FIELD TEST OF VEHICLE DETECTION TECHNOLOGIES FOR USE AT SIGNALIZED INTERSECTIONS IN WINNIPEG

by

Colleen Flather, P. Eng.

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Department of Civil Engineering
University of Manitoba
Winnipeg, Manitoba

ABSTRACT

The research analyzes the operating performance of three vehicle detection technologies for use in the City of Winnipeg. The technologies were: Autoscope Encore (video sensor), Iteris Vantage Edge2 (video sensor) and Matrix Wavetronix SmartSensor (microwave sensor). The sensors were tested in the two eastbound lanes and two turning lanes of the intersection of Bishop Grandin Blvd and St. Mary's Road in Winnipeg, Manitoba. The research considered 24 weather, illumination, wind and traffic conditions. Testing and analysis was completed at the stop bar, and advance zone as well as for count performance. Sensitivity is a measure of the number of calls missed by the sensor. In terms of sensitivity, Iteris performed best overall, performing with greater sensitivity than Autoscope and Matrix in 17 of 24 conditions at the stop bar and outperforming in 11 of 12 conditions for advanced zone detection in this research. For count performance the Iteris had better accuracy when compared to ground truth established by Miovision Technologies than Autoscope and Matrix.

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DEDICATION

This research is dedicated to my husband, Wayne Flather, and my children, Abby and Jack. My parents especially deserve a wealth of gratitude and appreciation for their support. Without the endless support and patience of my family and friends this research and degree would never have come to fruition. I love you all with a depth I never knew possible. Thank you.

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1. INTRODUCTION

1.1. RESEARCH PURPOSE

The purpose of this research was to evaluate the performance of three vehicle detection sensors as a function of weather, illumination, and traffic conditions. Detector performance is measured in terms of sensitivity. Sensitivity refers to a detector's ability to detect vehicles within a defined zone. Any vehicle not detected in a zone within a set time threshold is considered a "missed" call and reduces the sensor's sensitivity rating. The evaluation was done for stop bar zone detection, advanced zone detection and counting. The stop bar is commonly referred to as the stop line; the advance zone is located prior to the stop bar in the area commonly referred to as the dilemma zone.

The evaluated sensor products were: (1) Wavetronix SmartSensor (microwave), (2) Autoscope Encore (video), and (3) Iteris Vantage Edge 2 (video) sensors.

1.2. BACKGROUND AND NEED

Historically the City of Winnipeg has used inductive loop sensors for vehicle detection at traffic signals, providing accurate detection data of 98 percent or greater if installed and maintained properly (Foord & Morgan, 2011). Both Edgar (2002) and Middleton (2002) report loop accuracies of 93 to 98 percent. The intrusive installation and maintenance of inductive loops create problems associated with traffic disruption, pavement degradation, and damage to the loops due to construction. In addition, loops are limited in their placement; they are not feasible on bridge decks or decorative pavement and not replaceable during cold weather (Rhodes, et al., 2006).

Winnipeg needs a technology that overcomes the maintenance and installation problems associated with loops, performs adequately under Winnipeg's extreme weather conditions, and provides comprehensive and reliable data for the development of a traffic monitoring program.

Vehicle detection technologies include video, microwave radar, infrared, magnetic, ultrasonic, passive acoustic array, and light emitting diode (LED) optical technologies, as well as combined technologies such as passive infrared, ultrasonic, and radar sensors. This research selected two video technologies and one microwave radar technology to be evaluated due to their reported advantages of: ease of installation, maintenance with minimal traffic disruptions, broader range of traffic and incident-related data capabilities, and ease of data transmission to traffic monitoring centers (UMTIG, 2011). The video sensors also have the advantage of providing visual monitoring for validation of data.

With the continuing advancements of vehicle detection technologies, there was a need to test the performance of new and upgraded sensor products to evaluate their performance in various weather, traffic and illumination conditions to identify the most suitable product for use by the City of Winnipeg.

1.3. OBJECTIVES AND SCOPE

The objectives of this research were to:

- Develop an understanding about existing technologies used for vehicle detection and counting.
- Design and implement a field test to evaluate three technologies for potential application to Winnipeg.
- Evaluate the sensitivity of the three technologies selected with respect to weather, illumination and traffic volume.

The research was conducted in Winnipeg, Manitoba over a two-year period starting in July 2011 and concluding in May 2013.

1.4. THESIS ORGANIZATION

This thesis is organized into five chapters. *Chapter 2* summarizes the findings from the environmental scan conducted for the selection of sensor products for the field test. The environmental scan involved a literature review, jurisdictional survey, and vendor interviews. Using the information collected during the environmental scan, three sensor products were selected for testing.

Chapter 3 discusses the methodology developed and applied to the field test to evaluate the performance of each selected vehicle detection sensor. The field test was designed based on the literature review and interviews conducted with experienced personnel in this area of research. The field test design consisted of five components: site selection, installation and data collection process, assessed conditions, sample size and evaluation methodology.

