Evaluation of Vehicle Detection Systems for Traffic Signal System Operations

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Authorization to Submit Thesis

This thesis of Riannon L. Zender, submitted for the degree of Master of Science with a Major in Civil Engineering and titled "Evaluation of Vehicle Detection Systems for Traffic Signal System Operations," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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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 eight alternative vehicle detection systems (four video, one radar, one infrared, 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. With several exceptions, performance degraded in nighttime when compared with day light conditions, and in adverse versus favorable weather conditions. In general, radar and hybrid systems performed with the greatest accuracy.

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Chapter 1: Introduction

1.1 Background

Typical vehicle detection systems used in traffic signal operations are comprised of inductive loop detectors (ILD). ILDs require installation into the roadway surface, saw cutting of pavement, lane closures, and workers in or adjacent to traffic. Multiple loops are usually required to equip one location and resurfacing of the roadway creates the need for reinstallation of sensors. The wire loops are also subject to stress from traffic and weather, and maintenance creates the need for lane closures and workers in or near traffic.

In recent decades, many new detection technologies have been introduced to the traffic industry as an alternative to ILDs. Some of these new sensor types include video image processors, microwave radar, video-radar hybrids, and passive infrared sensors. These types of detection systems do not require installation on or into the road surface, are mounted overhead 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: missed detections and false detections. During a missed detection a sensor fails to detect the presence of a vehicle, which can lead to a skipped phase and a driver growing impatient and violating the red indication.

False detections have less of an implication on intersection safety, but major implications on efficiency and capacity. If detection occurs when no vehicle is present, the controller can waste time serving a direction with no traffic. Clearly, missed detections that could lead to safety problems are of a greater concern to agencies than operational inefficiencies presented by false detections. However, this does not mean that false detections should not be considered, and detector types that minimize both types of errors would be ideal.

This thesis evaluated eight non-intrusive, commercially available traffic detection systems for accuracy in conjunction with a request developed by The Idaho Transportation

Department (ITD). Systems include video image processors, microwave radar, video-radar hybrids, and infrared. ITD also requested the development of standards that could be used in the future procurement of traffic detection systems.

1.2 Objectives

The objectives of this research include conducting a systematic evaluation of the detection accuracy of eight commercially available traffic detection systems (including four video, one radar, one infrared and two video-radar hybrid).

1.3 Thesis Organization

This thesis outlines the methodology and results of field-testing of eight NIT vehicle detection systems. First, a literature review of detection system research will be discussed. Second, the methodology for data collection and data reduction will be presented. Next, the results of the data analysis are presented. Finally, conclusions and recommendations for future study are discussed.

Chapter 2: Literature Review

2.1 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.[1] 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 the most 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 of previous research related to NIT vehicle detection. First, video-based detection research will be discussed. Second, a summary of

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[1] A 1977 Interview with The Evening Sun (now The Baltimore Sun) quoted Alder as saying, “After it was installed, it blinked like a dime-store Christmas tree until we discovered that the cows were activating it every time they mooed.”

radar vehicle detection research will be presented. Third, infrared detection research will be discussed. Fourth, video-radar hybrid detection system research will be discussed. Finally, conclusions regarding discussed research will be presented.

2.2 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. 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 (17).

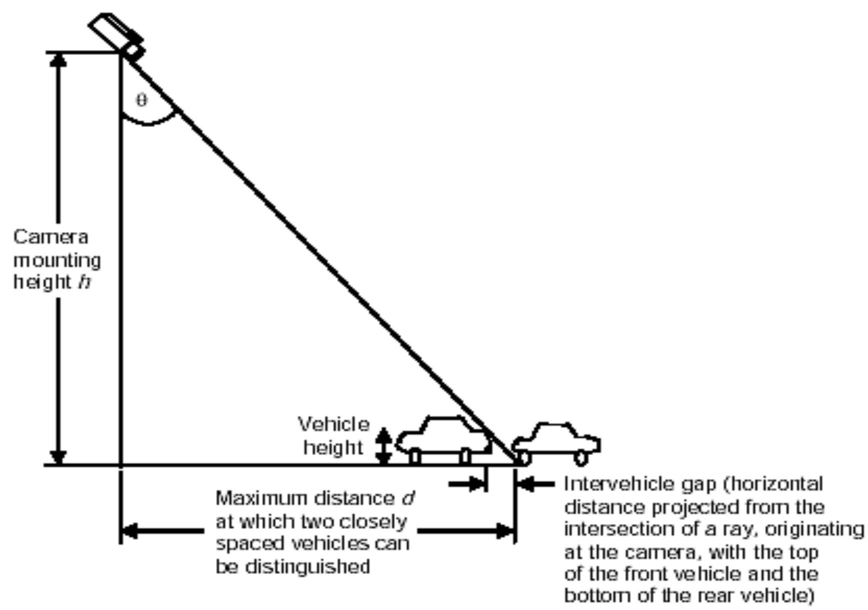

Figure 1: Video detection line-of-sight geometry (1).

