IDAHO TRANSPORTATION DEPARTMENT

RESEARCH REPORT

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RP 236

Evaluation of Vehicle Detection Systems for Traffic Signal Operations

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16. Abstract

Typical vehicle detection systems used in traffic signal operations are comprised of inductive loop detectors. Because of costs, installation challenges, and operation and maintenance issues, many alternative "non-intrusive" systems have been developed and are now commercially available. Field-testing was conducted to evaluate nine alternative vehicle detection systems (four video, two radar, one thermal, and two hybrid) at the stop bar zone of a signalized intersection under six conditions: (a) daytime, (b) nighttime, (c) favorable conditions, (d) windy conditions, (e) rain, and (f) snow. The sensors were set up with two detection zones: one for the through and right-turn movements (Zone 1) and one for the left-turn lane (Zone 2). Trained personnel installed all systems, and decisions on the mounting locations were made by each system manufacturer.

Based on the results of this study, it can be concluded that there is no single system that universally performs better than all other systems. Depending on the time of day or weather condition, many of the system types tested could claim that their technology outperforms all others. However, based on the percentage of false and missed detections for all of the products representing the different system types, there are opportunities for future improvement and enhancement. The acceptable tolerance level ultimately must be decided upon by the agency operating a particular signal, and it is recommended, based on the results from this study, that specific performance standards be defined when solicitation of signal detection equipment occurs in the future.

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ft	feet	0.3048		m	m	meters	3.28	feet	ft
yd	yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
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yd^2	square yards	0.836	meters squared	m^2	km^2	kilometers squared	0.39	square miles	mi^2
mi^2	square miles	2.59	kilometers squared	km^2	ha	hectares (10,000 m^2)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
^{o}F	Fahrenheit temperature	5/9 (^{o}F-32)	Celsius temperature	^{o}C	^{o}C	Celsius temperature	9/5 ^{o}C+32	Fahrenheit temperature	^{o}F
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

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Technical Advisory Committee

Each research project is overseen by a technical advisory committee (TAC), which is led by an ITD project sponsor and project manager. The Technical Advisory Committee (TAC) is responsible for monitoring project progress, reviewing deliverables, ensuring that study objective are met, and facilitating implementation of research recommendations, as appropriate. ITD's Research Program Manager appreciates the work of the following TAC members in guiding this research study.

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Executive Summary

There are many vehicle detection systems used for intersection traffic signal operations that utilize inductive loop detectors (ILD). ILDs require installation into the roadway surface, saw-cutting of pavement, lane closures, and maintenance staff working in or adjacent to traffic are common attributes. Multiple loops are usually required to equip one location and routine resurfacing of the roadway may require reinstallation of these sensors. The ILDs are also subject to stress from traffic and weather.

Many new detection technologies have been introduced over time to the traffic industry as an alternative to ILDs. Some of these sensor types include video image processors, microwave radar, video-radar hybrids, and thermal sensors. These detection systems do not require installation on or into the roadway surface, and instead are mounted overhead on mast arms, signal poles, or on the side of a roadway and are considered non-intrusive technologies (NIT).

The safety of a signalized intersection is tied closely to the accuracy of its detection system. There are two types of possible detection errors that may occur with any detection system: missed detections and false detections. During a missed detection a sensor fails to detect the presence of an actual vehicle, which can lead to a skipped phase. A false detection occurs when the sensor erroneously acknowledges the presence of a vehicle when one is not physically present. Missed detections create operational inefficiencies by not serving drivers in a timely manner; false detections can have implications on system efficiency and capacity since the controller may give time to serve a direction with no actual traffic. For these reasons, detection systems that minimize both types of errors are ideal and desired.

This report presents the findings from the systematic evaluation of nine non-intrusive, commercially-available NIT traffic detection systems beginning in February 2015. The number of false and missed detections for each system type was determined as part of this research effort, which was initiated by the Idaho Transportation Department (ITD).

Research Objectives and Key Findings

The primary objective of this research was to conduct a systematic evaluation of the detection accuracy of nine commercially available traffic detection systems, including four video-based detectors, two microwave radar detectors, one thermal image sensor, and two video-microwave radar hybrid detectors. These systems were installed at the stop bar zone of a signalized intersection under six unique conditions: (a) daytime, (b) nighttime, (c) favorable conditions, (d) windy conditions, (e) rainy conditions, and (f) snowy conditions. In addition, two detection zones were established: one for the through and right-turn movements (Zone 1) and one for the left-turn lane (Zone 2). Trained personnel installed all systems, and decisions on the mounting locations were made by each system manufacturer.

False Detections

The results indicate that false detections for almost every system increased at night; the exception was one hybrid system which experienced a 3.8% decrease in Zone 1. In terms of system type, false detections for both of the radar systems did not exceed 1.9%. Radar systems were the only system type that exhibited a low level of false detection percentage for both daytime and nighttime detection.

The false detection results for Zone 2, were generally higher than Zone 1 for both daytime and nighttime. Error results ranged from a low of 0.5% (radar, nighttime) to 19.2% (thermal, nighttime). The increased error percentages was partially attributed to left-turning vehicles from the side street cutting across the left-turn lane of the subject approach when it was unoccupied. For this particular location and locations with similar channelization, we concluded that a tapered left turn lane would likely reduce the potential number of false detections in the future.

Missed Detections

Missed detections in Zone 1 and Zone 2 were comparably lower than false detections during both the daytime and nighttime, and the highest frequency of missed detections was 3.4% for one radar system at night. The lowest missed detection error frequency was 0.3% by one radar system during the daytime. During the day, six different systems exhibited missed detection percentages below one percent for Zone 1, and four systems exhibited missed detection percentages below one percent for Zone 2. At night, only two systems and one system exhibited missed detection percentages below one percent for Zone 1 and Zone 2, respectively.

The results for the comparison between favorable and less than favorable conditions (wind, rain, or snow) indicated that inclement weather does negatively affect these system types to varying degrees, particularly with regard to false detections. In Zone 1, the percentage of false detections during wind, rain, or snow was almost universally higher than during favorable conditions. In Zone 2, false detections during wind, rain, or snow was higher than during favorable conditions for every comparison with the percentage difference exceeding 30% in one case. When comparing favorable conditions with unfavorable conditions for missed detections, the percentage difference was much smaller. The missed detection percentage for all systems in both zones was between 0.7% and 2.1% during favorable conditions, and the highest missed detection percentage for a given system during wind, rain, and snow was 2.7%, 2.8%, and 2.7%, respectively.

Conclusions and Recommendations

Based on these results, it can be concluded that there is no single system that universally performs better than all other systems; depending on the time of day or weather condition, many of the system types tested could claim that their technology outperforms all others. However, based on the percentage of false and missed detections for all of the products representing the different system types, there are opportunities for further improvement and enhancement. The acceptable tolerance level ultimately must be decided upon by the agency operating a particular signal, and it is recommended, based on the results from this study, that specific performance standards be defined when solicitation of signal detection equipment occurs in the future.

Chapter 1: Introduction

Background

There are many vehicle detection systems used for intersection traffic signal operations that utilize inductive loop detectors (ILD). ILDs require installation into the roadway surface, saw-cutting of pavement, lane closures, and maintenance staff working in or adjacent to traffic are common attributes. Multiple loops are usually required to equip one location and routine resurfacing of the roadway may require reinstallation of these sensors. The ILDs are also subject to stress from traffic and weather.

Many new detection technologies have been introduced over time to the traffic industry as an alternative to ILDs. Some of these sensor types include video image processors, microwave radar, video-radar hybrids, and thermal sensors. These detection systems do not require installation on or into the roadway surface, and instead are mounted overhead on mast arms, signal poles or on the side of a roadway and are considered non-intrusive technologies (NIT).

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Objectives

The objectives of this research included conducting a systematic evaluation of the detection accuracy of nine commercially available traffic detection systems, including four video image processors, two microwave radar, one thermal, and two video-radar hybrids at the stop bar zone of a signalized intersection under six unique conditions: (a) daytime, (b) nighttime, (c) favorable conditions, (d) windy conditions, (e) rainy conditions, and (f) snowy conditions.

Report Organization

The remainder of this report is organized into four chapters. Chapter 2 provides a brief literature review of detection system and related research. Chapter 3 describes the methodology used for data collection and data reduction in order to evaluate the accuracy of the nine traffic NIT detection systems tested.

Chapter 4 provides the results from the data analysis. Lastly, Chapter 5 provides conclusions and recommendations for future study.

Chapter 2: Literature Review

Introduction

Vehicle detection began in the late 1920's in Baltimore, Maryland. A railroad signal engineer named Charles Adler, Jr. developed a horn-activated sensor that consisted of a microphone in a small box mounted to a nearby pole. It was installed at a Baltimore intersection in 1928 and enabled operation of the first semi-actuated signal. Around the same time, a pressure-sensitive pavement device was introduced that proved to function better and was more popular. The sensor used two metal plates that acted as contacts when pushed together under the weight of a vehicle. The device was the primary means of vehicle detection at actuated intersections for more than 30 years [1].

Mechanical problems with the plate sensor led to the introduction of electro-pneumatic sensors. Although these sensors were used for a short time, they were costly to install, capable only of passage (motion) detection, and had poor counting accuracy. By the early 1960's, ILD systems were being implemented for traffic signal operations and have since become widely used vehicle detection technology. However, problems such as the cost of installation and maintenance and the need for closures during maintenance created the demand for alternative systems [(1)].

In the late 1980's, video imaging detection systems appeared in United States (US) and international markets, warranting the need for research to determine the viability as a replacement to ILDs. In 1990, California Polytechnic State University (Cal Poly) began testing 10 video detection systems that were either prototypes or commercially available in the US. Since the 1990's, several more NIT detection system types have been introduced including microwave radar, infrared sensors, and hybrid systems, warranting the need for extensive research [(2)].

The following sections present a summary discussion of previous research related to NIT vehicle detection, including video-based, infrared, and video-radar hybrid systems. Conclusions regarding discussed research follow the summary.

