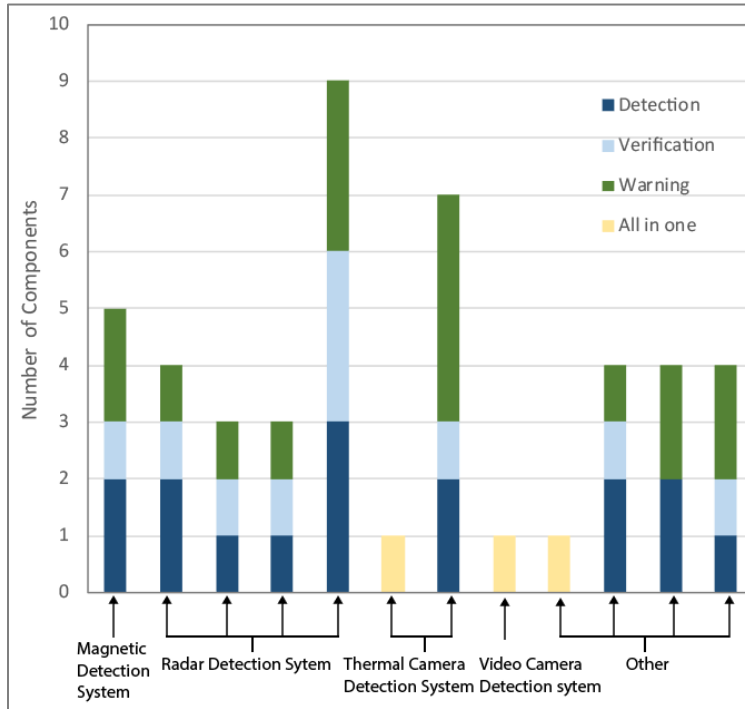


Figure 3-1 Number of Components of Each System

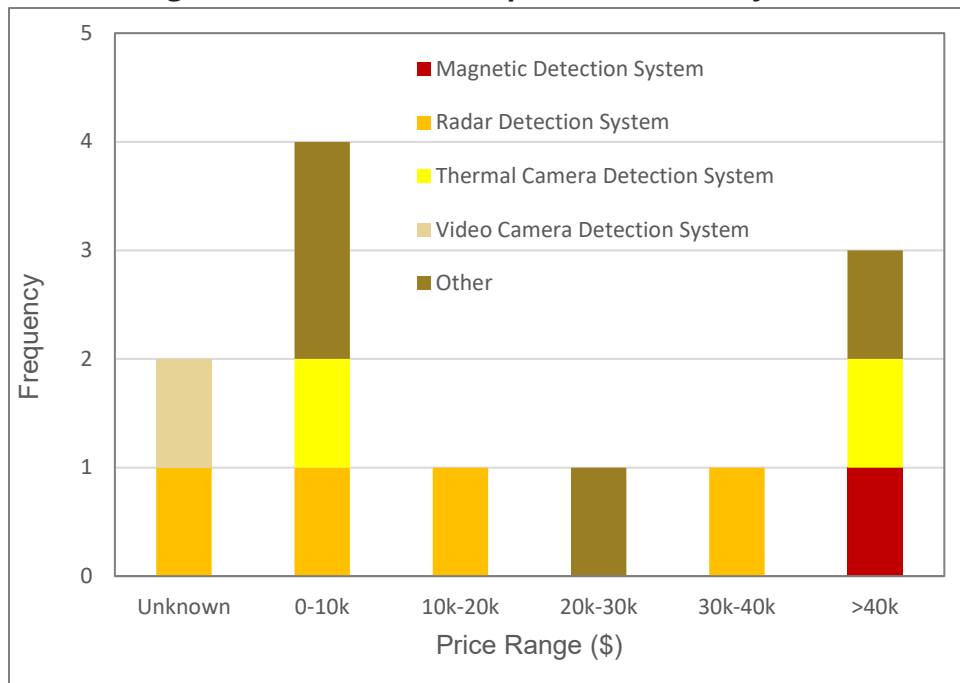


Figure 3-2 Total System Cost by Technology

In addition to system components, the total cost of the technology was provided, as shown in Figure 3-2. The horizontal axis represents different price ranges, the vertical axis addresses the number of technologies within that price range, color-coded by technology type.

Operation and Maintenance

The operation and maintenance aspects were represented by the following elements: installation cost and time, expected lifetime, and maintenance cost, as shown in Figure 3-3 and Figure 3-4. Similar in Figure 3-2, the horizontal axis represents different categories, the vertical axis shows the number of participants in that category, color-coded by technology types.