2.3 Radar Detection

As shown in Figure 2, 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).

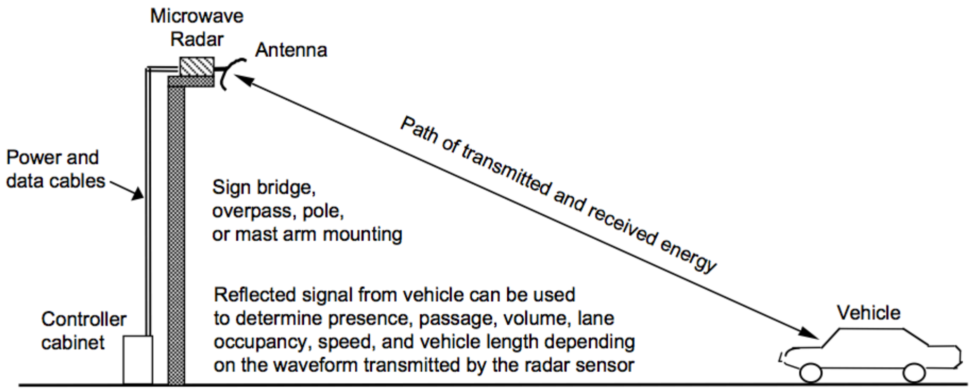

Figure 2: Microwave radar operation (18).

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).

Study of radar detection at signalized intersections is limited and there have only been several reports completed to date. 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%. Performance of both systems heavily degraded under snowy conditions 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).

2.4 Passive Infrared 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 but emit no energy of their own. As Figure 3 shows, 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).

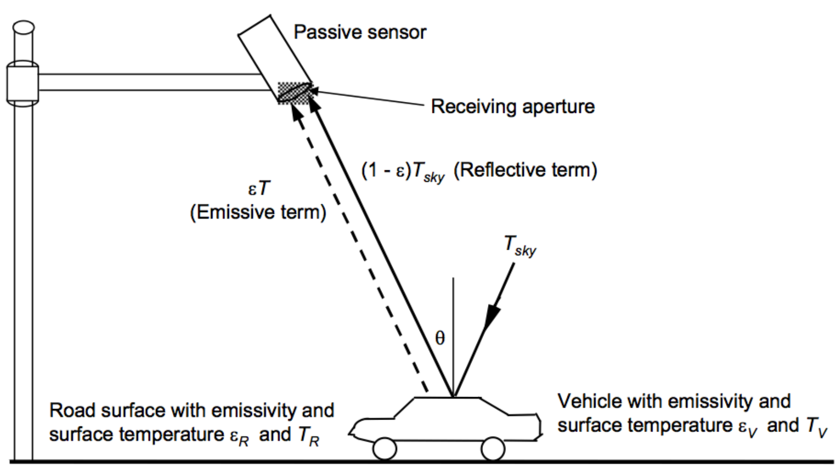

Figure 3: Emission and reflection of energy by vehicle and road surface (18).

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).

2.5 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.

2.6 Conclusion

ILDs 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 maintenance also creates the need for lane closures and workers in or adjacent to traffic. 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 thesis is to address these issues by evaluating and comparing the accuracy of eight 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: Methodology

3.1 Data Collection

Test Site and Infrastructure

The evaluation site for this study was the intersection of US Highway 95 (also knows as North Main Street) and D Street in Moscow, Idaho, and the northbound approach of this intersection (south leg) was instrumented for the analysis. The posted speed limit on US 95 is 25 mph. U.S. 95 serves more than 16,000 vehicles per day (vpd) and D Street serves more than 6,000-vpd. The signal system uses ILDs as its primary form of detection for both stop bar presence and advanced detection. The ILD layout is in accordance of standard ITD practice, using a 6-ft loop at the stop bar and a second one 10-ft upstream from it, for a nominal stop-bar detection area of 22-ft.

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 eight systems analyzed included four video-based detectors, one microwave radar detector, one passive infrared sensor, and two video-microwave radar hybrid detectors. Table 1 shows a list of the systems evaluated along with the type of detection that the system employs. For H2, one lane per detection zone was possible. The remaining sensors were set up with two detection zones: one for the left-turn lane and one for the through and right-turn movements. The through lanes are defined together as Zone 1 and the left-turn lane is defined as Zone 2. These detectors were installed on the northbound approach, with all eight sensors mounted to 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 at the intersection.