Video Detection

Video detection systems typically consist of one or more cameras, a microprocessor-based computer to process the video image, and software to interpret images and convert them into traffic flow data. Different systems use different approaches for the process. Some identify when a target vehicle enters the video field of view and continues to track it through the field of view. Others systems identify a target area on the pavement. When the image changes due to a passing vehicle, the image is processed. Other systems use a combination of these approaches. Video detection has the ability to report vehicle presence and classification, volume, occupancy, and speed for each lane observed. Other parameters that are potentially available are density and link travel time.

Previous research involving video-based intersection detection is moderately plentiful and describes testing protocols and evaluation metrics that can be adapted to include other system types [(3-14)]. The majority of this research was based on product evaluation and compares the accuracy of a system or systems to the accuracy of loop detectors [3, 5-14]. Many agencies have been employing video detection at intersections for well over a decade, and some states, such as Texas, have developed manuals for implementation [15].

Cal Poly's 1990 evaluation of 10 video-based detection systems yielded vehicle count and speed errors of less than 20% over a mix of low, moderate, and high traffic densities. However, transitional light conditions, occlusion, and slow-moving, high-density traffic conditions reduced the accuracy of these systems [2]. Video detection research over the past two decades has indicated that lighting conditions are the main cause of detection errors and that night periods are usually characterized as having more problems due to headlight glare [3, 12, 16]. Daytime sun position can have an impact on detector operation as well. The sun can create stationary or moving shadows that can confuse the detector, and glare can reduce camera visibility [3, 4].

A critical finding in a study by Minnesota Department of Transportation (DOT) was that mounting video detection devices was more complex than previously realized. The placement of the camera is crucial to the successful and optimal performance of the system because of lighting and weather impacts [2]. Based on line-of-sight considerations, the maximum distance that a camera can differentiate two closely spaced vehicles is a function of camera height, inter-vehicle distance or gap, and vehicle height as shown in Figure 1 [17]. Other factors to be considered when installing video systems are vertical and lateral viewing angles, the number of observed lanes, stability with respect to wind and vibration, and image quality.

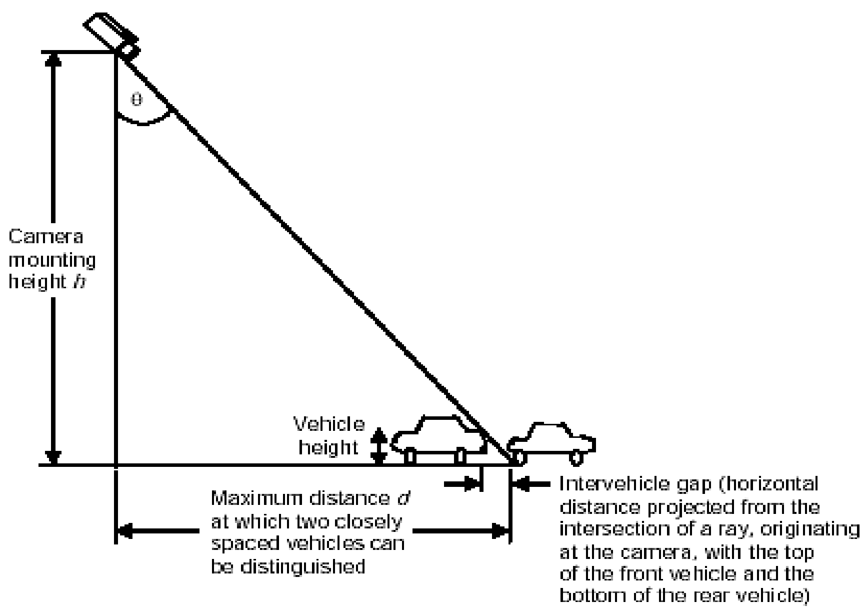

Figure 1: Video Detection Line-of-Sight Geometry

Radar Detection

Radar detectors transmit energy toward an area of roadway from an antenna that is mounted overhead. When a vehicle passes through the beam of energy, a portion of the energy is reflected back to the antenna and detection is made. Radar detectors can sense the presence of stationary vehicles and multiple zones through their range finding ability (17). This concept is illustrated in Figure 2 (18).

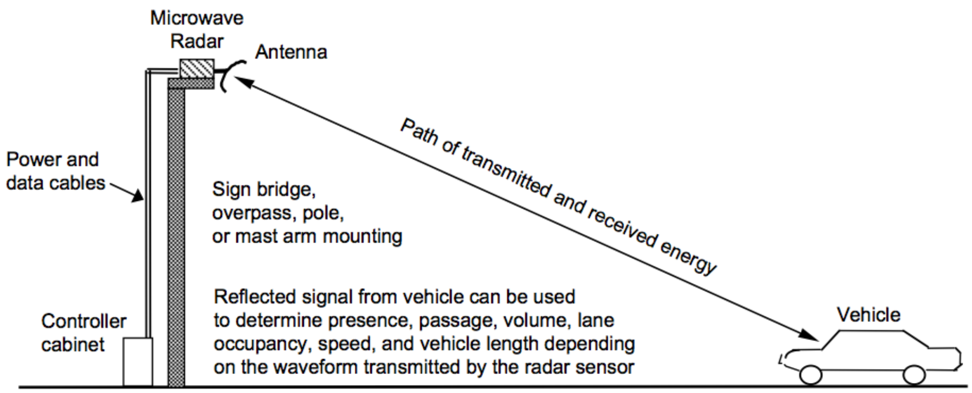

Figure 2: Microwave Radar Operation

Previous studies on microwave radar detectors have mainly focused on freeway applications and few have considered intersection applications (17, 19, 20). One product evaluation study by the Minnesota DOT found an error of 4.9% in volume count, a 9.7% error in speed, and a 5.6% error in length-based vehicle classification (19). A second study initiated by Minnesota DOT found about 5% error in vehicle counts, a 3-mph error on average speed, and significant errors both over and under-counting over-sized vehicles (20).

A later study by the Minnesota DOT in which a radar vehicle detector was installed on a three-lane freeway approach found a margin of error of 1.6% in volume counts during periods of light traffic. Errors increased to up to 20% in periods of heavy congestion (17). Zwalen et al. obtained similar results in which discrepancies totaled over 15% in congested conditions (21).

Studies of radar detection systems at signalized intersections is limited. A 2002 study by the Oregon DOT compared a radar detection system's vehicle counts at a signalized intersection with loop detectors. Results showed undercounting of 5.7% by the radar system (22). A 2008 study evaluated the ability of several different radar systems to track vehicles in the dilemma zone. Results showed that vehicle locations were mostly within five feet of Global Positioning System data and speeds errors were less that 2-mph (23).

Medina et al. completed an evaluation of two radar detection systems at a signalized intersection to determine accuracy in adverse weather conditions. Performance during favorable weather conditions revealed up to 4% false detections and 6% missed detections. Similar performance outcomes were determined under windy conditions except for one advance detection zone where false detections exceeded 50%. Under snowy conditions the performance of both systems heavily degraded but for different reasons. One system experienced most false detections with no vehicles present near the detection zone, while the other system experienced most errors while vehicles were present adjacent to the zone. False detections reached 56% and missed detections reached 12%. Rain was also determined to be a factor in performance degradation with up to 17% false detections and 5% missed detections (24).

Passive Infrared and Thermal Image Sensors

Passive infrared sensors (PIS) have been available to the traffic industry for some time and are currently being marketed by some companies as thermal sensors. A PIS measures energy that is emitted from the vehicles, road surfaces, and other objects within view that emit no energy of their own. As Figure 3 (18). shows that when a vehicle enters the sensor's field of view, it generates a signal that is proportional to the product of the difference in emissivity (ε) between the road and vehicle, and the difference between the absolute temperature of the road surface (T_R) and the temperature of the sky (T_{sky}) (18).

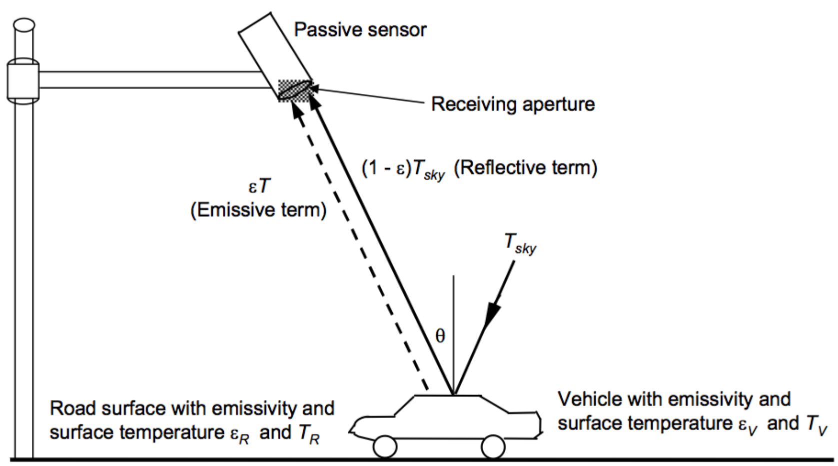

Figure 3: Emission and Reflection of Energy by Vehicle and Road Surface

Although PIS sensors have been available for some time now, there has been limited detailed analysis of their on-street performance to date. Early implementations produced anecdotal reports of solving specific problems, such as periods of glare or shadows. A recent study by Grossman et al. tested one video detection system side by side with two thermal image systems. No missed detections over a 10 second threshold were experienced in a 24-hour period and false detections were modest in all systems tested. Day and night nighttime periods were compared and, as expected, revealed nighttime detection challenges for the video system. However, the thermal detection systems had virtually no change in operation between day and nighttime periods (25).