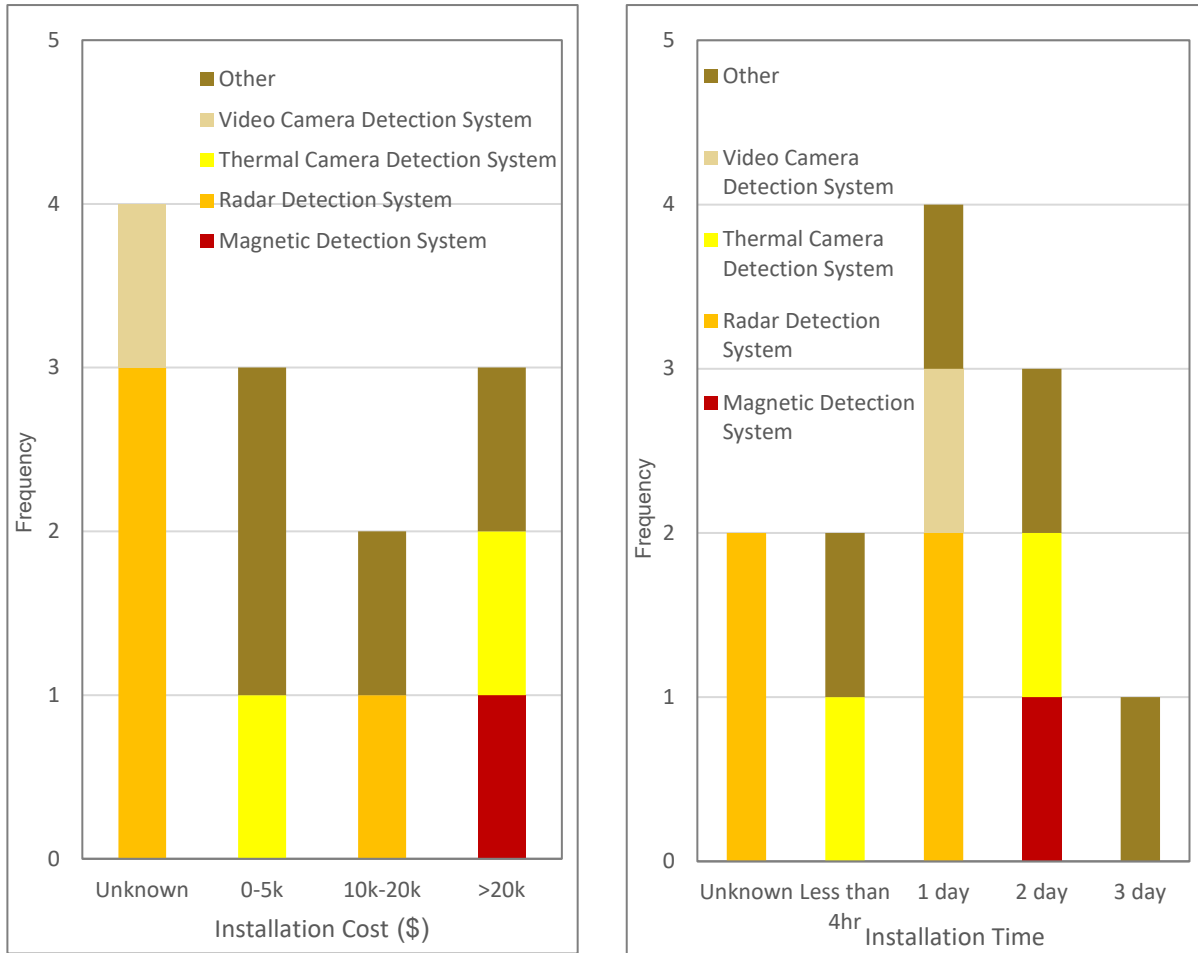


Figure 3-3 Installation Cost and Time by Technology

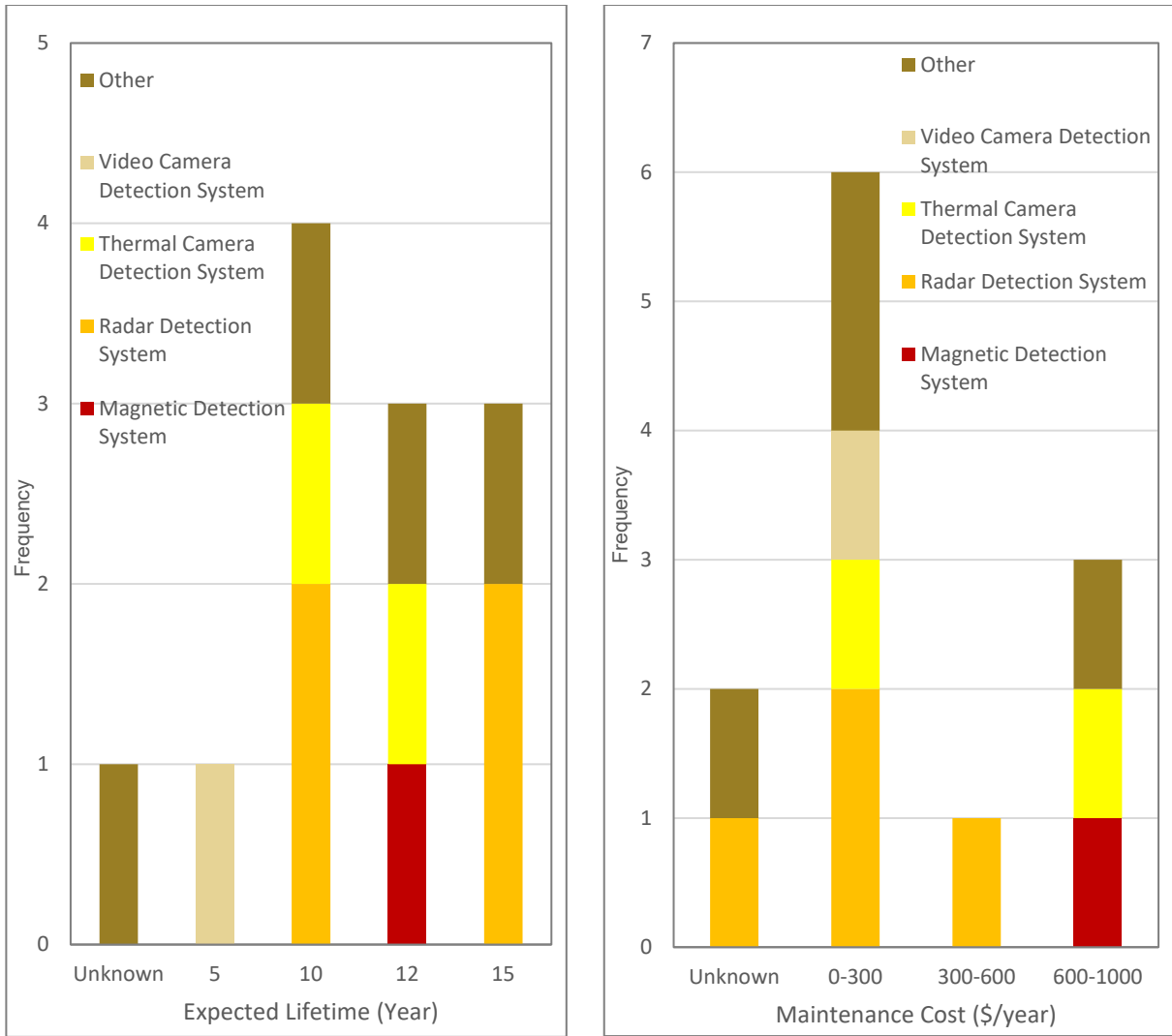


Figure 3-4 Expected Lifetime and maintenance cost by technology

System Feature and Usage

This section examines whether a technology can satisfy the five following criteria: (1) be used for other purposes (e.g., traffic count); (2) Do require additional lighting; (3) works in all-weather condition; (4) works in all lighting condition; and (5) tested by DOTs, as shown in Figure 3-5. The vertical axis shows five Yes/No questions for the participant and the horizontal axis represents the percentage of participants answering "Yes", color-coded by technology type. For example, upon being asked whether the technology can be used for other purposes, 50% of the technology using radar detection system answer yes.

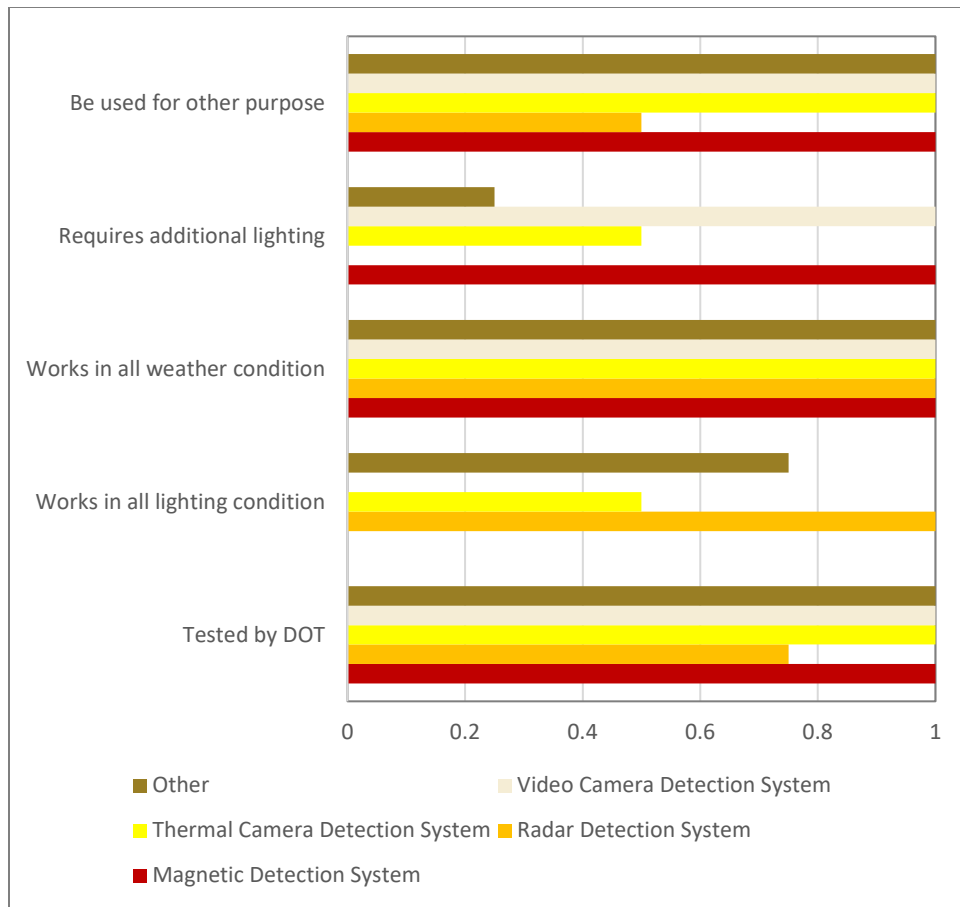


Figure 3-5. System Environment Capability

If the participants answer “Yes” to whether the technology is tested by DOT, they were requested to provide the name of DOT whom they provide services to. Figure 3-6 shows the number of DOT tested by technology type.

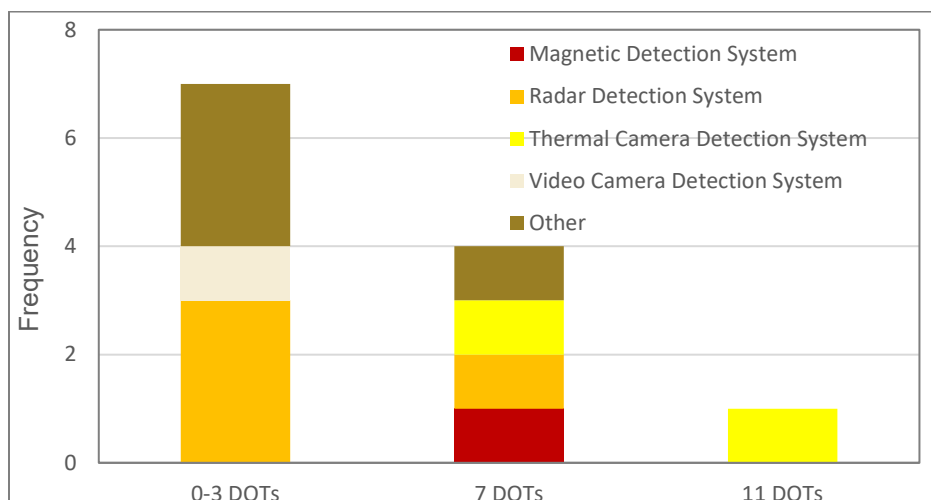


Figure 3-6. Number of DOT Tested by technology type

3.1.1 Technology Screening

The purpose of this step is to quickly discard technologies that do not satisfy any of the mandatory criteria proposed below:

- The technology must work in all-weather condition
- The technology must work in all lighting condition and requires no additional lighting
- The technology must be tested by transportation agencies

Through this screening process, we have narrow down the shortlist technologies under consideration. This shortlist contains the technologies with an answer ID as follow: Stantec, FLIR, Wavetronix, MS Sedco, MH Corbin, and TraffiCalm.

3.1.2 Alternative Analysis

After the screening analysis, there are six technologies under consideration. We examine the technology based on eight aspects: total system cost, installation time and cost, expected lifetime, maintenance cost, number of DOT using, accuracy, and whether it can be used for other applications. For each aspect, the technology receives a score from the 1-10 scale, where 10 represents the most desirable characteristics (i.e., high accuracy) and 1 represents the least desirable. We assign a weight for each aspect and all the weights sum up to 100. So, the technology can score at most 1000 and at least 1. Table 2 shows the score on each aspect of every alternative as well as the final weighted score.

In summary of Section 3.1, we first design the Wrong Way Prevention Technological Survey to gather information related to available technology on the market. A total of 12 responses were recorded and from which, we contact the top five companies based on screening and alternative analysis. After contacting these companies, we negotiated the rental of the product for the real-world testing in the next task. Due to various issues, the selected companies do not necessarily follow the ranking order of TABLE VIII and the tested companies were:

- TraffiCalm
- MH Corbin
- Wavetronix

This alternative analysis is only for selecting the proper WWPS for further testing and its result will not be used in the WWPS performance evaluation and recommendation section.

TABLE VIII. Alternative Analysis Result

	Weight	Stantec		FLIR		Wavetronix		MS Sedco		MH Corbin		TraffiCalm	
		Statistic	Score	Statistic	Score	Statistic	Score	Statistic	Score	Statistic	Score	Statistic	Score
Total System Cost	20	\$1,500	10.0	\$7,500	7.0	\$7,000	7.2	Unknown	1	\$20,000	1.0	\$18,000	1.7
Installation Time	10	1 day	1.0	15 mins	10.0	Unknown	1.0	Unknown	1	<4 hours	8.6	1 day	1.0
Installation Cost	10	\$500	10.0	\$1,000	9.6	Unknown	1.0	Unknown	1	\$1,500	9.1	\$10,000	1.0
Expected Lifetime	10	15	10.0	10	7.5	10	7.5	15	10	10	7.5	10	7.5
Maintenance Cost	10	\$250	5.0	\$250	5.0	\$0	10.0	Unknown	1	\$0	10.0	\$450	1.0
Number of DOT using	10	3	2.8	11	10.0	3	2.8	1	1	3	2.8	7	6.4
Accuracy	15	99	9.9	98	9.8	Unknown	1.0	Unknown	1	95	9.5	99	9.9
Can be used for other application	15	Yes	10.0	Yes	10.0	Yes	10.0	No	1	Yes	10.0	No	1.0
Weighted Score		786.5		857.4		532.7		190.0		692.5		367.2	
Ranking		2nd		1st		4th		6th		3rd		5th	

3.1.3 Wrong-way Prevention System Mechanism

In the current state of practice across many states, a typical WWPS usually consists of three main components as follow:

- A Detection Component: it detects the wrong-way movement of the WWD vehicle. In addition, this component should not be triggered when there is no wrong-way vehicle due to various factor such as weather condition, shaking pole due to unstable footing, or other objects rather than WWD vehicle (i.e., pedestrian, bicycle, or flying object) triggering the component.
- An on-site physical warning component: it is triggered whenever the WWD vehicle is detected and aims to warn the driver. In addition, it should gain the driver's attention, discourage him/her in continuing the wrong way, come to a complete stop, and make a self-correction u-turn. The Wrong-Way Sign R5-1A with LED-Enhanced border (as discussed in Section 2.1.6) is widely used as a warning component. The component should also be dynamic (blinking) instead of static to make it more noticeable.
- An alert component: it will send alert to the authority when there's a WWD event. This can either in means of an email, SMS text, alert via accompanying software, or all of the above. In addition, the component should record the evidence of the event (i.e., media images or videos) as a second layer of confirmation that there is a wrong-way event and not a false detection.