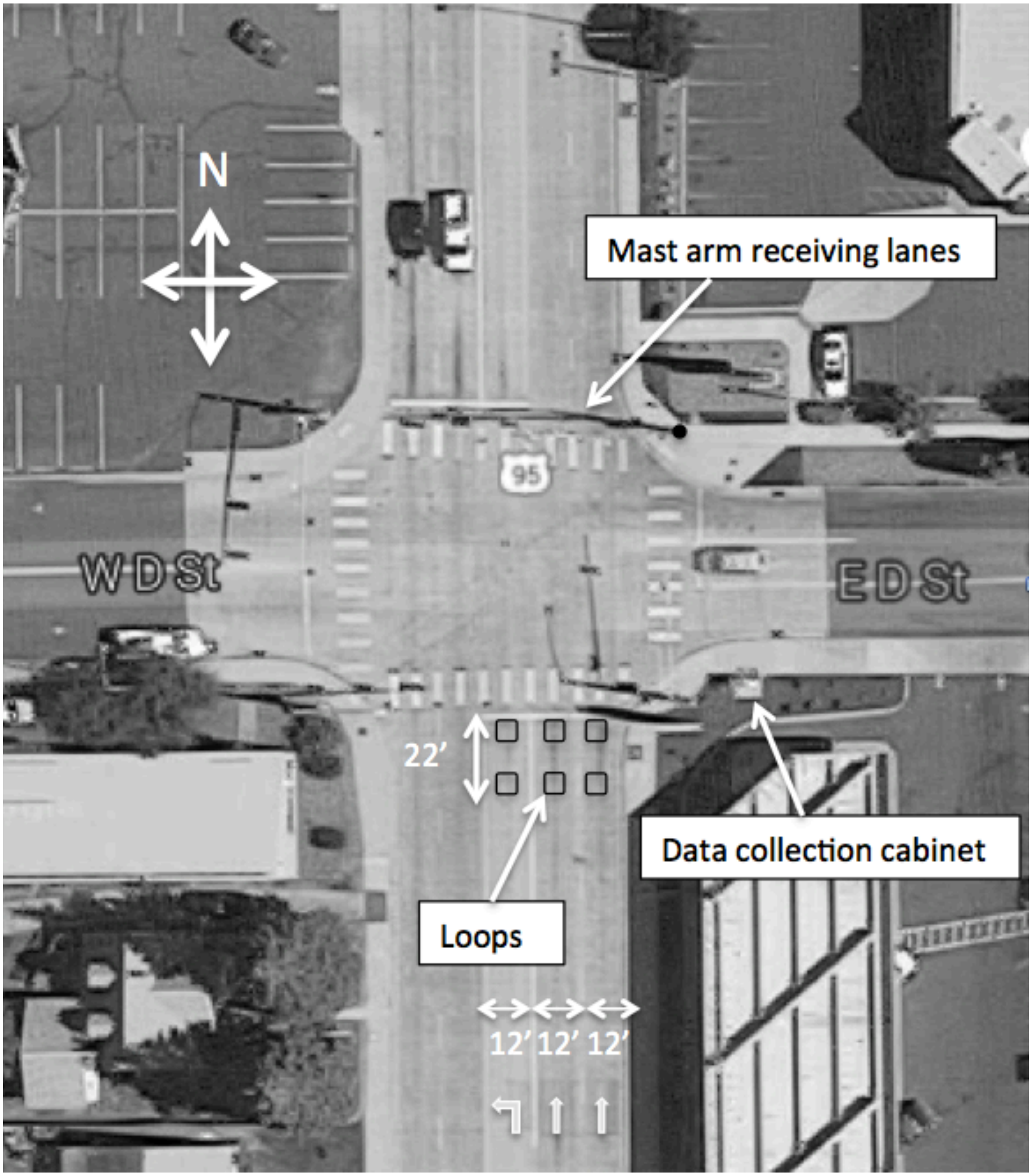

Figure 4: Intersection layout.