Thermal Infrared Sensors detect wavelengths that show heat emitted by objects. This ability to view the heat patterns in a video stream made it an easy to replace an analog optical camera with a similar setup of an analog thermal video camera. This made it easier for thermal sensors to be integrated into the current setup parameter, coax and power to interface to the cabinet. The sensor is set up with a standard gain control on the image, it is set to pick a hot item in the field of view and a cold item and set the contrast to give the best image based on the scene it is looking at. The thermal energy viewed by each pixel are digitized and converted to an analog video stream so it can pass over the coax cable. This signal is then converted from analog back to digital by the analytics processor in the traffic control cabinet so the detection algorithms can do their work. The video being processed is a simple thermal video stream showing black and white (hot vs cold) 8-bit video stream. The 8-bit video used in these early deployment of thermal sensing represents 256 levels of grayscale very similar to the way an optical camera is deployed. New thermal sensors that use the full 14-bit thermal stream to analyze the energy value of each pixel enable energy levels emitted to be viewed in greater giving greater detection accuracy and allow for a more reliable tracking of moving objects.

Video-Radar Hybrid Systems

Hybrid video-radar detection systems combine video and microwave radar detection technologies and merge information to produce detection data. The fusion of multi-sensor data can provide advantages over single sensor systems. An example of a benefit of hybrid detection exists with a moving object, such as an airplane, that is observed by both radar and infrared imaging. Radar has the ability to accurately determine the airplane's range but is unable to determine its angular direction. In contrast, the infrared sensor is able to accurately determine angular direction but not range. If data fusion from both sensors is properly associated, the multi-sensor system could provide improved accuracy in the determination of location over an independent sensor system. Hybrid systems not only employ the use of two or more sensors, but also require a data fusion system or algorithm that is able to analyze and process the multisensory data.

The merging of video and radar information has been widely used in intelligent vehicle systems, but mostly within lane recognition, collision avoidance, and adaptive cruise control applications. There are currently very few video-radar hybrid systems available on the commercial market. To date, no systematic studies involving hybrid detection systems in intersection applications are available and the majority of research has been focused on development and analysis of algorithms for data fusion.

Summary

Inductive Loop Detectors are a trusted and mature vehicle detection system, but they are intrusive and their installation requires lane closures and workers in or adjacent to traffic. They are subject to the stresses of vehicles and weather and are inflexible in construction traffic control settings and when needing to make adjustments due to vehicle off-tracking or other unforeseen problems. While loop detectors give information concerning the presence and passage of vehicles, other operational characteristics must be inferred from algorithms that interpret and analyze the data. The parameters that are calculated from the loop data can be less accurate than what is necessary for the application, such as link travel time calculations. Additionally, the data may be insufficient for use in certain applications such as rapid freeway incident detection.

Some of the four types of detection systems presented in the previous sections have been commercially available for over two decades, but there is still the need for further study under adverse weather conditions like rain and wind. The lack of research regarding hybrid systems clearly exhibits the need for systematic evaluation. Additionally, studies that currently exist comparing multiple detection systems side-by-side are dated. Manufacturers have had time to respond to the findings of previous evaluations to improve their products and technologies have also advanced. The focus of this report is to address these issues by evaluating and comparing the accuracy of nine detection systems that include four different NIT system types under daytime, nighttime, favorable (calm wind and little to no precipitation), rain, wind, and snow conditions.

Chapter 3: Data Collection Methodology

Test Site and Infrastructure

The evaluation site for this study was the intersection of US Highway 95 (also known as North Main Street) and D Street in Moscow, Idaho. US-95 serves more than 16,000 vehicles per day and D Street serves more than 6,000 vehicles per day; the typical peak hour volumes at this intersection are shown in Table 1. The northbound and southbound approaches on US-95 have two through lanes and one left-turn lane. The eastbound approach on D Street has one lane to serve all movements and the westbound approach has one through lane and one left turn lane. The intersection layout can be seen in Figure 4.

The northbound approach of this intersection (south leg), with a posted speed limit of 25 miles per hour, was instrumented for this analysis. The signal system currently uses ILDs as its primary form of detection for both stop bar presence and advanced detection. The ILD layout is in accordance with standard ITD guidelines, using a six-foot loop at the stop bar and a second one ten feet upstream from it, for a nominal stop-bar detection area of twenty-two feet.

Table 1: Peak Hour Volume at US 95 and D Street (PM, May 2015)

	North Bound	South Bound	East Bound	West Bound
Left-Turn	116	184	29	177
Through	844	597	91	72
Right-Turn	189	29	20	83

The nine systems analyzed included four video-based detectors, two microwave radar detectors, one thermal image sensor, and two video-microwave radar hybrid detectors. Table 2 shows a list of the systems evaluated along with the type of detection that the system employs. The sensors were set up with two detection zones: one for the through and right-turn movements (Zone 1) and one for the left-turn lane (Zone 2). As these detectors were installed for the northbound approach, almost all of the sensors were mounted on the mast arm located above the receiving lanes of the subject approach. Trained personnel installed all systems, and decisions on the mounting locations were made by each system manufacturer. Figure 5 shows the sensors installed on the mast arm located above the north leg; only the second radar system (R2) was installed on the mast arm at the south leg of the intersection and is shown as an inset in Figure 5.