In order to be effective, WWPS usually operates based on a two-zone setup, which are (1) Alert Zone and (2) Confirmation Zone. A typical zone layout is shown in Figure 3-7. The following explains the sequence of action during a WWD event:

1. Once the vehicle crosses the alert zone, the warning components (i.e., R5-1a with blinking borders) are triggered to warn the driver and force them to a complete stop and u-turn. The alerts to authority are not sent at this point. However, the wrong-way movement data is internally saved in the system.
2. However, if the driver ignores the warning and continues to go past the confirmation zone, then the WWPS will send the alerts to authority along with an evidence of the event which is usually in form of a short video clip capturing the wrong-way movement.

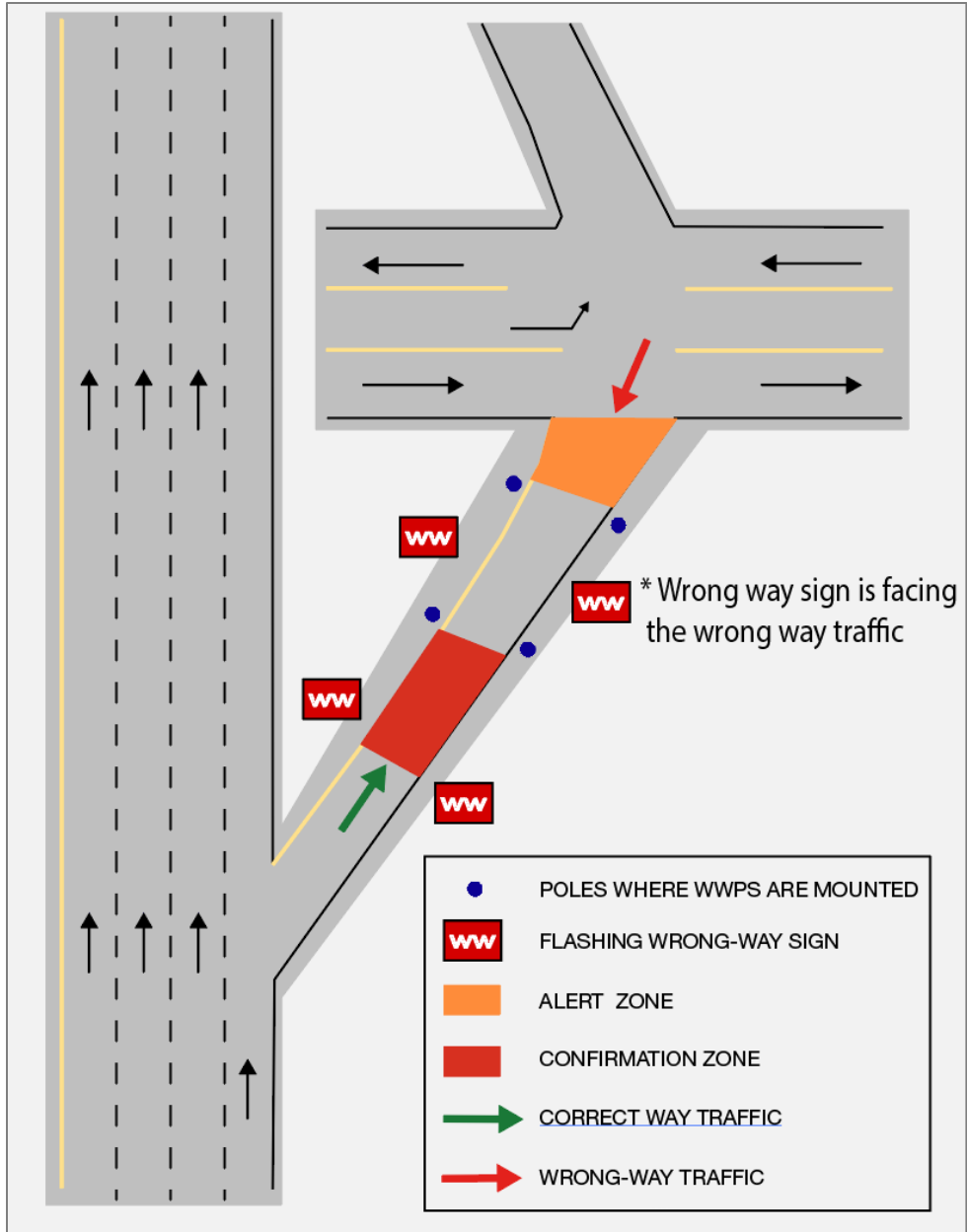
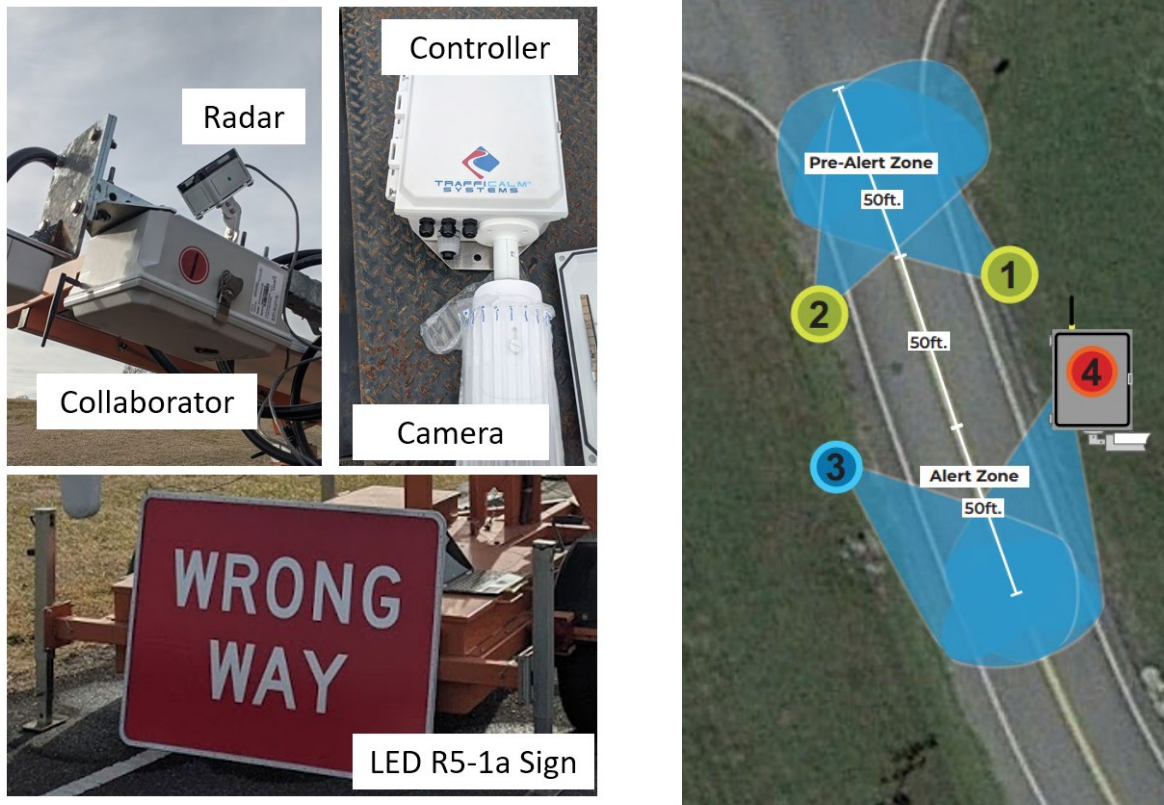


Figure 3-7 WWPS Two Zone Setup Example.

3.1.4 TrafficCalm

TrafficCalm WWPS is based mainly on Radar detection technologies. In a typical deployment, the detection components consist of four radar overlooking two detection zone. The radar is based on the Doppler effect where it constantly beams out a radio wave to a potential wrong-way vehicle and measures the wrong-way speed from the expected change in frequency of the returning wave. The radar has up to 450ft of detection range. These four radars are then connected to three collaborators and one controller, which serves as the logical units of the system. The use of multiple radars, controllers, and detection zones help minimizing false detections while ensuring wrong-way vehicle is captured. In addition, a camera is integrated to provide live feed and capture the evidence of WWD event.

The system can be powered by solar and generate it owns internet connection. These two features allow the system to be physically standalone and not relying on local electricity or cellular. TrafficCalm also designs and manufactures their LED Flashing Wrong-way signs in house as oppose to other company which relies on third-party manufacturer. This dynamic sign provides excellent nighttime visibility and attention and is usually regarded as the most effective method of noticing driving and forcing him to a complete stop and u-turn.



(a) System Components

(b) Two zone Setup

Figure 3-8 TrafficCalm Components and Installation Layout

TraffiCalm WWPS sends alert via three channels: (1) email to authority, (2) web-based observing software, and (3) a dedicated monitor showing the camera live feed, which is usually installed at a Traffic Management Center. Figure 3-9 shows the landing page of TraffiCalm’s software, which is currently showing on repeat a WWD event of a firetruck. In the dedicated monitor, only the video will be shown. The system also follows a two-zone setup as discussed in Section 3.1.3 and an example of which is shown in Figure 3-8b.