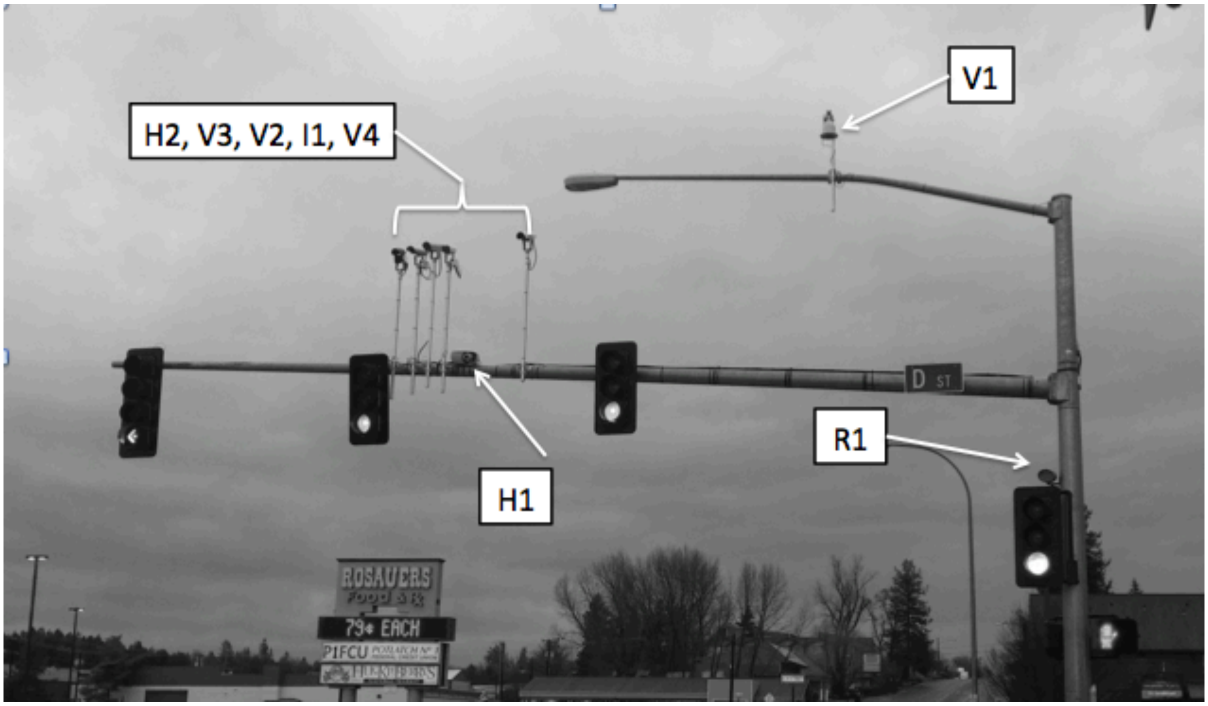

Figure 5: Sensors installed and mounted to mast arm.

Table 1: List of Tested Products

Abbreviation	Manufacturer, Product	Detector Type
V1	Aldis, Gridsmart	Video
V2	Iteris, RZ-4 Advanced WDR	Video
V3	Traficon, Video Detector	Video
V4	Peek, Color Video Traffic Detection Camera	Video
R1	MS Sedco, Intersector	Radar
I1	Traficon, FLIR FC-T Series	Infrared
H1	Iteris, Vantage Vector Hybrid	Hybrid
H2	Econolite, Autoscope Duo	Hybrid

A signal control cabinet housed all the equipment needed for data collection from the ILDs and eight other systems. The installation allowed for obtaining two types of data: (a) time stamps associated with activation and deactivation times of the loops and eight 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 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. Manufacturers were then given the option of making adjustments to the configuration their systems before official data collection began.

Figure 6: Screenshot captured from video recordings.

Evaluation Criteria

To evaluate the effectiveness of the eight systems, they were individually compared with the ILDs. 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.

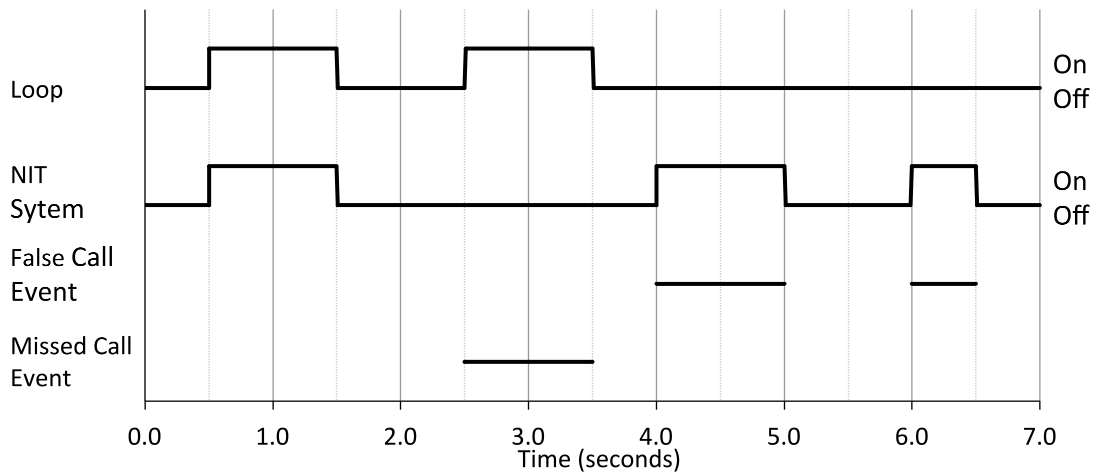

Figure 7: Example of false and missed detection concepts.

Algorithm Description

For computing the measures of performance, computer algorithms compared time stamps from ILDs to those of the eight 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.