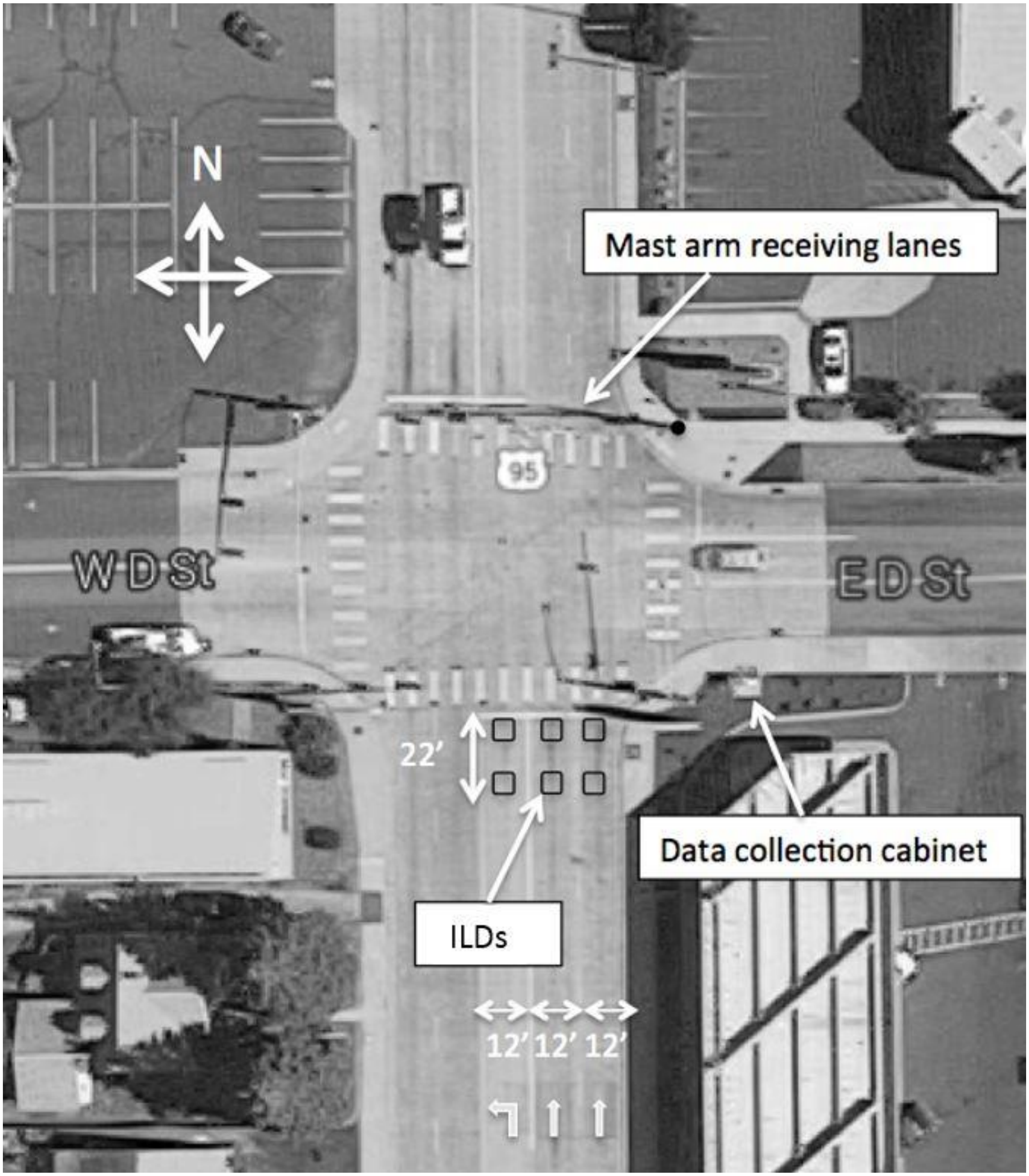

Figure 4: Intersection Layout

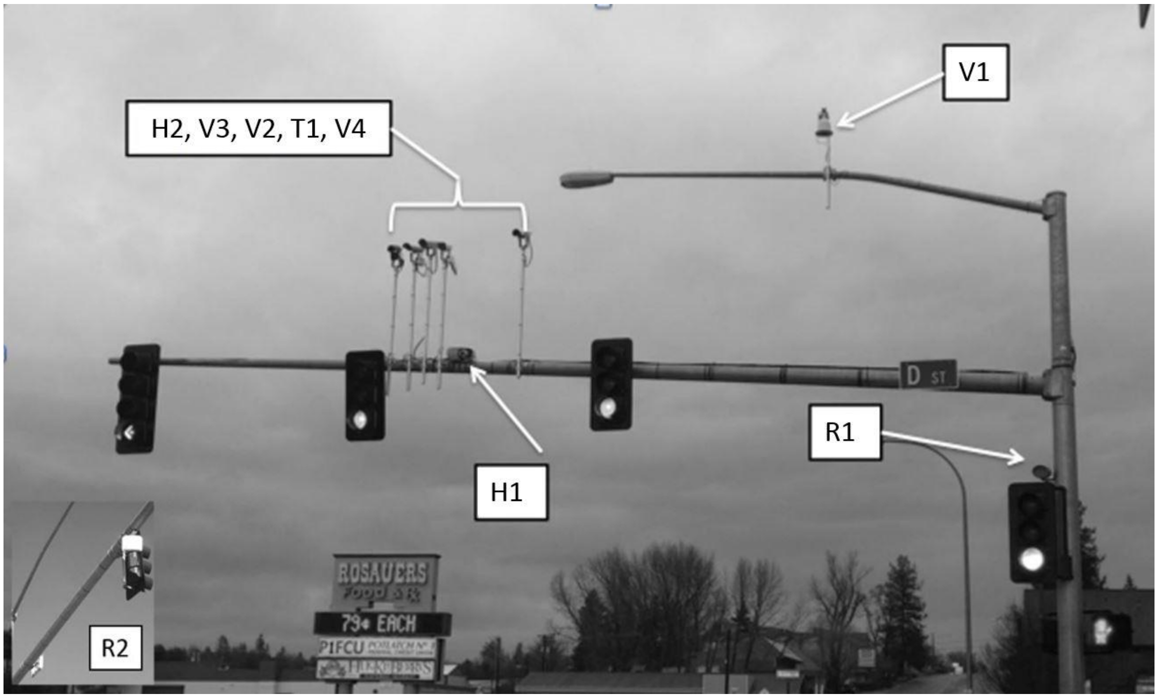

Figure 5: Sensors Installed and Mounted to Mast Arm

Table 2: List of Tested Systems

Abbreviation	Manufacturer, Product	Detector Type
Video System 1 (V1)	Aldis, Gridsmart	Video
Video System 2 (V2)	Iteris, RZ-4 Advanced WDR	Video
Video System 3 (V3)	Traficon, FLIR VIP 3D.2 video detection board with an RDP optical camera	Video
Video System 4 (V4)	Peek, Color Video Traffic Detection Camera	Video
Radar System 1 (R1)	MS Sedco, Intersector	Radar
Radar System 2 (R2)	Wavetronix	Radar
Thermal System 1 (T1)	Traficon, FLIR VIP 3D.2 video detection board with a FLIR FC-T Thermal Sensor	Thermal
Hybrid System 1 (H1)	Iteris, Vantage Vector Hybrid	Hybrid
Hybrid system 2 (H2)	Econolite, Autoscope Duo	Hybrid

A signal control cabinet housed all the equipment needed for data collection from the ILDs and nine other systems. The installation allowed for obtaining two types of data: (a) time stamps associated with activation and deactivation times of the ILDs and nine systems and (b) video images of the subject approach. An input-output device that monitored the status of all ten systems collected time stamps every 10 milliseconds. This high-resolution data output allowed for the development of computer algorithms that automatically identified potential detection errors. The recorded video images were used to conduct manual comparison of the accuracy of different detection systems. They were also used to visually verify the potential detection errors that were identified by the computer algorithm, and were also used to determine weather, lighting, and traffic conditions. A screenshot captured from the video recordings can be seen in Figure 6.

After the installation of all systems was complete, an initial report documenting detection accuracy was shared with each system manufacturer representative. Manufacturers were then given the option of making adjustments to the configuration their systems before official data collection began and three vendors who felt that their system would perform better chose to make minor field adjustments.

Figure 6: Screenshot captured from video recordings.

Evaluation Criteria

To evaluate their effectiveness, the nine systems were individually compared with the ILDs. The review of the ILDs was manually conducted and represented the ground truth data for this study. Previous studies of video, infrared, and microwave radar detection technologies have used ILDs as the basis of comparison [3-15, 24, 25]. Two measures of performance were used to quantify the detection errors: missed detections and false detections. The measures of performance are illustrated in Figure 7 and briefly defined as follows:

- A false call occurred when no vehicle was present in the detection zone but a call was generated (by a vehicle in an adjacent lane or even when there is no vehicle near the zone).
- A missed call occurred when a vehicle physically occupied the detection zone, but the sensor failed to generate a call.

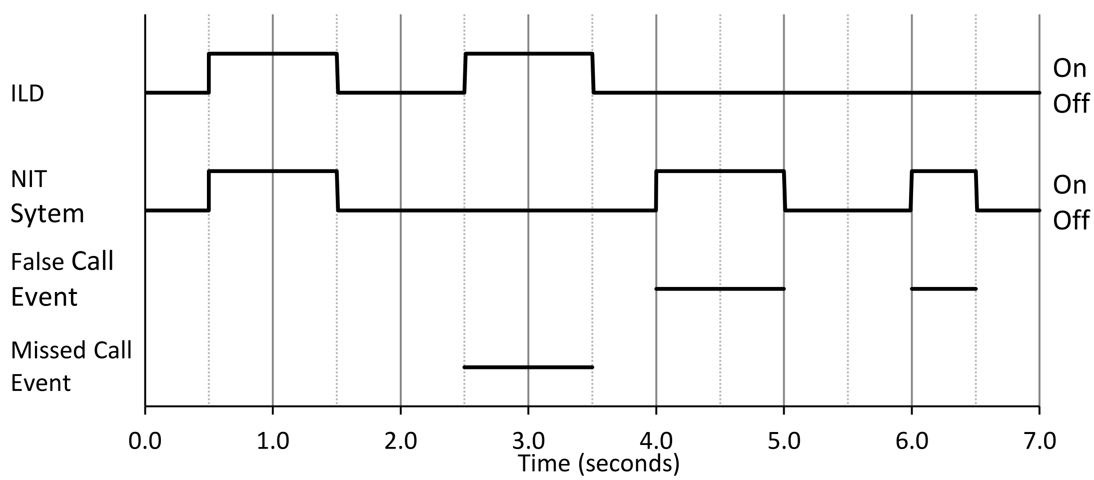

Figure 7: Example of False and Missed Detection Concepts

Algorithm Description

For computing the measures of performance, computer algorithms compared time stamps from ILDs to those of the nine systems to determine if there were significant discrepancies with their activation and deactivation range. A case in which a system did not have exactly the same activation and deactivation range as the ILD did not necessarily represent an error as long as it provided a reasonable representation of vehicle presence. A threshold of difference in call times between ILDs and the alternate system was determined for each system by trial and error and allowed for small discrepancies in physical detection zones.

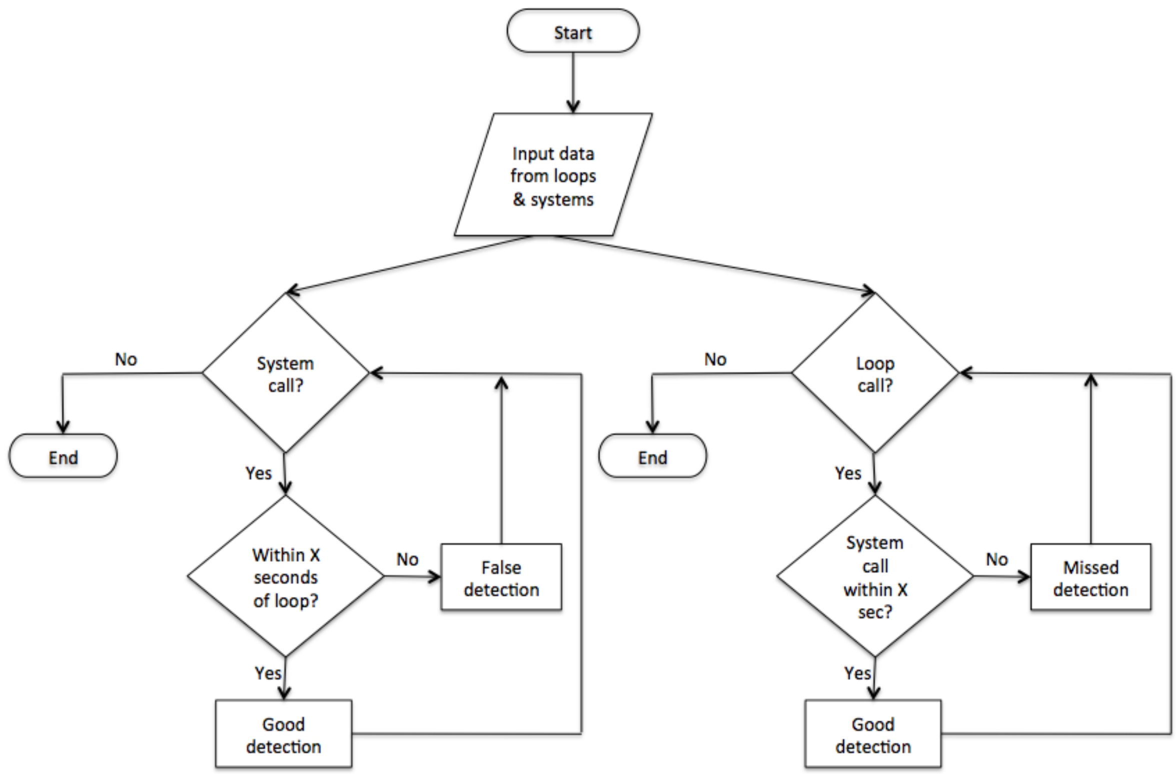

Figure 8: Algorithm Process

A flowchart representing the general process of the algorithm can be seen in Figure 8. The algorithm evaluated data from each alternate system for false detections by comparing its timestamps with ILD call timestamps. If the call was placed within a specified time threshold, the detection was considered "good". If the alternate system call did not have a corresponding call from the ILD data, then the call was counted as a false detection. This time threshold, denoted as "X" in Figure 8, varied slightly from system to system and was dependent on each product's detection configuration.