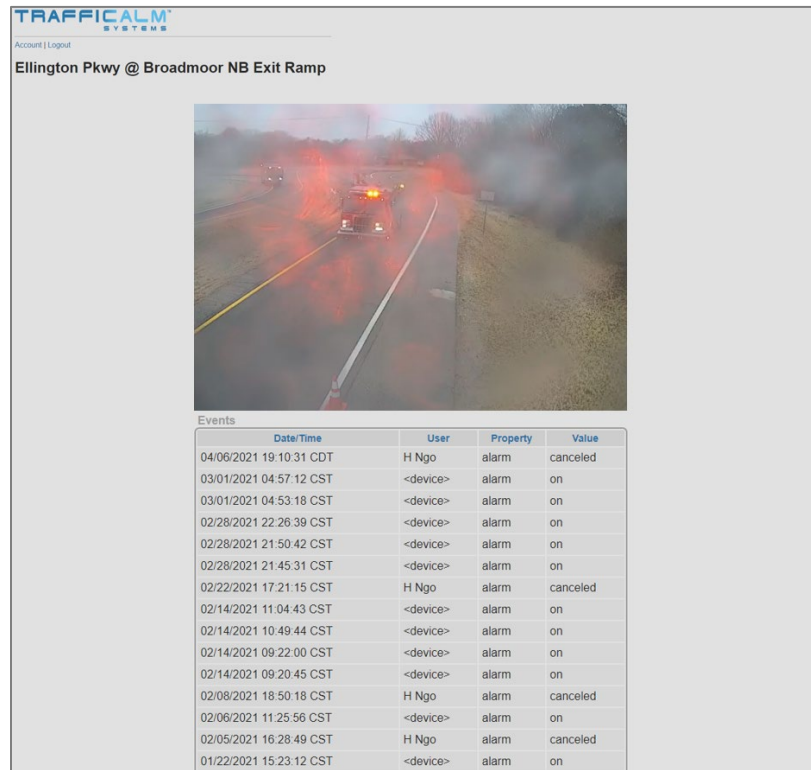
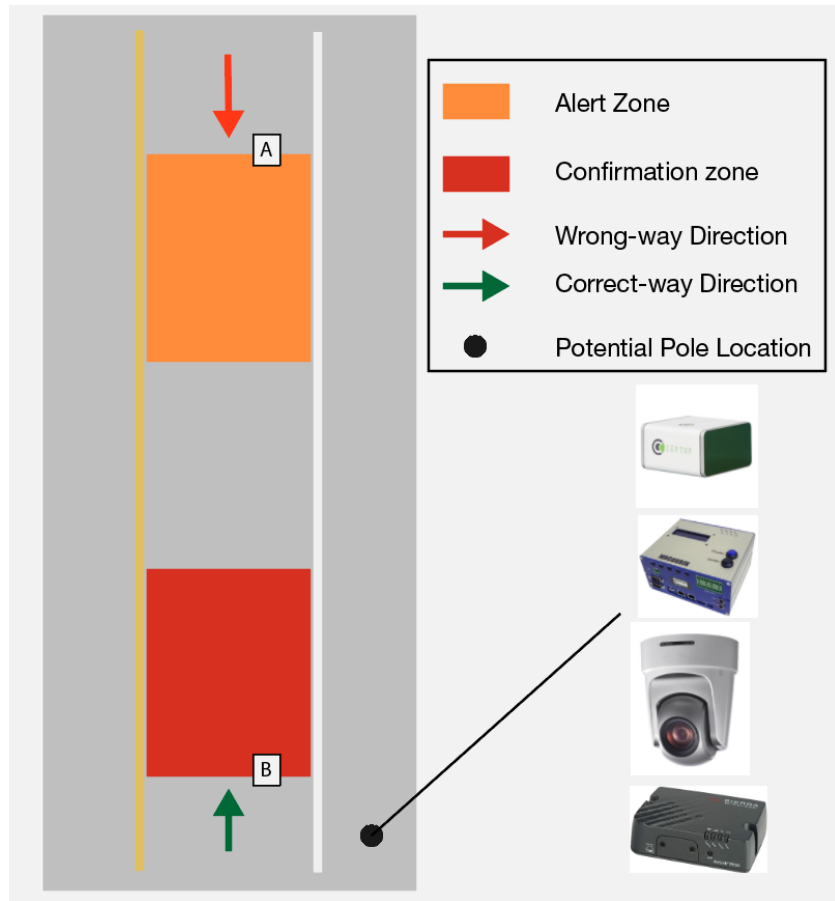


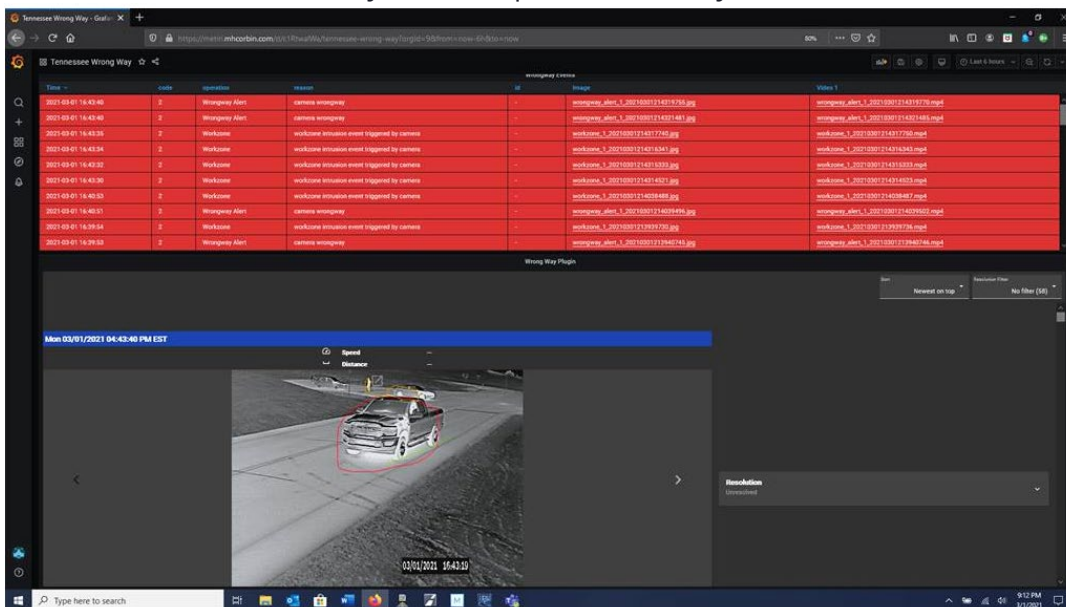
Figure 3-9 TraffiCalm Software Main Screen

3.1.5 MH Corbin

MH Corbin WWPS is based on Lidar Detection technology. Lidar technology sends out several beams of laser and by measuring the time it takes for the returning laser to comeback, it can calculate the distance between the object and the source. By constantly sending out these beams and measuring distances, the Lidar sensor along with algorithm located in the ConnectITS, MH Corbin WWPS can detect the wrong-way vehicle. The system has four main components, which are (1) Lidar Sensor, (2) Camera, (3) ConnectITS (logical component), and (4) a wireless modem providing internet connection. MH Corbin does not provide warning components in house and relies on third-party provider. For integrating with third-party component, MH Corbin uses a relay which either connect or cutoff the power of the warning component (i.e., Flashing Wrong Way Sign) based on what the ConnectITS module asks it to do. The IP camera is to provide the media evidence of the event and the wireless module is for providing local power. MH Corbin also follow the two-zone setup as discussed in Section 3.1.3.



(a) System Components and Layout



(b) Metri Software Dashboard
Figure 3-10 MH Corbin WWPS

3.1.6 Wavetronix

Wavetronix is recognized across the country as a leader using patented radar-based technology to solve ITS and Traffic challenges with over 18 years of experience in detection. TDOT has deployed various Wavetronix sensors across the State of Tennessee with proven long-term success with example such as signalized intersections, stopbar and setback, or real-time monitoring of vehicle's speed, volume, and class on Interstates. Currently, their product is used in I24 Smart Corridor project for both advance protection (Dilemma Zone) as well as ITS.

At the time of testing, Wavetronix has yet to provide a complete package for wrong-way driving solution. SmartSensor HD uses dual beam "High Definition" bandwidth (245 Mhz) providing very granular and defined detection and accurately determine the vehicle speed across multiple lanes or blocking object. Based on initial configuration, a positive speed would indicate correct-way traffic and negative speed refers to wrong-way movement.



(a) Smartsensor HD's sensing ability



(b) Installation of Smartsensor HD on an existing pole

Figure 3-11 Smartsensor HD as Detection Component

3.2 Deployment and testing of WWPS

A typical WWD prevention system consists of detection components, verification components and warning components. Most WWPS aim to avoid the WWD event by the following procedure:

1. Detect the Wrong-Way Vehicle by using the detection component within the WWPS.
2. If the vehicle goes past the alert zone, WWPS will actively warn the driver by using a warning component, usually in form of a flashing object.
3. If the driver self-corrects the situation by making a U-Turn, WWPS would not trigger an alarm to an authority.
4. If the driver does not self-correct and goes past the confirmation zone, the WWPS shall verify the event and send alert to the authority such as Traffic Management Center at which several other steps can be executed which can be:
 - Noticing a nearby Officer to stop the Wrong-Way vehicle.
 - Putting the text “Wrong-way Vehicle is entering the highway” on the highway Variable Message Board (VMS) to warn the right way vehicle.

Testing of chosen wrong way driving systems will be carried out in two stages. For the first stage, testing will be conducted in a controlled environment herein referred to as Closed Environment Testing (CET). For the second stage, each of the systems chosen will be installed on an exit ramp and monitored over a period of time. The second stage herein is referred to as Real World Testing (RWT).

3.3 Phase 1 of Controlled Environment Testing

CET will evaluate the systems based on three criteria; missed detection, false detection, and warning delays.

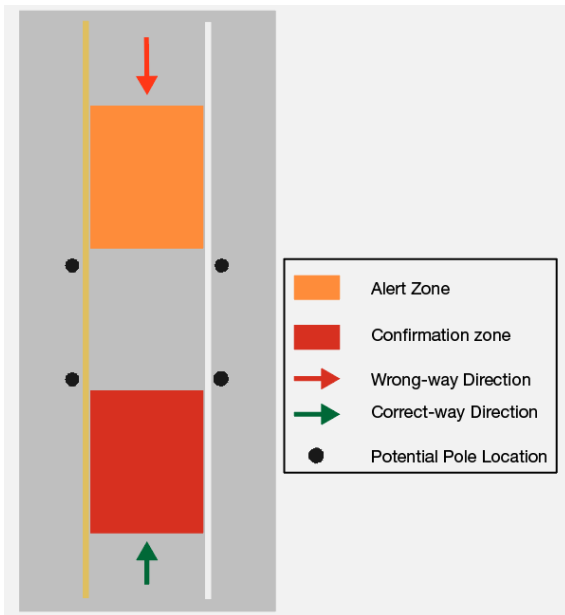
1. Missed detection: Missed detection is the situation when a system fails to detect a vehicle travelling in the wrong direction. Therefore, with this test our objective is to test the rate of false negative alerts provided by the systems. For a system to be effective, low rate of missed detection is desired.
2. False detection: This test will evaluate the rate of false positives alerts produced by the systems. False detection occurs when a non-wrong way driving incident is registered by the system as a wrong way driving system.
3. Warning delay: Delay in the warning process in our tests refer to the period between vehicle crosses the zones and corresponding counter measurement.

Ideally, WWPS should be tested on a real-world off ramp since this is where the system will ultimately be deployed. However, in the missed detection, it would require a ramp closure to install the WWPS, drive the test vehicle the wrong-way, and document the WWPS, which would

disrupt the normal traffic flow for several hours, and even then, the activities are still very dangerous for the on-site participants. Therefore, we coordinate with TDOT and select a close controlled testing environment and the chosen location along with layout is shown in TABLE IX and Figure 3-12. In addition, the testing activities and dates are shown in TABLE X.