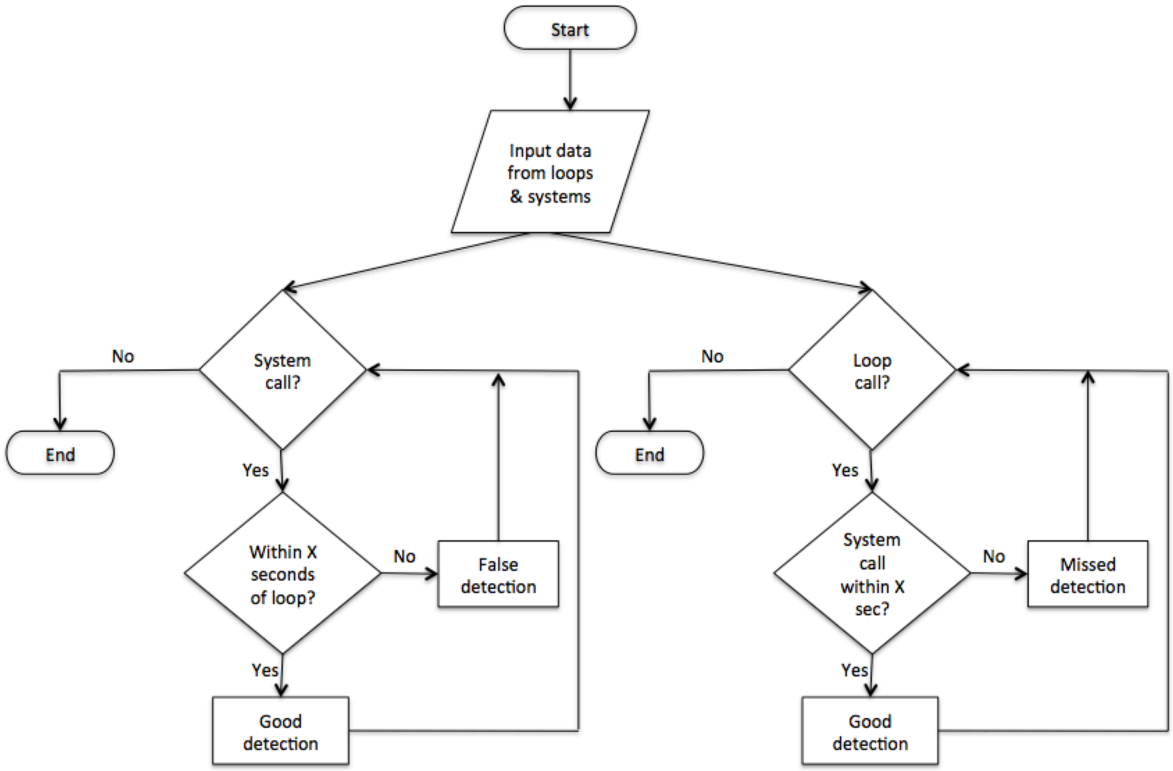

Figure 8: Algorithm process.

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.

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 in February, March, October, and November 2015 for the eight 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 2.

Favorable conditions combined data from the day and nighttime, 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 Beauford 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.

After data sets were selected, weather conditions were confirmed through records from the weather station at Pullman-Moscow Region 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 2: Datasets, Vehicle Counts, and Conditions

					60-min Data Points					
			Vehicle Counts		**Min. Wind Speed (mph)**	**Max. Wind Speed (mph)**	**Min. Wind Gust (mph)**	**Max. Wind Gust (mph)**	**Min. Hourly Precip. (in)**	**Max. Hourly Precip. (in)**
Conditions	**Dates**	**Hour Count**	**Thru**	**Left**						
Day	2/12/15 to 3/20/15	20	3699	1090	calm	16	--	19	0	0
Night	2/12/15 to 3/20/15	20	1699	581	calm	19	--	24	0	0.02
Favorable	2/12/15 to 3/20/15	20	2934	780	calm	12	--	17	0	0
Wind	3/12/15 to 3/16/16, 11/17/15	11	1518	379	20	49	25	69	0	0.26
Rain	3/11/15 to 3/18/15, 10/31/15	6	697	185	4	15	--	22	0.1	1.62
Snow	11/16/15	3	182	36	10	16	--	29	0.1	0.1

Chapter 4: Results

Data were analyzed from each stop bar zone. Results from each zone are described in this section and are identified by the following labels:

- Both through lanes = Zone 1
- Left-turn lane = Zone 2

With the exception of the ILDs and system H2, data from both through lanes was combined during the collection process. This allowed the detection accuracy of system H2 to be evaluated in each lane independently. The left through lane is considered Lane 1 and the right through lane is identified as Lane 2.

Error counts were evaluated for statistical significance by considering the number of ILD activations as the number of trials. On the basis of this, a two-tailed test of hypothesis was performed on the proportion of errors of each system under the different conditions. Equation 1 represents the proportion of false detections for each system and Equation 2 represents the proportion of missed detections for each system.

$$P_{false} = \frac{System\ False\ Detections}{Total\ ILD\ Detections} \qquad \text{Eq. 1}$$

$$P_{missed} = \frac{System\ Missed\ Detections}{Total\ ILD\ Detections} \qquad \text{Eq. 2}$$

The null hypothesis that the proportion of errors (P_1 and P_2) is the same for systems under different weather and/or lighting conditions is expressed as follows:

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 follows:

H_a: $P_1 \neq P_2$

If the difference in the proportion of errors were found to be statistically significant, an asterisk is used to indicate this significance in the tables presented in the following sections. The comparison of performance of the systems during day vs. night is presented next, followed by favorable vs. adverse conditions.