Missed detections were tabulated in much the same way, except the ILD calls were compared with the timestamps of the alternative system calls. If an ILD call had a corresponding call placed by the alternate system within the specified time threshold, the detection was considered "good". If there was no call from the alternate system corresponding with the ILD call then it was counted as a missed detection. This process was repeated until the end of the dataset and performed on each system.

Data Description

Data were collected between February 2015 and January 2016 for the nine separate NIT systems and ILDs. The objective of the study was to analyze the various sensors under the following conditions: (a) daytime, (b) nighttime, (c) favorable conditions, (d) windy conditions, (e) rain, and (f) snow. A summary of the wind speed, wind gust, and precipitation criteria for each condition along with the number of vehicles and selected data sets are shown in Table 3.

Favorable conditions combined a randomly generated subset of daytime and nighttime data, and represented weather conditions with calm winds and little to no precipitation. Selected windy data sets included gusts in excess of 25 mph and up to 69 mph with sustained winds of more than 20 mph and up to 49 mph. Data selection was based on the Beaufort wind force scale and ranged from "fresh breeze" to "violent storm" on the scale. Rainy data sets had a variety of precipitation intensities from 0.1 inches to 1.62 inches in 60-minute periods, while the snow data set represented conditions with measureable snowfall. It should also be noted that the designation of windy, rainy, and snowy conditions was intended to be based on conditions that distinguished favorable conditions from these unfavorable conditions. However, distinguishing such conditions required that thresholds based on engineering judgment be established.

After data sets were selected, weather conditions were confirmed through records from the weather station at Pullman-Moscow Regional Airport, located about five miles away from the test site. Additionally, visual confirmation of the desired condition was determined from recorded images (see Figure 6).

Table 3: Datasets, Vehicle Counts, and Conditions

				Average Wind and Precipitation Data					
		Vehicle Counts							
Conditions	**Hour Count**	**Thru**	**Left**	**Min. Wind Speed (mph)**	**Max. Wind Speed (mph)**	**Min. Wind Gust (mph)**	**Max. Wind Gust (mph)**	**Min. Hourly Precip. (in)**	**Max. Hourly Precip. (in)**
Day	246	45200	12765	calm	16	--	19	0	0
Night	184	13276	5114	calm	19	--	24	0	< 0.1
Favorable	105	15176	5003	calm	12	--	17	0	0
Wind	19	2722	703	20	49	25	69	0	0.3
Rain	34	4001	1055	4	15	--	22	0.1	1.6
Snow	19	1216	273	10	16	--	29	0.1	0.1

Chapter 4: Results

For this study, detection data were analyzed from two defined stop bar zones. Zone 1 consisted of the two northbound through lanes, while zone 2 represented the northbound left-turn lane. The results from each zone are described separately in this chapter.

Error counts were evaluated for statistical significance by considering the total number of ILD activations as the number of trials. On the basis of this condition, a two-tailed test of the hypothesis was performed on the proportion of errors of each system under the different conditions. The proportion of false detections for each system (P_{false}) was calculated by dividing the number of false system detections by the total number of ILD detections. Similarly, the proportion of missed detections for each system (P_{missed}) was calculated by dividing the number of missed system detections by the total number of ILD detections.

The null hypothesis that the proportion of errors (P_1 and P_2) was the same for systems under different conditions can be expressed as [H_0: $P_1 = P_2$]. The alternative hypothesis represents the case in which the proportion of errors for the same system under different conditions is significantly different. The alternative hypothesis can be expressed as [H_a: $P_1 \neq P_2$]. If the difference in the proportion of errors was found to be statistically significant, an asterisk was used to indicate this significance.

The comparison of system performance during daytime versus nighttime conditions is presented in the next section, and is followed by favorable versus different adverse (wind, rain, and snow) conditions.

Performance During Day vs. Night

The performance of all nine systems in Zone 1 during daytime and nighttime conditions is summarized in Table 4. Daytime and nighttime performance were collected over multiple days with the results tested for statistical significance.

False detections in Zone 1 during the daytime were less than 5.4% for all systems, while false detections during the nighttime increased to as high as 13.7%. For each system, false detections at night were comparably higher with the exception of the R2 and H2 systems. In fact, the performance of the H2 system during the night produced the lowest percentage of false detections in Zone 1 (1.0%) compared to all other systems. The frequency of false detections by R1 increased by only 0.4% during the night and was one of two systems (R1 and R2) that did not exhibit any statistically significant difference between its daytime and nighttime data. The V2, V3, T1, and H1 systems all produced nighttime false detections exceeding 10%.

Missed detections during the daytime did not exceed 1.8% for all systems in Zone 1. The frequency of missed calls during the nighttime increased slightly for some systems (V2, V3, V4, R1, R2, T1, and H1), while the frequency decreased in others (V1 and H2). For the purposes of full disclosure, a subset of data was removed in the reporting of the missed detection data for three of the systems due to a processing malfunction observed by the research team.

Table 4: Day vs. Night Individual System Performance in Zone 1

ZONE 1	False Detections		Missed Detections	
System	**Day**	**Night**	**Day**	**Night**
Video System (V1)	3.7%	9.6%*	0.9%	0.7%
Video System (V2)	4.3%	12.3%*	0.8%	1.1%*
Video System (V3)	2.0%	13.7%*	0.8%	0.9%*
Video System (V4)	5.4%	9.6%*	1.8%	2.0%
Radar System 1 (R1)	1.4%	1.8%	0.6%	3.4%*
Radar System 2 (R2)	1.9%	1.3%	0.8%	1.6%*
Thermal System 1 (T1)	5.4%	12.9%*	0.4%	2.0%
Hybrid System 1 (H1)	4.7%	11.3%*	1.0%	1.2%*
Hybrid System 2 (H2)	4.8%	1.0%*	1.4%	1.0%

* Indicates nighttime result is statistically significantly different than daytime.

To provide a comparison of system types at a higher level, the collective performance of each system type (i.e., video, radar, thermal, and hybrid) was grouped and this information is summarized in Table 5. It should be carefully noted that since there were an unequal number of systems for each type, the results provided in Table 5 (and subsequently in Tables 7, 9, 11, 13, and 15) have been intentionally reported in ranges of one-half percent (0.5%). The intent of this table (and similar tables) is to give the reader a general sense as to how one system type compared with the other three types; however, the use of individual system data (as shown in Tables 4, 6, 8, 10, 12, and 14) is encouraged when describing actual performance. (For example, when describing the performance of false detections during the daytime for video systems, it may be more desirable to state that the performance was 2.0%, 3.7%, 4.3%, and 5.4%, depending on the system, rather than stating that performance *ranged* from approximately 2.0% to 5.5%.)

Based on Table 5, the radar system performed with the greatest accuracy for false detection calls. All systems performed well in terms of missed detection calls and did not exceed the 3.5% threshold. The video and thermal systems experienced a notable increase in false detections between daytime and nighttime conditions, and the radar and thermal systems experienced a slight increase in missed detections between daytime and nighttime conditions.

Table 5: Day vs. Night Average Performances in Zone 1

ZONE 1	False Detections		Missed Detections	
System	**Day**	**Night**	**Day**	**Night**
Video	2.0% - 5.5%	9.5% - 14.0%	0.5% - 2.0%	0.5% - 2.0%
Radar	1.0% - 2.0%	1.0% - 2.0%	0.5% - 1.0%	1.5% - 3.5%
Thermal	5.0% - 5.5%	12.5% - 13.0%	0.0% - 0.5%	1.5% - 2.0%
Hybrid	4.5% - 5.0%	1.0% - 11.5%	1.0% - 1.5%	1.0% - 1.5%

Daytime and nighttime performance from Zone 2 is summarized in Table 6. False detections in Zone 2 were significantly higher for both daytime and nighttime periods when compared with those in Zone 1. A manual review of the recorded images determined that westbound vehicles turning left from D Street occasionally cut across the northbound left-turn lane of the subject approach when it was unoccupied. As a result, this behavior was a primary contributor of false detections in Zone 2.

Missed detections were generally low for both daytime and nighttime in Zone 2. The frequency of missed calls increased for V2, V3, V4, R1, R2, T1, and H1 during the nighttime period. The V4 system experienced the highest number of missed calls during the day at 2.7%. V1 and H2 had a slight decrease in missed calls during the nighttime period, which mirrored their results from Zone 1.

Table 6: Day vs. Night Individual System Performance in Zone 2

Zone 2	False Detections		Missed Detections	
System	**Day**	**Night**	**Day**	**Night**
Video System 1 (V1)	8.0%	16.2%*	1.8%	1.1%*
Video System 2 (V2)	4.5%	18.3%*	1.2%	1.6%*
Video System 3 (V3)	11.2%	19.1%*	1.0%	1.4%*
Video System 4 (V4)	6.1%	7.3%*	2.7%	3.2%*
Radar System 1 (R1)	1.1%	0.6%	0.3%	1.6%*
Radar System 2 (R2)	1.4%	0.5%	0.8%	1.6%*
Thermal System 1 (T1)	17.6%	19.2%	1.1%	3.2%*
Hybrid System 1 (H1)	7.7%	16.4%*	0.9%	1.7%*
Hybrid System 2 (H2)	3.1%	7.0%*	0.9%	0.5%

* Indicates nighttime result is statistically significantly different than daytime.

The average performance of each system type is shown in Table 7. The radar system performed with the greatest accuracy with regard to false detections during the daytime and nighttime periods. The errors experienced by the other systems in Zone 2 fluctuated from the 3.0% - 8.0% range (hybrid, daytime false detections) to the 19.0% - 19.5% range (thermal, nighttime false detections). All of the systems performed better with regard to missed detections as the highest error percentage range was 3.0% to 3.5% (thermal, nighttime).