TABLE IX. Phase 1 CET Testing Location

Name	Tennessee Department of Safety Training Center
Address	283 Stewarts Ferry Pike, Nashville, TN 37214
Coordinates	36.163062, -86.638934
Description	The training center has a virtual site that imitate a highway and an exit ramp, which can be used for testing.



(a) Conceptual Two Zone Configuration



(b) Testing Segment (Source: Google Map)



(c) On-Site Photo Layout

Figure 3-12 Phase 1 CET Location and Layout

TABLE X. Testing Activities and Dates

Date	Time	Test Conducted
1/19/2021	08:00 – 12:00	Wavetronix Installation
	12:00 – 16:00	Wavetronix Missed Detection and Warning Delay Test
1/20/2021	08:00 – 12:00	Wavetronix False Detection Test
1/21/2021	12:00 – 16:00*	TraffiCalm Installation
1/22/2021	08:00 – 12:00	TraffiCalm Missed Detection and Warning Delay Test
	12:00 – 16:00	TraffiCalm False Detection Test
02/06/2021	08:00 -12:00	TraffiCalm Phase 2 Installation and Deployment
03/01/2021	08:00 – 12:00	MH Corbin Installation
	12:00 – 16:00	MH Corbin Missed Detection and Warning Delay Test
03/02/2021	08:00 – 12:00	MH Corbin False Detection Test

3.3.1 Missed Detection and Warning Delay Test

Objective: Check if the WWPS has any missed detection and calculate the warning delay

Missed detection: is the situation when there is a vehicle driving the wrong-way at the test site, but the detection system fails to detect it as a WWD event. For a system to be effective, the missed detection rate should be very low. When the vehicle crosses both alert and correction zone, all of the counter measurements (i.e., flashing wrong-way sign and alert to authority) must be triggered and any of those fail to do so would be classify as a missed detection.

Warning Delay: There are two warning delay to be determined. The first delay refers to the period between the vehicle exceeds the alert zone and the warning component (i.e., Blinker Sign) is triggered. The second delay is the period between the vehicle exceeds the correction zone and when either corresponding personnel receives alert SMS or BlinkLink sends alert, whichever comes first.

Procedure:

1. Instruct the drivers to drive the test **vehicle pickup truck** through the **two zones from A to B** as shown in Figure 1 at **10 mph**. Note that the vehicle should be at the 10mph speed at the end of the alert zone so it would need to make an acceleration phase.
2. Start stopwatch **S1** when the vehicle reaches **point A**. When the **flashing beacon is triggered**, records the lap time on **S2**.
3. If **flashing beacon is triggered**, note the observations as a **tick mark**, otherwise a **X mark**.
4. Start stopwatch **S2** when the vehicle reaches **point B**. When the **email/SMS alert is received**, records the lap time on **S2**.
5. If **email/SMS is received**, note the observations as a **tick mark**, otherwise a **X mark**.

6. Repeat the process 1-7 for different trials, three types of vehicles, and different speeds.

***NOTE:** In Car-10-T3, Car-20-T3, Truck-10-T3, and Truck-20-T3, the driver will drive through the alert zone only (pass point A). Then he will come to a complete stop and make a u-turn/backup.

Figure 3-13 shows the missed detection test for Wavetronix and TraffiCalm. In the first photo showing Wavetronix, the convertible is moving the wrong way through the first zone and the flashing beacon on lower right is triggered. The second photo of TraffiCalm's also shows the event where the blinking wrong-way sign is triggered. Note that the zone's location, size, and the blinking sign's location can be easily configured when developed a WWPS layout. Ideally, the blinking sign should be located further down to the highway than the first zone so that the driver has enough time to be warned.



(a) Wavetronix Missed Detection Test



(b) TraffiCalm Missed Detection Test

Figure 3-13 Missed Detection Test Example

3.3.2 False Detection Test

False detection can happen when there is no WWD vehicle in the road segment and the WWPS alerts there is an WWD event. Many of these false detections were due to the shaking of camera mounting poles during storms, windshield of the moving vehicles, pedestrians, bicycles, and birds.

Procedure:

Part 1: Correct way vehicle movement

1. Instruct the drivers to drive the test vehicle pickup truck through the two zones from B to A (correct way) as shown in Figure 2 at 10 mph.
2. Check if the WWPS sends an alert to the authority and the WWD blinker sign flashes.
3. If **flashing beacon is triggered**, note the observations as a **tick mark**, otherwise a **X mark**.
4. If **email/SMS is received**, note the observations as a **tick mark**, otherwise a **X mark**.
5. Repeat the process 1-4 for different trials, 2 types of vehicles, and different speeds.

Part 2: Bicycle and Pedestrian movement

1. Instruct the pedestrian to walk through the two zones from A to B (wrong way) as shown in Figure 1.
2. Check if the WWPS sends an alert to the authority and the WWD blinker sign flashes.
3. If **flashing beacon is triggered**, note the observations as a **tick mark**, otherwise a **X mark**.
4. If **email/SMS is received**, note the observations as a **tick mark**, otherwise a **X mark**.
5. Repeat the process 1-4 for different trials and bicycles.

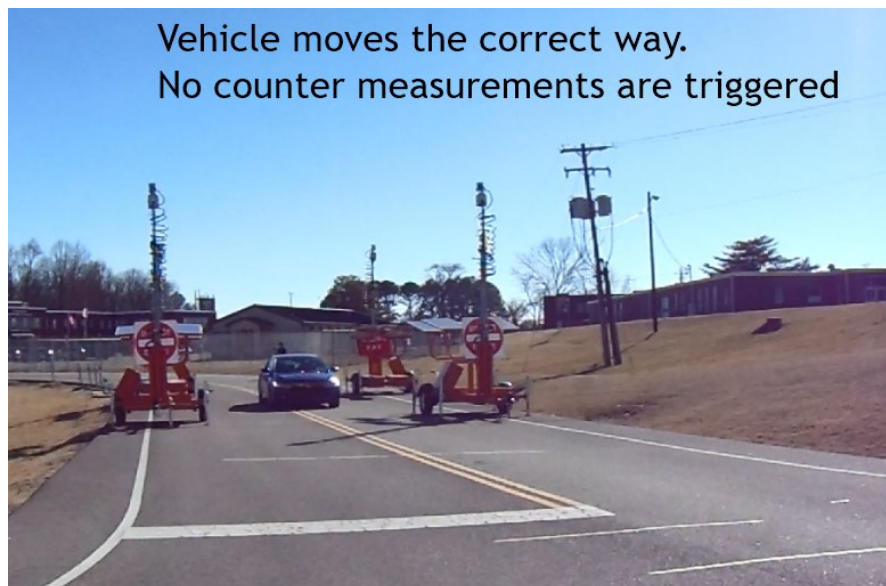


Figure 3-14 Example of False Detection Test

3.4 Phase 2 of Real-World Testing

In this phase 2 of RWT, we will install WWPS on a different location for a period of one month as a pilot deployment. In this phase, we rather aim for the statistics gained from the WWPS deployment. We also need to determine the number of False Detection and Missed Detection and the definition of which is as follow:

- **RWT False Detection:** When any of the alert or warning component triggers but there's no evidence from the thermal camera that there's a Wrong-way Driving event.
- **RWT Missed Detection:** When there's a Wrong-way Driving event informed to TDOT by any means other than the WWPS (i.e., 911 call, correct-way driver's camera recording of wrong-way vehicle) and the authority confirms that there is one but not all of the alert and warning components are triggered. This wrong-way driving event shall be on a highway segment related to WWPS implemented exit ramp and be no further than 5 miles away from the WWPS. We also need to check the video sequence from the WWPS's thermal camera for the period 30 minutes prior to the event.

For each of the false or missed detection event, at least one contributing factor must be determined. We suggest the following possibilities:

- Factors inducing shaking of mounting structures: Wind, nearby heavy vehicle causing
- Ground motions, and storms event
- Object giving false detection: birds, pedestrian
- System cabling issue
- Thermal reflection from vehicle's windshield
- Incorrect sensitivity setting

TABLE XI. Phase 2 Deployment Location and Time

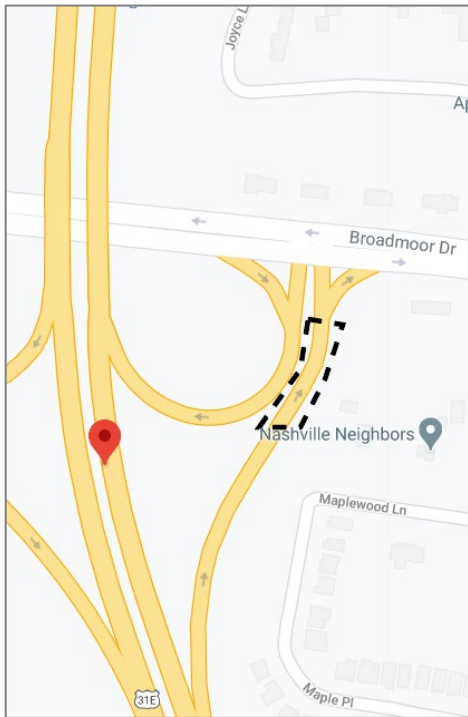
Company	Location	Duration
TraffiCalm	Northbound Exit Ramp at Ellington Pkwy and Broadmoor Dr	02/06 – 03/06
MH Corbin	Northbound Exit Ramp at Ellington Pkwy and Douglas Ave	04/10 – 05/10
Wavetronix	Southbound Exit Ramp at Ellington Pkwy and Broadmoor Dr	04/10 – 05/10

Procedure:

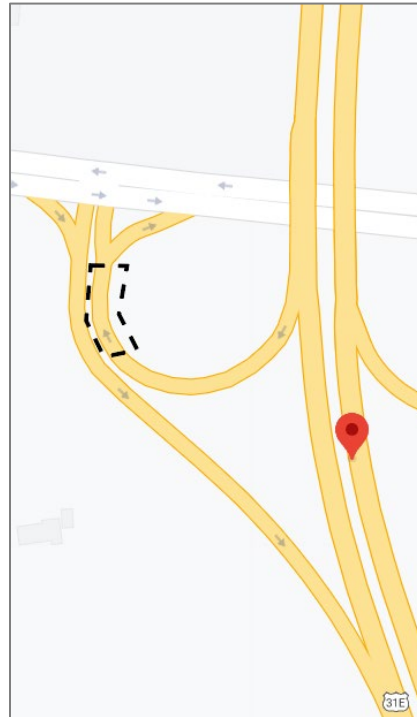
The following section shows the steps of conducting phase 2 of RWT

1. Install the system as discussed in the previous section. Make sure the system is connected to proper electricity and internet connection if needed.
2. Assign one person for receiving wrong-way driving alert via SMS and Email Messages.