Performance During Day vs. Night

Performance of all systems in Zone 1 during daytime and nighttime can be seen in Table 3. Day and night performance was compared and the difference tested for statistical significance. Twenty hours of daylight conditions from several different days were combined and analyzed. Twenty hours of nighttime conditions from several different days were combined and analyzed.

In general, false detections in Zone 1 during the day were less than 6% for all systems. Nighttime analysis produced a higher frequency of false detections in all systems but H2 and R1. H2's performance actually improved during the night and produced no false detections in Zone 1. The frequency of false detections produced by R1 increased by only 0.4% during the night and was the only one not found to be statistically significantly different from daytime. V2, V4, I1, and H1 all produced over 20% false detections in the night.

Missed detections during daylight were less that 4% in Zone 1. R1, I1, and H2 did not experience any missed calls during the day. The frequency of missed calls during the nighttime analysis increased only slightly for some systems, and the frequency actually decreased in some systems. V4 experienced about 4.2% more missed calls a night. This is an interesting observation because the frequency of false detections in the V4 system is so high during the analysis period.

Table 3: Day vs. Night Individual System Performance in Zone 1

ZONE 1	**False Detections**		**Missed Detections**	
System	**Day**	**Night**	**Day**	**Night**
V1	4.7%	9.6%*	0.9%	0.7%
V2	4.7%	21.1%*	4.4%	3.4%*
V3	2.0%	30.7%*	2.6%	6.8%*
V4	5.4%	9.6%*	1.8%	2.0%
R1	1.4%	1.8%	0.0%	3.4%*
I1	5.4%	21.9%*	0.0%	2.0%*
H1	4.7%	26.3%*	3.5%	4.1%*
H2: Lane1	5.6%	0.0%*	0.0%	0.0%
H2: Lane2	4.3%	0.0%*	1.6%	0.0%*

* Indicates nighttime result is statistically significantly different than daytime.

The average performance of each system type can be found in Table 4. Radar performed with the greatest accuracy for false detections and all systems performed well (errors 3.2% or less) in terms of missed detections. All system types but radar saw a dramatic increase in false detections from day to night. Radar and Infrared both experienced no missed detections in the daytime analysis, and radar experienced the highest frequency of nighttime missed detections at 3.2%

Table 4: Day vs. Night Average Performances in Zone 1

ZONE 1	False Detections		Missed Detections	
System	**Day**	**Night**	**Day**	**Night**
Video	4.2%	17.8%*	2.4%	3.2%*
Radar	1.4%	1.8%*	0.0%	3.4%*
Infrared	5.4%	21.9%*	0.0%	2.0%*
Hybrid	4.8%	13.2%*	2.2%	2.1%*

* Indicates result is statistically significantly different than daytime.

Day and night performances from Zone 2 can be seen in Table 5. False detections in Zone 2 were significantly higher for both day and nighttime periods in most systems than in Zone 1. Review of the recorded images showed that vehicles turning left from the westbound approach would cut across the left-turn lane of the subject approach when it was unoccupied. This is likely the cause of the majority of false detections in Zone 2.

R1 had no false detections in either time period analyzed, and H1 experienced no false detections during the daytime analysis period. The increases in false detections between the day and night periods in V2, V4, I1, and H1 are consistent with the increases seen in Zone 1.

Missed detections were generally low for both analysis periods in Zone 2. The frequency of missed calls increased slightly for V3, R1, I1, and H1 during the night analysis. V4 had the largest increase of missed calls at 6.5%. V1 and V2 had a slight decease in missed calls during the night, which is consistent with the results from Zone 1.

Table 5: Day vs. Night Individual System Performance in Zone 2

Zone 2	False Detections		Missed Detections	
System	Day	Night	Day	Night
V1	35.0%	20.0%*	1.8%	1.1%*
V2	4.5%	64.3%*	6.9%	5.3%*
V3	18.2%	77.1%*	4.1%	10.6%*
V4	9.1%	0.0%*	2.7%	3.2%*
R1	0.0%	0.0%	0.0%	1.6%*
I1	63.6%	63.0%	0.0%	3.2%*
H1	22.7%	71.4%*	5.5%	6.4%*
H2	0.0%	10.0%*	0.0%	0.0%

* Indicates nighttime result is statistically significantly different than daytime.

The average performance of each system type can be seen in Table 6. Radar performed with the greatest accuracy in both the false and missed detections analyses. Radar experienced no false detections in day or night periods and no missed detections during the day. The errors experienced by the other systems in Zone 2 ranged from 11% to over 64%. All systems performed well in the missed detection analysis with the greatest error frequency equal to about 5%.