Table 7: Day vs. Night Average Performances in Zone 2

ZONE 2	False Detections		Missed Detections	
System	**Day**	**Night**	**Day**	**Night**
Video	4.5% - 11.5%	7.0% - 19.5%	1.0% - 3.0%	1.0% - 3.5%
Radar	1.0% - 1.5%	0.5% - 1.0%	0.0% - 1.0%	1.5% - 2.0%
Thermal	17.5% - 18.0%	19.0% - 19.5%	1.0% - 1.5%	3.0% - 3.5%
Hybrid	3.0% - 8.0%	7.0% - 16.5%	0.5% - 1.0%	0.5% - 2.0%

Additional figures describing all results can be found in the Appendix.

Performance in Favorable vs. Adverse Conditions

To further explore the results from the false and missed detections, a subset of the daytime and nighttime data was analyzed that separated favorable from non-favorable weather conditions. As described earlier, the non-favorable conditions included weather conditions that could qualitatively be described as windy, rainy, and snowy.

False Detections in Zone 1

The results from false detection performance of each system in Zone 1 when comparing favorable with adverse conditions are shown in Table 8. False detections had an occurrence of less than 10% in Zone 1 under all conditions (except for V3, V4, and H1 during snow). The performance of most systems during windy and rainy conditions degraded when compared to their performance in favorable conditions. The percentage change deviated to a greater extent when favorable and snow conditions were compared.

The percentage of false detections in adverse conditions when compared with favorable conditions were higher across the board for almost all systems. During adverse weather conditions, only the performance of T1 (rain) and H1 (wind and rain) improved. The performance of every system in wind, rain, and snow conditions was determined to be statistically significantly different from favorable conditions.

Table 8: Favorable vs. Adverse Individual System False Detections in Zone 1

System	Favorable	Wind	Rain	Snow
Video System 1 (V1)	5.6%	7.2%*	6.1%*	8.0%*
Video System 2 (V2)	5.7%	7.9%*	6.2%*	9.7%*
Video System 3 (V3)	6.2%	7.3%*	7.9%*	23.9%*
Video System 4 (V4)	5.2%	8.3%*	9.9%*	10.9%*
Radar System 1 (R1)	1.5%	6.1%*	4.5%*	7.0%*
Radar System 2 (R2)	1.9%	5.3%*	3.1%*	6.3%*
Thermal System 1 (T1)	6.5%	7.8%*	5.1%*	8.5%*
Hybrid System 1 (H1)	5.4%	2.0%*	4.6%*	14.0%*
Hybrid System 2 (H2)	4.5%	5.4%*	4.6%*	5.3%*

* Indicates result is statistically significantly different than favorable.

Table 9 shows the average false detection performance of each system type in Zone 1. Radar produced the fewest false detections in favorable weather with an error range of 1.5% - 2.0%. Hybrid performed with the greatest accuracy in wind, while radar generally performed with the greatest accuracy in rain and snow. All systems experienced some decline in performance in snowy conditions, while the video, radar, and hybrid system experiencing a potential tripling from favorable to snowy conditions based on percentage.

Table 9: Favorable vs. Adverse Average False Detections in Zone 1

System	Favorable	Wind	Rain	Snow
Video	5.0% - 6.5%	7.0% - 8.5%	6.0% - 10.0%	8.0% - 24.0%
Radar	1.5% - 2.0%	5.0% - 6.5%	3.0% - 4.5%	6.0% - 7.0%
Thermal	6.0% - 6.5%	7.5% - 8.0%	5.0% - 5.5%	8.0% - 8.5%
Hybrid	4.5% - 5.5%	2.0% - 5.5%	4.5% - 5.0%	5.0% - 14.0%

False Detections in Zone 2

Tables 10 and 11 show the results of the false detection analysis comparing favorable with adverse conditions in Zone 2. Zone 2 experienced significantly more false detections than Zone 1, and as mentioned previously, this increase was attributed to westbound drivers cutting across the northbound left-turn lane. False detection percentages in Zone 2 for all systems in all conditions ranged from 1.0%

(R1, favorable) to nearly 38% (V4, rainy conditions). Most of the systems experienced an increase in false detections when adverse conditions were experienced.

Table 10: Favorable vs. Adverse False Detections in Zone 2

System	Favorable	Wind	Rain	Snow
Video System 1 (V1)	9.6%	26.9%	31.3%*	33.8%*
Video System 2 (V2)	7.3%	17.7%*	18.6%*	20.5%*
Video System 3 (V3)	12.8%	11.3%*	24.1%*	21.4%*
Video System 4 (V4)	6.3%	20.8%*	37.9%*	36.2%*
Radar System 1 (R1)	1.0%	14.6%*	14.3%*	16.0%*
Radar System 2 (R2)	1.2%	8.6%*	11.1%*	11.2%*
Thermal System 1 (T1)	17.9%	18.3%*	26.3%*	29.8%
Hybrid System 1 (H1)	9.4%	21.4%	14.7%*	23.3%*
Hybrid System 2 (H2)	3.9%	19.3%*	14.1%*	19.6%*

* Indicates result is statistically significantly different than favorable

The average false detection results of each system type in Zone 2 are summarized in Table 11. With the exception of radar in favorable conditions, all systems experienced significantly higher error frequencies. The radar system performed with the most accuracy in all weather conditions.

Table 11: Favorable vs. Adverse Average False Detections in Zone 2

System	Favorable	Wind	Rain	Snow
Video	6.0% - 13.0%	11.0% - 27.0%	18.5% - 38.0%	20.5% - 36.5%
Radar	1.0% - 1.5%	8.5% - 15.0%	11.0% - 14.5%	11.0% - 16.0%
Thermal	17.5% - 18.0%	18.0% - 18.5%	26.0% - 26.5%	29.5% - 30.0%
Hybrid	3.5% - 9.5%	19.0% - 21.5%	14.0% - 15.0%	19.5% - 23.5%

Missed Detections in Zone 1

The results for Zone 1 missed detection analysis are shown in Table 12. Missed detections experienced in Zone 1 during favorable conditions were lower than 2.1% for every system, and the performance degradation was limited to about 1.1% during adverse conditions on all systems. Due to data collection issues, data from the R2 system were not available for processing.

Although the performance differences were less than 1.0% between favorable and adverse conditions, these adverse condition results were found to be statistically significantly different than the results during favorable conditions due to the amount of data collected.

Table 12: Favorable vs. Adverse Missed Detection in Zone 1

System	Favorable	Wind	Rain	Snow
Video System 1 (V1)	1.3%	1.8%*	1.6%*	1.7%*
Video System 2 (V2)	1.5%	1.8%*	1.9%*	1.8%*
Video System 3 (V3)	1.0%	1.4%*	0.80%	1.0%
Video System 4 (V4)	2.1%	2.3%*	2.8%*	2.7%*
Radar System 1 (R1)	0.7%	1.4%*	1.6%*	1.7%*
Radar System 2 (R2)	n/a	n/a	n/a	n/a
Thermal System 1 (T1)	1.1%	1.7%*	1.7%*	2.3%*
Hybrid System 1 (H1)	1.3%	1.7%*	1.8%*	1.7%*
Hybrid System 2 (H2)	1.5%	1.4%	2.5%*	1.9%*

* Indicates result is statistically significantly different than favorable.

The average missed detection performance based on system type in Zone 1 is summarized in Table 13. All of the systems did not exceed the 3.0% error range for all of the different weather conditions.

Table 13: Favorable vs. Adverse Average Missed Detections in Zone 1

System	Favorable	Wind	Rain	Snow
Video	1.0% - 2.5%	1.0% - 2.5%	0.5% - 3.0%	1.0% - 3.0%
Radar	0.5% - 1.0%	1.0% - 1.5%	1.5% - 2.0%	1.5% - 2.0%
Thermal	1.0% - 1.5%	1.5% - 2.0%	1.5% - 2.0%	2.0% - 2.5%
Hybrid	1.0% - 1.5%	1.0% - 2.0%	1.5% - 2.5%	1.5% - 2.0%

Missed Detections in Zone 2

Missed detection analysis results from Zone 2 are shown in Tables 14 and 15. The percentage results of missed detections in Zone 2 were similar to those in Zone 1. Missed detection frequencies did not exceed 2.7% for all systems under all conditions, and system performance degradation was limited to

1.5% (V3, snow) during adverse weather conditions. Differences between favorable and adverse weather conditions were all found to be significantly different from a statistical standpoint.

Table 14: Favorable vs. Adverse Missed Detection in Zone 2

System	Favorable	Wind	Rain	Snow
Video System 1 (V1)	1.0%	1.9%*	2.0%*	1.8%*
Video System 2 (V2)	1.3%	2.3%*	2.0%*	1.9%*
Video System 3 (V3)	1.2%	2.5%*	2.0%*	2.7%*
Video System 4 (V4)	1.4%	2.3%*	2.1%*	2.0%*
Radar System 1 (R1)	1.9%	2.6%*	2.1%*	2.1%*
Radar System 2 (R2)	n/a	n/a	n/a	n/a
Thermal System 1 (T1)	1.2%	2.1%*	1.8%*	2.2%*
Hybrid System 1 (H1)	1.0%	2.4%*	1.6%*	1.8%*
Hybrid System 2 (H2)	1.6%	2.7%*	2.1%*	2.2%*

* Indicates result is statistically significantly different than favorable.

Table 15 shows the system type averages for the missed detection analysis in Zone 2. All of the systems recorded error frequencies that did not exceed 3.0%.

Table 15: Favorable vs. Adverse Average Missed Detections in Zone 2

System	Favorable	Wind	Rain	Snow
Video	1.0% - 1.5%	1.5% - 2.5%	2.0% - 2.5%	1.5% - 3.0%
Radar	1.5% - 2.0%	2.5% - 3.0%	2.0% - 2.5%	2.0% - 2.5%
Thermal	1.0% - 1.5%	2.0% - 2.5%	1.5% - 2.0%	2.0% - 2.5%
Hybrid	1.0% - 2.0%	2.0% - 3.0%	1.5% - 2.5%	1.5% - 2.5%

Chapter 5: Conclusions

Field-testing was conducted to evaluate nine NIT vehicle detection systems at the stop bar zone of a signalized intersection under six conditions: (a) daytime, (b) nighttime, (c) favorable conditions, (d) windy conditions, (e) rain, and (f) snow. The evaluation first established the performance of each detection system under daylight conditions and then compared them to the performance under nighttime conditions. Next, the performance of the systems under favorable weather conditions was established and then compared to their performance under windy, rainy, and snowy conditions.