3. Whenever there is a missed or false detection (see definitions in Section 1) do the following:
 - a. Fill out the reporting form on next page.
 - b. Export the video of the event.
 - c. Identify one or more contributing factors if possible.
4. Repeat step 2 for a period of one month.



(a) TrafficCalm



(b) Wavetronix



(c) MH Corbin

Figure 3-15 Phase 2 Site Selection

Chapter 4 Results and Discussion

4.1 Phase 1 Testing Result

4.1.1 Missed Detection and Warning Delay

Missed Detection Rate:

A low missed detection rate is the most important factor for determining the effectiveness of a WWPS. Failure to detect the wrong-way vehicle can result in letting the vehicle entering the main highway without notice and collide with oncoming traffic and likely result in a fatal crash. As discussed in Section 3.3.1, we drove the vehicle the wrong-way at different speed and alternate between car and truck since these two types have significantly different profiles. In order to be effective, the WWPS should have a Missed Detection Rate equal to zero. The Missed Detection Rate can be determined in Equation (1) as follow:

$$\text{Missed Detection Rate} = \frac{\text{Number of Missed Detection}}{\text{Number of Test Performed}} \times 100\% \tag{1}$$

The Missed Detection Rate is equal to the number of missed detections as a percentage of the number of tests performed in that category. For example, for each vehicle type and speed, the tests are performed three times and one missed detection will result in a Missed Detection Rate of 33%. After the Missed Detection testing performed on three WWPS, we obtain the Missed Detection Rate as shown in TABLE XII.

TABLE XII. Missed Detection Result

Vehicle Type	Speed (mph)	Missed Detection Rate (%)		
		Wavetronix	TraffiCalm	MH Corbin
Car	10	0	0	0
	20	0	0	0
	30	0	0	33
	40	0	0	33
Truck	10	0	0	0
	20	0	0	0
	30	0	0	0

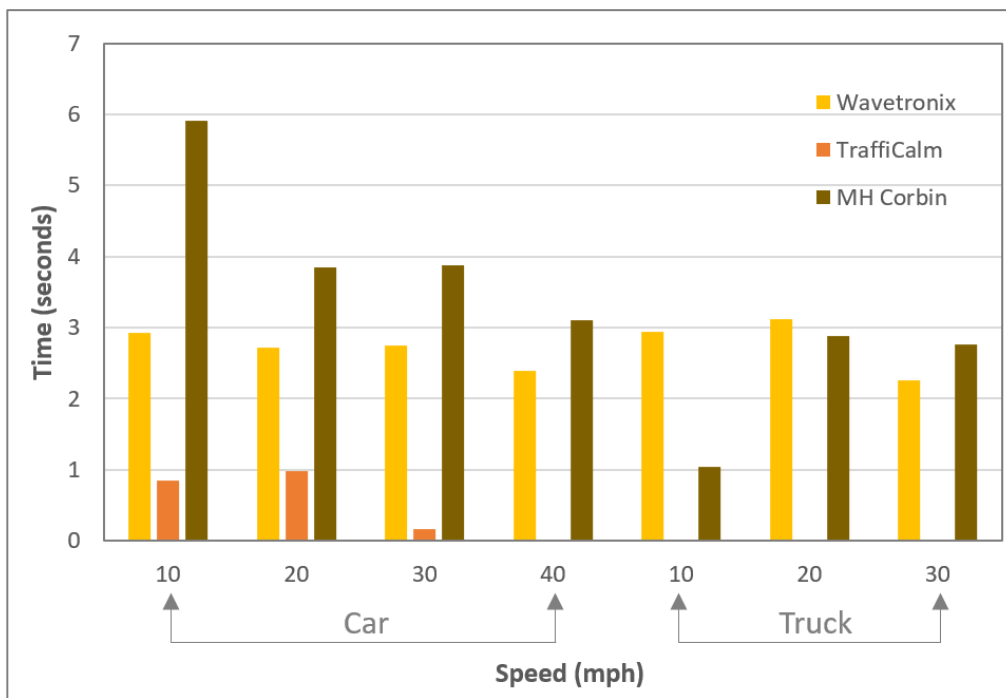
We make the following observations regarding the testing activities and results:

- Wavetronix and TraffiCalm successfully detects the wrong-way vehicle movement for both car and truck and at all tested speed. The two corresponding countermeasures, which are flashing wrong-way sign and alert to authority, are successfully triggered.
- MH Corbin has two missed detection during the car test at speed of 30 and 40 mph. This is mainly due to the camera angle of the detection component is too low and it is not sensitive to such high speed. After raising the mast arm and adjust the speed sensitivity, the WWPS is able to capture the wrong-way vehicle at 30 and 40 mph.

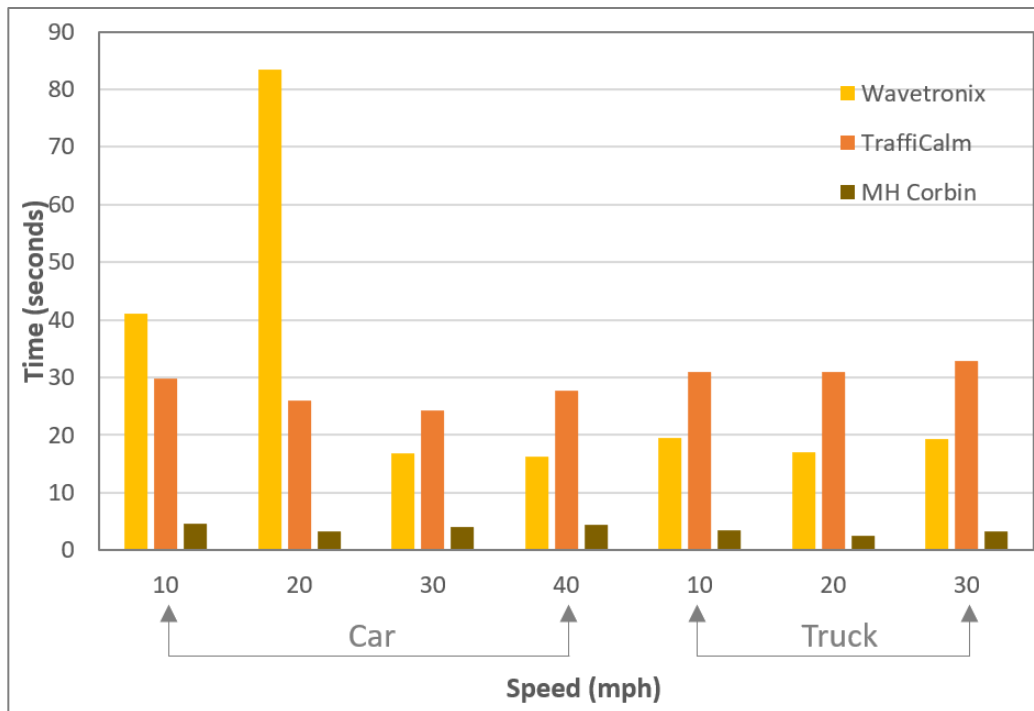
- On experiment where the vehicle is instructed to cross the alert zone, come to a complete stop, and make a u-turn, for all three WWPS, only the first countermeasure which is the warning component is triggered. The second countermeasure being the alert to authority is not triggered. This ensures the system's two-zone setup works as intended.

Within the Missed Detection test, we also measure the Warning Delay 1 between the vehicle crossing the alert zone and wrong-way sign being triggered. This is the second most important factor for an effective WWPS after low Missed Detection Rate. The sooner the flashing wrong-way sign is triggered, the more time it appears on the driver sight and the more likely it can capture his/her attention. If the Warning Delay 1 is too high, then it's likely that the driver will drive past the warning sign before the sign is triggered and continue to the highway, thus making the entire operation ineffective. After the Missed Detection Test, we gather the result and plot the Warning Delay 1 in Figure 4-1a shown.

In addition to Warning Delay 1, we also measure Warning Delay 2, which is the time between the vehicle crosses the confirmation zone and alert is received by the authority. This is the third most important factor in an effective WWPS system because the slower the response time is, the more distance the vehicle can travel the wrong-way and significantly increases the likelihood of colliding with oncoming traffic. We gather the results and plot the Warning Delay 2 in Figure 4-1b below.



(a) Delay between vehicle crossing alert zone and flashing wrong-way sign triggered



(b) Delay between vehicle crossing confirmation zone and alert to authority sent

Figure 4-1 Warning Delay Result

We make the following observation regarding Warning Delay 1 as follow:

- Wavetronix has approximately 2.5s for Warning Delay 1, which is an average result. If the vehicle is traveling at 30 mph and assuming a 2.5s perception and reaction time, then the vehicle will travel at least 200ft before the flashing sign is triggered. This means that the flashing sign must be located at least 200ft away from the end of the alert zone. Given the average ramp length of 600ft or just a circular ramp geometry, this can be quite challenging.
- TraffiCalm has close to zero Warning Delay 1, which is the best result out of three companies. TraffiCalm WWPS is equipped with multiple radars having the capability of scanning a larger zone and multiple collaborators and controllers for faster processing power. These two features help them to trigger the flashing sign quickly.
- MH Corbin has on average around 3.5s for Warning Delay 1, which is still an average result. However, we need to mention that on the phase 1 CET testing day, MH Corbin was not able to connect to flashing beacon as the first countermeasure. The electrical relay, which integrates third-party flashing beacon to MH Corbin's System, was not working properly and we use email notification as the first countermeasure.

We make the following observation regarding Warning Delay 2 as follow:

- Wavetronix has on average 20s of Warning Delay 2, which is average. If the wrong-way vehicle is traveling with a speed at 30 mph, it would travel at least 0.17 mile in the wrong-way before the local officer is dispatched. However, Wavetronix is developing the accompanying software which will provide close to real-time live feed of the environment. This will drastically reduce the Warning Delay 2.
- TrafficCalm has on average 28s of Warning Delay 2. The main reason is in the email sent to authority, a 20 second video showing the wrong-way driving event is attached thus increases the amount of data being delivered and ultimately slow down the arrival time. However, TrafficCalm has a dedicated monitor connected to a module for showing wrong-way driving event only. The monitor shows the live feed of the exit ramp and will blink red along with alerting audio whenever there's a wrong-way event. After that, the wrong-way evidence video will be played on repeat until the user decides to cancel. This method appears to be faster than email and will reduce Warning Delay 2.
- MH Corbin has fairly low Warning Delay 2 at only less than 5s. The number does not vary much by speed or vehicle type.