Table 6: Day vs. Night Average Performances in Zone 2

ZONE 2	False Detections		Missed Detections	
System	Day	Night	Day	Night
Video	31.4%	40.4%*	3.9%	5.1%*
Radar	0.0%	0.0%	0.0%	1.6%*
Infrared	63.6%	63.0%	0.0%	3.2%*
Hybrid	11.4%	40.7%*	2.8%	3.2%*

* Indicates result is statistically significantly different than daytime.

Performance in Favorable vs. Adverse Conditions

False Detections in Zone 1

Results from false detection performance of each system in Zone 1 for favorable and adverse conditions are shown in Table 7. In general, false detections had an occurrence of less than 11% in Zone 1 under all conditions. The performance of most systems during windy conditions degraded slightly compared to the performance in favorable conditions. Average increases in false detections were approximately 3%. The systems’ performances under rain and snow conditions were similar to wind performance in that most systems saw a degradation of several percent.

The proportions of false detections in adverse conditions were generally higher for V1, V2, V3, V4 and R1. Systems I1, and H2 saw the least increase in false detections in adverse weather conditions, and the performance of H1 actually improved. The performance of every system in wind, rain, and snow conditions were found to be statistically significantly different from favorable conditions performance.

Table 7: Favorable vs. Adverse Individual System False Detections in Zone 1

System	Favorable	Wind	Rain	Snow
V1	5.6%	7.2%*	6.1%*	8.0%*
V2	4.7%	6.9%*	4.2%*	6.7%*
V3	6.2%	7.3%*	5.9%*	23.9%*
V4	4.2%	8.3%*	9.9%*	10.9%*
R1	3.5%	6.1%*	4.5%*	7.0%*
I1	5.5%	5.8%*	5.1%*	6.5%*
H1	5.4%	2.0%*	4.6%*	14.0%*
H2: Lane1	4.9%	5.6%*	5.4%*	6.6%*
H2: Lane2	4.3%	5.2%*	4.1%*	5.8%*

* Indicates result is statistically significantly different than favorable.

Table 8 shows the average false detection performance of each system type in Zone 1. Radar produced the lease false detections in favorable weather with 3.5% errors. Hybrid performed with the greatest accuracy in wind and rain, and infrared experienced the least errors in snow with 6.5%. Video and hybrid both experienced an increase of about double from favorable to snow conditions.

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

System	Favorable	Wind	Rain	Snow
Video	5.2%	7.4%*	6.5%*	12.4%*
Radar	3.5%	6.1%*	5.5%*	7.0%*
Infrared	5.5%	5.8%*	5.1%*	6.5%*
Hybrid	5.0%	3.7%*	4.7%*	10.1%*

* Indicates result is statistically significantly different than favorable.

False Detections in Zone 2

Table 9 and Table 10 show results of the false detection analysis for favorable and adverse conditions in Zone 2. Zone 2 experienced significantly more false detections than Zone 1. Again, this can be attributed to drivers cutting across the left-turn lane of the subject approach. False detection proportions in Zone 2 for all systems in all conditions ranged from about 10% to over 36%. However, Zone 2 results differed from Zone 1 because some systems experienced a decrease in false detections during adverse conditions. This suggests that mounting issues are not necessarily the cause of the false detections in Zone 1.

Table 9: Favorable vs. Adverse False Detections in Zone 2

System	Favorable	Wind	Rain	Snow
V1	26.2%	26.90%	31.3%*	33.8%*
V2	15.0%	17.7%*	18.6%*	20.5%*
V3	18.1%	11.3%*	24.1%*	21.4%*
V4	31.8%	20.8%*	37.9%*	36.2%*
R1	11.0%	14.6%*	14.3%*	16.0%*
I1	30.0%	18.3%*	26.3%*	29.8%
H1	22.2%	21.40%	14.7%*	23.3%*
H2	15.7%	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 can be found in Table 10. All systems experienced significant error frequencies ranging from 11% to 30%. Radar performed with the most accuracy in all weather conditions. Hybrid and radar had very similar performance in rain.

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

System	Favorable	Wind	Rain	Snow
Video	22.8%	19.2%*	28.0%*	28.0%*
Radar	11.0%	14.6%*	14.3%*	16.0%*
Infrared	30.0%	18.3%*	26.3%*	29.8%*
Hybrid	19.0%	20.4%*	14.4%*	21.5%*

* Indicates result is statistically significantly different than favorable.

Missed Detections in Zone 1

Results for Zone 1 missed detection analysis can be found in Table 11. Missed detections experienced in Zone 1 during favorable conditions were lower than 3% for every system. Performance degradation was limited to about 1.5% during adverse conditions on all systems, and V3 experienced a performance increase of about 0.5% during rain and snow. Although the performance differences were small between favorable and adverse conditions, most adverse condition results were found to be statistically significantly different than favorable results.