The results indicate that false detections for almost every system increased at night; the exception was one hybrid system which experienced a 3.8% decrease in Zone 1. In terms of system type, false detections for both of the radar systems did not exceed 1.9%; this was the only system type that exhibited this level of false detection percentage for both daytime and nighttime detection.

When examining the false detection results for Zone 2, they were generally higher than Zone 1 for both daytime and nighttime. Error results ranged from a low of 0.5% (radar, nighttime) to 19.2% (thermal, nighttime). The increased error percentages was partially attributed to left-turning vehicles from the side street cutting across the left-turn lane of the subject approach when it was unoccupied. For this particular location and locations with similar channelization, this research effort concluded that a tapered left turn lane would likely reduce the potential number of false detections in the future.

Missed detections in Zone 1 and Zone 2 were comparably lower than false detections during both the daytime and nighttime, and the highest frequency of missed detections was 3.4% for one radar system at night. The lowest missed detection error frequency was 0.3% by one radar system during the daytime. During the day, six different systems exhibited missed detection percentages below one percent for Zone 1, and four systems exhibited missed detection percentages below one percent for Zone 2. At night, only two systems and one system exhibited missed detection percentages below one percent for Zone 1 and Zone 2, respectively.

The results for the comparison between favorable and less than favorable conditions (wind, rain, or snow) indicated that inclement weather does negatively affect these system types to varying degrees, particularly with regard to false detections. In Zone 1, the percentage of false detections during wind, rain, or snow was almost universally higher than during favorable conditions. In Zone 2, false detections during wind, rain, or snow was higher than during favorable conditions for every comparison with the percentage difference exceeding 30% in one case.

When comparing favorable conditions with unfavorable conditions for missed detections, the percentage difference was much smaller. The missed detection percentage for all systems in both zones was between 0.7% and 2.1% during favorable conditions, and the highest missed detection percentage for a given system during wind, rain, and snow was 2.7%, 2.8%, and 2.7%, respectively.

Conclusions and Recommendations

Based on these results, it can be concluded that there is no single system that universally performs better than all other systems; depending on the time of day or weather condition, many of the system types tested could claim that their technology outperforms all others. However, based on the percentage of false and missed detections for all of the products representing the different system types, there are opportunities for further improvement and enhancement. The acceptable tolerance level ultimately must be decided upon by the agency operating a particular signal, and it is recommended, based on the results from this study, that specific performance standards be defined when solicitation of signal detection equipment occurs in the future.

This project has prompted several areas for additional work. First, the alignment of the detectors, in terms of its physical position on the mast arm and how it is pointed toward traffic, should be further analyzed. From this study, it is unclear if the physical position of each device, some of which were several feet away from the centerline of a particular lane, would have affected the data. Second, given the fact that inclement weather contributed to the elevated inaccuracies associated with false and missed detections, there is merit to studying the effectiveness of the devices and understanding how certain weather conditions could be mitigated to reduce these error levels. For example, under extremely windy conditions, comparing the detection results when a device is installed on the signal pole instead of the mast arm would represent one possible future test.

Lastly, it is important to acknowledge that detection capabilities continue to evolve. The data collection process for this study commenced in early 2015; since then hardware and software upgrades for many of the systems have occurred. These updates would alter, and may improve, system performance in future tests.

References

1. Federal Highway Administration. (2006). *Traffic Detector Handbook, Volume 3* Washington, DC.
2. Middleton, D., R. Parker and R. Longmire. (2007). Investigation of Vehicle Detector Performance Publication FHWA/TX-07/0-4750-2. Texas Transportation Institute, Texas Department of Transportation, and FHWA.
3. Rhodes, A., Bullock, D. M., Sturdevant, J., Clark, Z., and Candey, D. G. (2005). Evaluation of Stop Bar Video Detection Accuracy at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 1925, 134–145.
4. Rhodes, A., Jennings, K., and Bullock, D. (2007). Consistencies of Video Detection Activation and De-activation Times Between Day and Night Periods. *ASCE Journal of Transportation Engineering*, 133(9), 505–512.
5. Rhodes, A., Smaglik, E., Bullock, D. M., and Sturdevant, J. (2007). Operational Performance Comparison of Video Detection Systems. Proc., 2007 ITE International Annual Meeting and Exhibit.
6. MacCarley, C. A., and Palen, J. (2003). Evaluation of Video Traffic Sensors for Intersection Signal Actuation: *Methods and Metrics. Presented at 81st Annual Meeting of the Transportation Research Board*. Washington, DC.
7. Grenard, J. L., Bullock, D. M., and Tarko, A. P. (2002). Evaluation of Selected Video Detection Systems at Signalized Intersections. Publication FHWA/IN/JTRP-2001/22. Joint Transportation Research Program, Indiana Department of Transportation, and Purdue University, West Lafayette, IN.
8. Oh, J., and Leonard, J. D. (2003). Vehicle Detection Using Video Image Processing System: Evaluation of Peek Videotrak. *Journal of Transportation Engineering*, 129(4), 462–465.
9. Middleton, D., and Parker, R. (2002). Vehicle Detector Evaluation. Publication FHWA/TX-03/2119-1. Texas Transportation Institute, Texas Department of Transportation, and FHWA.
10. Chitturi, M. V., Medina, J. C., and Benekohal, R. R. F. (2010). Testbed for Evaluation of Vehicular Detection Systems. *Journal of Advanced Transportation*. 44(3), 123-133.
11. Medina, J. C., Benekohal, R. F., and Chitturi, M. V. (2008). Evaluation of Video Detection Systems, Volume 1: Effects of Configuration Changes in the Performance of Video Detection Systems. Research report ICT-08-024. Illinois Center for Transportation.

12. Medina, J. C., Benekohal, R. F., and Chitturi, M. V. (2009). Evaluation of Video Detection Systems, Volume 2: Effects of Illumination Conditions. Research report ICT-09-046. Illinois Center for Transportation.
13. Medina, J. C., Benekohal, R. F., and Chitturi, M. V. (2009) Evaluation of Video Detection Systems, Volume 3: Effects of Windy Conditions in the Performance of Video Detection Systems. Research report ICT-09-047. Illinois Center for Transportation.
14. Medina, J. C., Benekohal, R. F., and Chitturi, M. V. (2009) Evaluation of Video Detection Systems, Volume 4: Effects of Adverse Weather Conditions in the Performance of Video Detection Systems. Research report ICT-09-039. Illinois Center for Transportation.
15. Abbas, M., and Bonneson, J. (2002) Video Detection for Intersection and Interchange Control. Publication FHWA/TX-03/4285-1. Texas Transportation Institute, Texas Department of Transportation; FHWA, U.S. Department of Transportation.
16. Medina, J. C., Benekohal, R. F., and Chitturi, M. V. (2009). Changes in Video Detection Performance at Signalized Intersections Under Different Illumination Conditions. In *Transportation Research Record: Journal of the Transportation Research Board*, 2129, 111–120.
17. Minge, E., and SRF Consulting Group, Inc. (2010). Evaluation of Non-Intrusive Technologies for Traffic Detection. Research report, Final Project No. 2010-36. Minnesota Department of Transportation, Saint Paul.
18. The Vehicle Detection Clearinghouse. (2007). *Summary of vehicle detection and surveillance technologies used in intelligent transportation systems.* Las Cruces, NM: New Mexico State University.
19. Middleton, R., Longmire, R., and Turner, S. (2007). *State of the Art Evaluation of Traffic Detection and Monitoring Systems, Volume I: Phases A & B: Design.* Report No. FHWA-AZ-07-627. Arizona Department of Transportation, Phoenix, AZ.
20. SRF Consulting Group, Inc. (2009). *Ramp Queue Detection: Final Report.* SRF No. 0086298. Minnesota Department of Transportation, Saint Paul, MN.
21. Zwahlen, H. T., Russ, A., Oner, E., and Parthasarathy, M. (2005) Evaluation of Microwave Radar Trailers for Nonintrusive Traffic Measurements. In *Transportation Research Record: Journal of the Transportation Research Board,* 1917*,* 127–140.
22. Edgar, R. (2002) *Evaluation of Microwave Traffic Detector at the Chemawa Road/Interstate 5 Interchange.* Report No. FHWA-OR-DF-02-05. Oregon Department of Transportation, Salem, OR.

23. Sharma, A., Harding, M., Giles, B., Bullock, D. M., Sturdevant, J. R. and Peeta, S. (2008). Performance Requirements and Evaluation Procedures for Advance Wide-Area Detectors. *Presented at 87th Annual Meeting of the Transportation Research Board*, Washington, DC.

24. Medina, J. C., Ramezani, H., & Benekohal, R.F. Evaluation of Microwave Radar Vehicle Detectors at a Signalized Intersection Under Adverse Weather Conditions. *Transportation Research Record: Journal of the Transportation Research Board*, 2356, 100–108.

25. Grossman, J., Hainen, A. M., Remias, S. M., Bullock, D. M. (2012) Evaluation of Thermal Image Video Sensors for Stop Bar Detection at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 2308, 184–198.