4.1.2 False Detection Test

The False Detection Test aims to determine the False Detection Rate calculated as follow:

$$\text{False Detection Rate} = \frac{\text{Number of False Detection}}{\text{Number of Test Performed}} \times 100\% \quad (2)$$

TABLE XIII. False Detection Rate for Car and Truck

Vehicle Type	Speed (mph)	Missed Detection Rate (%)		
		Wavetronix	TrafficCalm	MH Corbin
Car	10	0	0	0
	20	0	0	0
	30	0	0	0
	40	0	0	0
Truck	10	0	0	0
	20	0	0	0
	30	0	0	0

In addition, to vehicle false detection, we also investigate how the system would react to pedestrian and bicycle. The Detection rate is calculated as number of detections divided by number of tests performed.

TABLE XIV. Detection Rate for Pedestrian and Bicycle

Type	Wavetronix	TrafficCalm	MH Corbin	
			Scenario 1*	Scenario 2**
Pedestrian	0	20	0	100
Bicycle	0	100	0	100

*In scenario 1, MH Corbin's Pedestrian/Bicycle detection feature is turn off

**In scenario 2, MH Corbin's Pedestrian/Bicycle detection feature is turn on

We make the following observation for the pedestrian and bike false detection test:

- For Wavetronix, the system is calibrated to not detect pedestrian or bicycle moving the wrong way. Therefore, the detection rate is 0%. This is the default mode and pedestrian/bicycle detection feature can be added upon request.
- For TraffiCalm, in the calibration phase, the minimum speed is set to 10 mph. For pedestrian, in one experiment out of five, the participant moved the wrong way at speed greater than 10 mph and triggered the detection. For bicycle, the speed is greater than 10 mph for all experiments and the detection picked up all the wrong-way movements.
- For MH Corbin, the system has a feature where pedestrian/bike detection can be turn on or off. For the first three experiment, this feature is turned off and the system did not pick up any WWD event. For the next two experiment, this feature is turn on and the system detects the WWD movement.

4.2 Phase 2 Testing Result

4.2.1 TraffiCalm

The installation of TraffiCalm's Phase 2 deployment was completed on the morning of 02/06/2021. During the installation, the ramp closure was scheduled and executed to ensure the safety of the participants. Since all of the components such as radar, controller, and collaborators were already installed on the portable trailers and delivered to the pre-defined mark at the real exit ramp location, the installation time only took less than 1 hour. These include:

- Drilling of telespars and mounting flashing wrong way sign on it. Connecting the sign power's cable to the collaborator.
- Aiming the radar angle to the middle of the road and calibrate the detection zone.
- Performing one test run in which a vehicle goes the wrong-way to see if all countermeasures (i.e., flashing wrong-way sign and email alert) are triggered.

The TraffiCalm phase 2 deployment layout follows the same two-zone setup as discussed in Section 3.2 and shown in Figure 4-2 below.



Figure 4-2 TrafficCalm Phase 2 Deployment

After the installation, we obtain the result as shown in TABLE XV and make the following observations:

- The system great performance in phase 1 at a controlled environment translates directly to phase 2 at a real-world ramp. During the installation, we perform one wrong-way test run and TrafficCalm's WWPS works perfectly as expected with all counter measurements being triggered.
- TrafficCalm WWPS has a dedicated monitor, which is installed at the TMC, to provide live feed of the ramp. When a WWD vehicle is detected, this monitor will blink red and repeat the evidence video of the WWD event. This is demonstrated on 02/14/2021 at 07:21 when a firetruck and emergency vehicles entered the exit ramp. Please click this link to view the video.
- Initially, TrafficCalm suggested connecting to local electricity power or using a power generator. However, both of these options were too complicated for temporary installation, so we utilized the existing solar panels from the trailers instead. During phase 2 testing period which happens in February, there are a lot of non-sunny days and apparently, on 02/14/2021, one out of four trailers is out of battery. The collaborator on that trailer cannot operate properly and caused five false detection. Therefore, if proper electricity power is used, then this likely would not happen. It's also important to mention that in the evidence video clip, there was hard rain at the site location. We do not count these 5 false detections toward the performance evaluation.

TABLE XV. TrafficCalm Phase 2 Result

Date and Time	Classification	Activities/Explanation
2/6/2021 09:26	True Detection	Test run vehicle the wrong way after completing the installation
2/14/2021 07:21	True Detection	A firetruck and emergency vehicle are moving the wrong way
2/28/2021 19:47	5 x False Detection*	Due to the continuing non-sunny days at the test site, the solar panel does not provide enough power.

*See the above third bullet points for detail explanations.

4.2.2 MH Corbin

The installation of MH Corbin Phase 2 was completed on the afternoon of April 9th. For testing purposes, MH Corbin used their own trailer to mount all of their components. The trailer also provides its own electricity via a solar panel. For this deployment, only the Bosch camera is used, and the Lidar is removed since the solar panel cannot sustain the power for both devices. The installation process is very simple and requires minimal help from TDOT. First, the trailer is towed to the prefer location. Then the camera angle is modified to get the best view of the system. The wrong-way sign and telespar post are installed with the help of TDOT personnel. Finally, the two-zone layout can be configured remotely from a computer. MH Corbin phase 2 completed on May 9th and the WWPS does not have any false and missed detection.



Figure 4-3 MH Corbin Phase 2 Deployment

4.2.3 Wavetronix

Wavetronix Phase 2 Installation was completed on April 10th and this process is longer and requires more step than the other two companies. First, the two trailers with solar panels are towed to the marked location. Then, the two blinking signs were installed with help from TDOT. The cables of these signs are wired underground to the Wavetronix Box to prevent unsuspected damage. Important components are SmartSensor HD, Tracking Camera, and the logical and electrical box. A ramp closure was executed to help calibrate the system. This calibration process, however, was quite extensive and took nearly 4 hours and thus it is not ideal. Nevertheless, Wavetronix's team were able to complete the installation. The researchers at the University of Memphis were on the site during this installation and we tested for both missed detection and false detection and the system works as intended with all the counter measurements being triggered while driving the vehicle wrong way. However, the system does not work to full capacity if we left it alone. Therefore, these trail runs on the installation day is counted as the missed and false detection for Wavetronix. Wavetronix Phase 2 was completed on April 11th and the WWPS records no missed or false detection.



Figure 4-4 Wavetronix Phase 2 Deployment

4.3 Life Cycle Cost Analysis

Evaluation of life cycle cost was done to provide TDOT an idea of potential cost incurred in implementing a system. Life cycle cost of each technology was based on price, manufacturer's recommendations, and results from controlled tests. The following equation was used to calculate life cycle cost of the technologies.

$$EUAC = Cap\left(\frac{A}{P}, i, n\right) + OM + (Disp - Sal)\left(\frac{A}{F}, i, n\right) \quad (3)$$

Where:

- $EUAC$: Equivalent Uniform Annual Cost of the WWPS
- Cap : the capital cost of the WWPS
- $\left(\frac{A}{P}, i, n\right)$: Capital recovery given interest rate i and useful life n
- OM : the annual operating and maintenance cost of the WWPS
- Sal : the salvage value of the WWPS at the end of its useful life
- $Disp$: the cost to dispose of the WWPS at the end of its useful life
- $\left(\frac{A}{F}, i, n\right)$: Uniform series sinking fund given interest rate i and useful life n
- i : the interest rate
- N : the predicted useful life of the WWPS

We make the following assumption on the site environment and requirement that will affect the life cycle cost:

- The WWPS should be a standalone system which relies on itself for electricity power and internet connection.
- The WWPS will be provided as a complete package where all detection, warning, and alerting components are included. Company which only provides detection can source the remaining from third-party company and integrates into their system.
- The WWPS shall have a two-zone setup as discussed in Section 3.2. In addition, the WWPS shall be able to capture the evidence of a wrong-way driving event. At least two wrong-way blinking signs are installed at each zone making a total of four signs needed.
- In the WWPS installation, operation, and maintenance, expected equipment, infrastructure, and human resource needed from TDOT will not be counted toward life cycle analysis.
- The manufacturer shall guarantee the equipment is reasonably weatherproof and no additional cabinets are required from TDOT.

4.3.1 TrafficCalm

TrafficCalm is the only company out of the three tested that manufacture and provide all components in house. The entire WWPS satisfies all the assumptions listed above. The operation and maintenance cost are negligible given that the components are not severely damaged due to unusual event (i.e., storm, vandalism, etc). The only annual cost is the modem service subscription and the WWPS has no salvage value or cost of disposal. The manufacturer expects the WWPS to operate for 15 years. Please see TABLE XVI for the full cost breakdown of TrafficCalm.

TABLE XVI. TrafficCalm Cost Breakdown

Components	Number of units	Total cost (US\$)	Comments
Capital			
Entire System	1	14,879	1 Controller powered by 150W Solar Panel and 140AH Battery Pack 3 Collaborators 3 Solar Panels 2 Wrong-way LED Rings 2 Do-Not Enter Rings 4 Radars
Wrong-way Sign*	2	560	Optional if TDOT doesn't have it in stock
Do Not Enter Sign*	2	330	Optional if TDOT doesn't have it in stock
TOC Notifier and Dedicated Monitor	1	3,000	A dedicated monitor covers all ramps installed with TrafficCalm and will be triggered whenever a WWD is detected. The item is usually installed at the TMC.
Annual Maintenance and Operation Cost (per Year)			
Modem Service	1	450	
Salvage value	All	0	
Cost of disposal	All	0	
Useful Life: 15 Years			
Life cycle cost:			

*Although being optional, these items will be counted toward life cycle cost.

4.3.2 MH Corbin

MH Corbin provides the detection and alerting components as their WWPS package. Therefore, TDOT would need to purchase warning components from third party company. Besides that, the WWPS satisfies all the assumptions in Section 4.3. The annual cost includes an annual subscription to Metri Dashboard software which provides live feed of the wrong-way driving event. MH Corbin WWPS has no salvage value or cost of disposal and will last for 7 years.