Table 11: Favorable vs. Adverse Missed Detection in Zone 1

System	Favorable	Wind	Rain	Snow
V1	1.3%	1.8%*	1.6%*	1.7%*
V2	1.5%	1.8%*	1.9%*	1.8%*
V3	1.0%	1.4%*	0.80%	1.0%
V4	2.1%	2.3%*	2.8%*	2.7%*
R1	0.7%	1.4%*	1.6%*	1.7%*
I1	1.1%	1.7%*	1.7%*	2.3%*
H1	1.3%	1.7%*	1.8%*	1.7%*
H2: Lane1	1.5%	1.70%	2.6%*	2.1%*
H2: Lane2	1.6%	1.2%*	2.4%*	1.8%

* Indicates result is statistically significantly different than favorable.

The average missed detection performance in Zone 1 can be found in Table 12. All systems performed well under all conditions and all error frequencies were less than 3%. The performances of each system type were very similar.

Table 12: Favorable vs. Adverse Average Missed Detections in Zone 1

System	Favorable	Wind	Rain	Snow
Video	1.5%	1.8%*	1.8%*	1.8%*
Radar	0.7%	1.4%*	1.6%*	1.7%*
Infrared	1.1%	1.7%*	1.7%*	2.3%*
Hybrid	1.4%	1.6%	2.2%*	2.8%*

* Indicates result is statistically significantly different than favorable.

Missed Detections in Zone 2

Missed detection analysis results from Zone 2 can be found in Table 13 and Table 14. The proportions of missed detections in Zone 2 were similar to those in Zone 1. Missed detection frequencies were less than 3% for all systems under all conditions, and system performance degradation was limited to about 1.5% during adverse weather conditions. Differences between favorable and adverse weather conditions were all found to be statistically significantly different.

Table 13: Favorable vs. Adverse Missed Detection in Zone 2

System	Favorable	Wind	Rain	Snow
V1	1.0%	1.9%*	2.0%*	1.8%*
V2	1.3%	2.3%*	2.0%*	1.9%*
V3	1.2%	2.5%*	2.0%*	2.7%*
V4	1.4%	2.3%*	2.1%*	2.0%*
R1	1.9%	2.6%*	2.1%*	2.1%*
I1	1.2%	2.1%*	1.8%*	2.2%*
H1	1.0%	2.4%*	1.6%*	1.8%*
H2	1.6%	2.7%*	2.1%*	2.2%*

* Indicates result is statistically significantly different than favorable.

Table 14 shows the system averages for the missed detection analysis in Zone 2. All systems performed well under all conditions and all error frequencies were less than 3%. The performances of each system type were very similar.

Table 14: Favorable vs. Adverse Average Missed Detections in Zone 2

System	Favorable	Wind	Rain	Snow
Video	1.2%	2.3%*	2.0%*	2.1%*
Radar	1.9%	2.6%*	2.1%*	2.1%*
Infrared	1.2%	2.1%*	1.8%*	2.2%*
Hybrid	1.3%	2.6%*	1.9%*	2.0%*

* Indicates result is statistically significantly different than favorable.

Chapter 5: Conclusion

5.1 Discussion and Recommendations

Field-testing was conducted to evaluate eight 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 the performance under windy, rainy, and snowy conditions.

Results indicate that the detection performance of most systems was affected negatively when operating at night. One video system had an increase in false detections of over 25% between day and night, however one hybrid system actually experienced fewer (from about 5% down to 0%) errors during the nighttime analysis. In comparison with the day, only one system's proportion of Zone 1 nighttime false detections was not found to be statistically significantly different. In terms of system type, all of the video detection systems nighttime errors were statistically significantly different than the daytime. The same statistical results were found for both hybrid systems.

False detection results for Zone 2 were significantly higher than Zone 1 under all conditions. Error results ranged from 0% (radar) to over 64% (infrared). This was determined to be due to left-turning vehicles from the east approach cutting across the left-turn lane of the subject approach when it was unoccupied. A tapered left turn lane is recommended here to minimize the amount of false detections.

Missed detections in Zone 1 and Zone 2 were generally low for all conditions. The highest frequency of missed detections was about 10% for the night analysis of a video system. The lowest missed detection error frequency was 0%, experienced by infrared, radar and hybrid systems during the day. The proportions of missed detections were slightly lower in Zone 2, and the significantly higher numbers of false detections experienced in Zone 2 could be the cause of this.

5.2 Future Work

Additional work could be completed to further compare the alternative systems. An analysis comparing each video system with each other could be performed to determine the most accurate video system under each condition. The same comparison could be done for the two hybrid systems. The results of this analysis could be used to determine the best video or hybrid system for the implementation area based on local climate and weather conditions.

Data collected during snowy conditions was limited and what was collected had very low traffic volumes. Additional data collection and analysis is recommended to improve the reliability of the snow condition results.

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