Appendix: System Performance Figures

System Types and Abbreviations (See Table 2 for a full list of tested systems):

Hybrid: H1, H2, Radar: R1, R2, Thermal: T1, Video: V1, V2, V3, V4

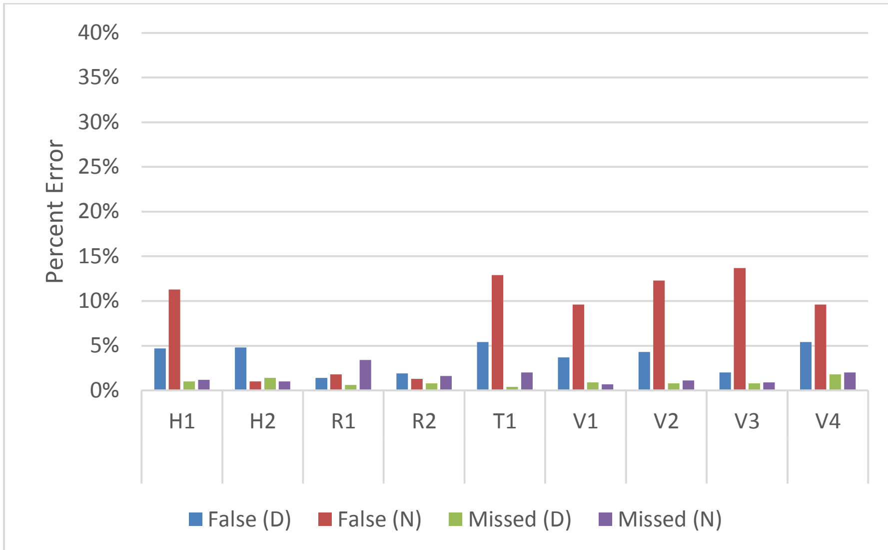

Figure 9 Zone 1 Detection (False vs. Missed and Day vs. Night)

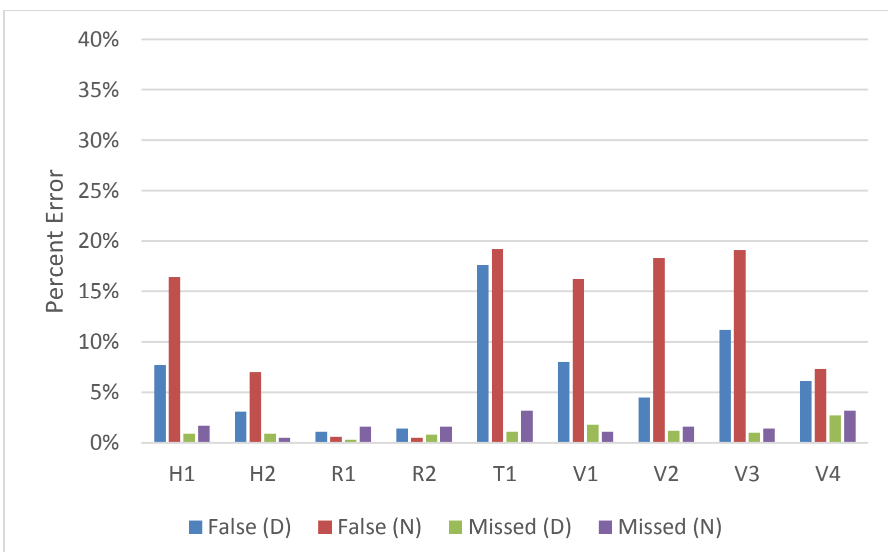

Figure 10 Zone 2 Detection (False vs. Missed and Day vs. Night)

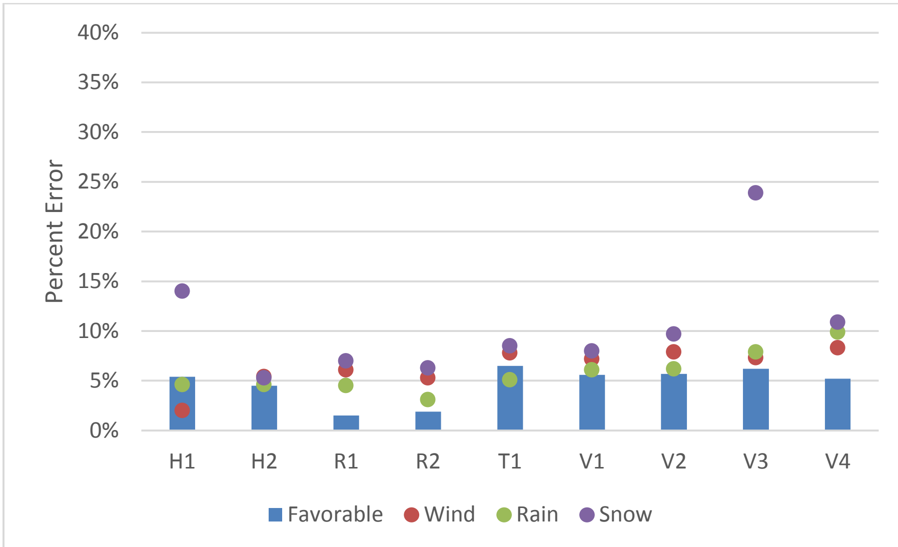

Figure 11 Zone 1 False Detection (Favorable vs. Unfavorable Weather Conditions)

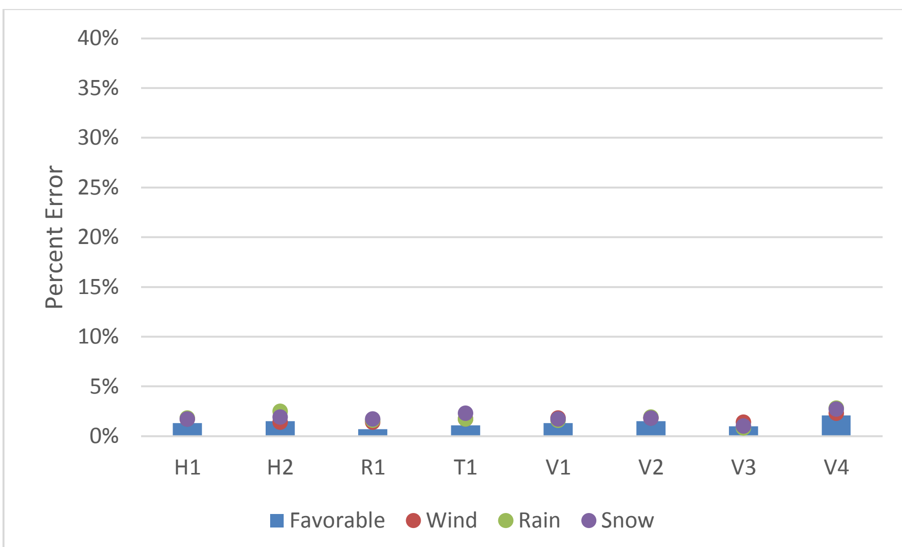

Figure 12 Zone 1 Missed Detection (Favorable vs. Unfavorable Weather Conditions)

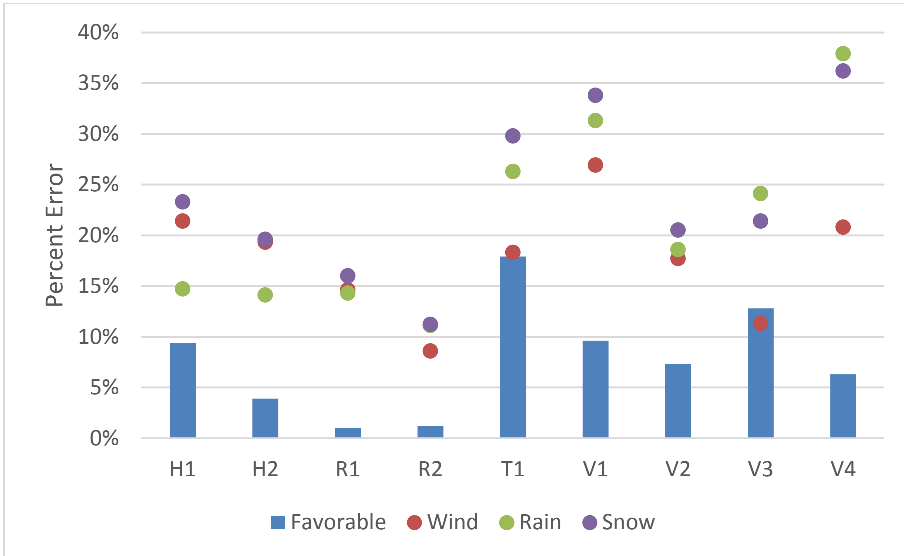

Figure 13 Zone 2 False Detection (Favorable vs. Unfavorable Weather Conditions)

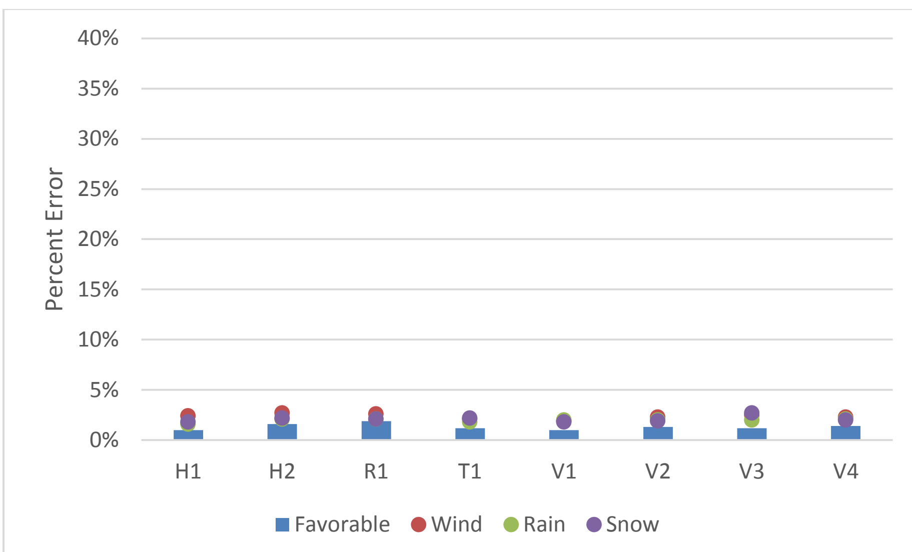

Figure 14 Zone 2 Missed Detection (Favorable vs. Unfavorable Weather Conditions)