TABLE XVII. MH Corbin Cost Breakdown

Components	Number of units	Total cost (US\$)	Comments
Capital			
Entire System	1	18,900	Connect ITS DIN Rail Bosch Dinion 8000 Thermal Camera NEMA Electronics Enclosure 4 x Solar Panels 190W Solar Panel Brackets NEMA 4X Battery Enclosure 4 x 180AH Batteries
*Onsite Assistant	1	2,500	Per Day
Annual Maintenance and Operation Cost (per Year)			
Metri Dashboard	1	3,600	
Salvage value	All	0	
Cost of disposal	All	0	
Useful Life: 7 Years			
Life cycle cost:			

4.3.3 Wavetronix

Wavetronix initially provides only the detection component which is the Smartsensor HD. However, after gaining the experience on wrong-way driving through two field testing events, they are able to put together a complete package for WWPS which satisfies the requirements in Section 4.3. Wavetronix is very flexible in their WWPS package and if less service is requested (i.e., using existing warning components instead of Wavetronix’s) they can omit it off the list and drive down the price. The capital cost of Wavetronix WWPS is listed in TABLE XVIII. The WWPS has no annual, salvage value, and cost of disposal cost and is expected to last 10 years.

TABLE XVIII. Wavetronix Cost Breakdown

Components	Number of units	Total cost (US\$)	Comments
Capital			
Detection Components	2	11,300	2 Smartsensor HD and its dependents. Required for 2 zone setups. Provided by Wavetronix
Evidence Camera	1	8,400	Digital camera Provided by Intermountain Environmental, Inc
Warning Components	4	25,250	4 Flashing Wrong-way Signs and its dependents. 1 Solar panels. Provided by Traffic Technology Integrators
*Onsite Services	1	2,500	Onsite assistance for installation

Annual Maintenance			
None	0	0	
Salvage value	All	0	
Cost of disposal	All	0	
Useful Life: 10 Years			
Life cycle cost:			

*This item is optional and will not be counted toward life cycle cost.

4.4 Multicriteria Evaluation

After conducting Controlled Environment Testing, Real-World Testing, and Life Cycle Cost Analysis, we have gathered enough data to conduct Multicriteria Evaluation (ME) of three WWPS of interest. Multicriteria evaluation determines the performance of WWPS by judging it on different criteria separately, multiplies the score by the criteria's weight, which reflects how important it is over other's, and combines multiplied score to get the final weighted score. The system with the highest score has the best performance in general. Within each criterion, there are multiple metrics which can then be multiplied and combined to get the final score for that criteria. Each metric is measured from a scale of 1 to 5 where 5 refers to the product with the best performance (i.e., from testing or data collection) and the remaining two products' score are scaled accordingly. We define the five main criteria as follow:

1. Accuracy: measures the rate at which the WWPS correctly determines the type of event. There are two metrics which are Missed Detection and False Detection Rate, which are calculated based on Phase 1 Testing as shown in Section 4.1. Here, the weight for Missed Detection Rate is double that of False Detection because a missed detection can result in a WWD crash and ultimately fatality.
2. Responsiveness: determines how quickly the WWPS reacts to the WWD event and triggers the countermeasures accordingly. There are two metrics which are Flashing Sign Delay and Authority Alert Delay. The first delay is much more important than the second since when the vehicle is going the wrong way, a 1 second period can be the different between the driver goes past the flashing sign without notice before it being triggered and otherwise.
3. Live tracking: represents how well the WWPS perform for an extended period of time, as tested in Phase 2 Real-World Testing.
4. Cost: calculates how competitive the cost of a WWPS compare to other two's cost.
5. Other: states how well the WWPS perform in (1) Ease of Installation, (2) Software Features, and (3) Product Seniority. Ease of installation is determined by the experiences of onsite installation process of both Phase 1 and 2 from both our researchers and the TDOT crew who help us. (2) Software features is determined by the hand-on experience on how to operate, supervise, and receive alerts from the WWPS. (3) Product Seniority refers how long the product has been developed and how many products have been deployed across the country.

TABLE XIX. Multicriteria Evaluation of three WWPS

Criteria	Metric	Weight	TraffiCalm	MH Corbin	Wavetronix
Accuracy	Missed Detection Rate	3.0	5.00	4.50	5.00
	False Detection Rate	1.5	5.00	5.00	5.00
Responsiveness	Flashing Sign Delay	3.0	5.00	0.43	1.35
	Authority Alert Delay	1.5	0.86	5.00	0.61
Live tracking	RWT Missed Detection	3.0	5.00	5.00	5.00
	RWT False Detection	1.0	5.00	5.00	5.00
Cost	Equivalent Annual Cost	2.5	5.00	1.55	1.94
Other	Ease of Installation	2.0	3.00	4.00	5.00
	Software Features	1.0	5.00	4.00	4.00
	Product Seniority	1.0	5.00	4.00	3.00
Weighted Score			89.79	72.15	71.79

In addition to the raw score as presented in TABLE XIX, we present the radar chart showing the performance of each WWPS by criteria. Since there are 5 criteria, the radar chart is in the form of a pentagon where each corner represents one criterion. The three WWPS are represented by line and color-coded to distinguish them. The closer the line gets to the corner, the better the performance of the WWPS in that criteria. All three WWPS perform very well in Accuracy, Live Deployment, and Other criteria. However, in Responsiveness and Cost, TraffiCalm outperforms the remaining two by a significant margin. Overall, TraffiCalm is the best product for WWPS.

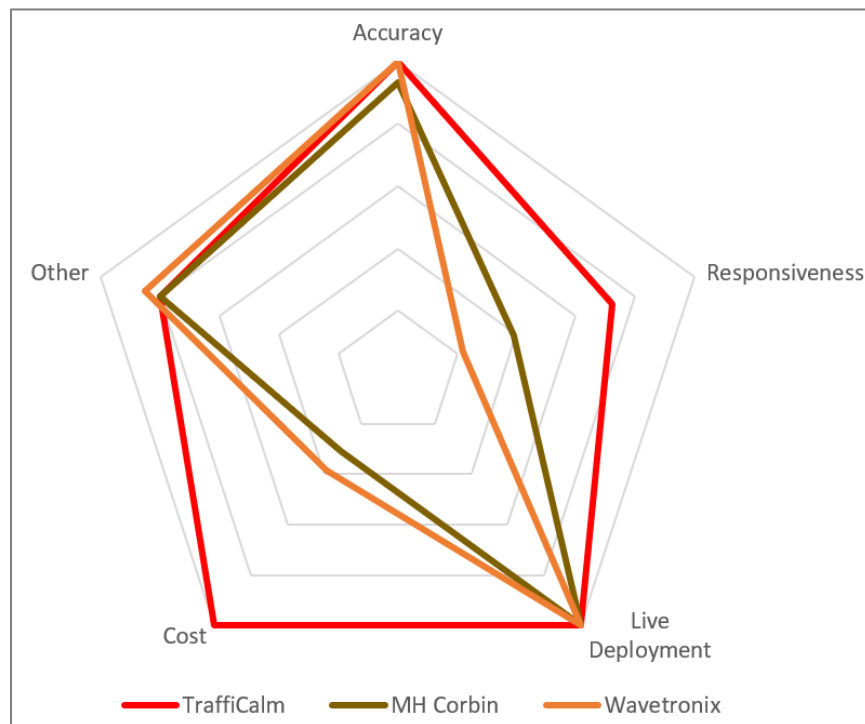


Figure 4-5 Performance of Three WWPS under Five Category

Chapter 5 Conclusion

This project performed an in-depth investigation on the best technologies to prevent wrong-way driving event throughout the State of Tennessee. This can be done in four main tasks. First, we conduct a thorough literature review on two departments (1) common wrong-way movement detection mechanism (i.e., radar, thermal) and (2) other states' solutions and experience on the deployment of WWPS. Second, to identify the potential contributing factors of WWD specifically in Tennessee, WWD crash data is gathered from TDOT's online database and analyzed. Third, based on market research and surveying potential WWPS, we select the top 3 WWPS and perform two phases testing. The first test was performed on a closed environment without external traffic and the test aims to measure the accuracy (i.e., missed and false detection) and the responsiveness (i.e., warning delay) of the system. In the second phase, we deployed the three WWPS on three real-world off-ramps for a period of one month and test whether the WWPS can replicate its performance from phase 1 given the real-world traffic, external weather condition, and unsuspected event. Fourth, based on the result gathered from the two phases of testing and the expected cost provided from the manufacturer, we evaluate the general performance of the WWPS on 5 main criteria namely accuracy, responsiveness, live deployment, cost, and "other" features.

5.1 System Selection Recommendation

Based on the result of the testing, we recommend the TrafficCalm WWPS system. Compare to other companies, TrafficCalm has four main advantages. First, it excels in detecting wrong-way vehicle and minimize false detection as shown in Phase 1 testing and a high accuracy score. For a two-zone setup, TrafficCalm utilizes four radar, two at each zone, and multiple logical units and these components integrates and interacts with each other to create more layers of detection, verification, and confirmation. This ensures the wrong-way driver is always detected and false detection is limited. Second, the flashing LED-enhanced wrong-way sign is very responsive to the WWD event with under 1 second of delay time. Since TrafficCalm has four signs, two at each zone and on both side of the road, it would most certainly alert the driver of his wrong-way movement and force him to a complete stop. Third, although the capital cost is competitive with other companies, TrafficCalm has longer useful life and thus, the life cycle cost is significantly lower. Finally, TrafficCalm is the only company out of three that provide a full package for WWD solution including detection, warning, and alert components. Their system has been tested, deployed, and operated effectively for several years in other States already.

However, TrafficCalm WWPS still has some disadvantages. First, the installation is more complex and require more step than the other two companies. Either a bucket truck or ladder is needed in order to get to top of the pole in order to calibrate the radar and camera. In addition, a ramp closure is needed to perform a wrong-way test run to ensure the system works as intended. Second, the Authority Alert Delay is longer than the other two. The main reason is the alert is delivered via email containing a 20 second evidence video which increases the mail's size and ultimately increases the delivering time. However, we then later contacted TrafficCalm about improving this delay and they suggest a dual alert notification. The first alert will be containing text noticing the wrong-way driving event and the latency is expected to be under 6 seconds. The second alert will still have all the capabilities as mentioned above. In addition to email, TrafficCalm

can send alert via the TOC notifier and a dedicated wrong-way driving monitor, which promise to prompt alert instantly as the wrong-way driver is detected.

5.2 Further Considerations

In this project, we have yet to consider the following elements. First, there are multiple companies providing WWPS that we do not have a chance to test due to budget limitation. One of which is TAPCO WWPS which uses thermal radar detection sourced from a Belgium company namely FLIR. Although being expensive, this system has been utilized by other states with great result. Second, the experiences in installation and operation are mainly taken from the University of Memphis's researcher. Since each WWPS has a different requirement in terms of human resources and infrastructure needed that we cannot collect a uniform perspective from everyone. Finally, although the descriptive statistic of wrong-way driving crash data in Tennessee is provided, we have yet to methodically identify one or more significant causal factors. These elements shall be considered in the future as a follow up research.

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