Chapter 4 presents the results of the stop bar and advance detection zones sensitivity performance of the Autoscope video, *Iteris far* video, and Wavetronix microwave sensors, as well as the count performance of the Autoscope video, *Iteris near* video, and *Iteris far* video sensors. Analysis was performed as a function of varying weather, illumination, and traffic conditions where possible. Also included in this chapter is a discussion of the limitations of this research and future research opportunities.

Chapter 5 discusses research findings and conclusions for the research.

2. ENVIRONMENTAL SCAN

This Chapter summarizes the findings from the environmental scan conducted for the selection of sensor products for the field test. The environmental scan involved a literature review, jurisdictional survey, and vendor interviews. Using the information collected during the environmental scan, three sensor products were selected for testing. The technologies selected were non-intrusive, meaning they were mounted either above the roadway surface or adjacent to the roadway, and were not embedded into the pavement or road bed.

2.1. LITERATURE REVIEW

A comprehensive review of literature was conducted to identify current vehicle detection technologies and products, their performance accuracy levels, and any installation, maintenance, and operational issues associated with them. Due to the constant evolution of vehicle detection technologies, the literature review was limited to literature from the past decade (post year 2000). This section summarizes the findings from the literature review. The details of the literature review, including principles of operation and findings of previous studies for each detector type are included in Appendix A.

The issues identified in the literature aided in selecting the conditions used for testing in this study. The literature review revealed studies discussing the performance of different vehicle detection technology types and products as listed in Table 1 (intrusive technologies) and Table 2 (non-intrusive technologies).

Table 1: Summary of Attributes of Intrusive Vehicle Detection Sensors

Intrusive Technologies – are technologies that are embedded in the roadway or subgrade of the roadway or are taped or otherwise attached to the surface of the roadway.			
Type	**Applications & Use**	**Advantages**	**Disadvantages**
Inductive Loop Detectors	• vehicle passage • presence • count • lane occupancy	• mature technology • insensitive to adverse weather • sufficient accuracy for most applications	• installation requires pavement cuts, requiring a lane closure • multiple loops are typically required to monitor an intersection
Magnetic Detectors	• traffic actuated signal control • count • lane occupancy • speed data	• well suited for cold weather • insensitive to adverse weather • less susceptible to traffic • some models can be installed via boring	• installation requires pavement cuts or boring, requiring a lane closure during installation • cannot detect stopped vehicles
Magnometer	• vehicle presence detection • count • traffic actuated signal control • locate, track and classify vehicles • occupancy • speed	• can identify stopped vehicles • survive longer in crumbling pavements • can accurately detect closely spaced vehicles	• installation requires pavement cuts or boring, requiring a lane closure • some models have small detection zones, requiring multiple units for full lane detection • two closely spaced monitors required for determining occupancy and speed
Piezoelectric	• count • classification • speed • vehicle weight	• can differentiate individual axles with a high degree of accuracy • have improved speed accuracy • classify based on weight	• installation requires pavement cuts or boring, requiring a lane closure • resurfacing of roadway can require reinstallation • can be sensitive to pavement temperature

Sources: The Vehicle Detector Clearinghouse, FHWA, 2007
Traffic Detector Handbook: Third Edition-Volume 1, FHWA, 2006
Martin et. al., Detector Technology Evaluation, 2003

Table 2: Summary of Attributes of Non-Intrusive Vehicle Detection Sensors

Non-Intrusive Technologies – are technologies that are mounted either above the roadway surface or adjacent to the roadway and are therefore not embedded in or on the pavement.			
Type	**Applications & Use**	**Advantages**	**Disadvantages**
Video Image Processing	• vehicle presence • volume • lane occupancy • speed • classification • scene analysis • dwell time • lane change • incident detection • surveillance	• wide range of capabilities • algorithms can identify non-traffic factors such as change in illumination, reflections, shadows, camera motion, inclement weather, vehicle induced vibration • cost effective	• vulnerability to obstructions • susceptible to interference from inclement weather, shadows, occlusion, camera motion due to strong winds, day to night transition, water, salt, grime • proper setup is essential to achieving satisfactory performance
Microwave Radar two types Continuous Wave (CW)Doppler and Frequency Modulated Continuous Wave (FMCW)	• mounting at the side of the intersection allows for monitoring of several lanes • direction dependent vehicle detection • volume • speed • traffic actuated signal control •	• insensitive to adverse weather • multiple lane operation • direct speed measurement	• Doppler sensors cannot detect stopped vehicles • Doppler sensor has poor count performance
Infrared Sensors	• volume • vehicle presence • density • vehicle length • speed • number of axles • classification • lane occupancy	• transmit multiple signals for more accurate measurement of vehicle position, speed and class • multiple lane operation	• require periodic lens cleaning, requiring a lane closure • reflection from the sun can cause problems • adverse weather can negatively impact performance

Sources: The Vehicle Detector Clearinghouse, FHWA, 2007
Traffic Detector Handbook: Third Edition-Volume 1, FHWA, 2006

Table 2 continued: Summary of Attributes of Non-Intrusive Vehicle Detection Sensors

• **Non-Intrusive Technologies** – are technologies that are mounted either above the roadway surface or adjacent to the roadway and are therefore not embedded in or on the pavement.			
Type	**Applications & Use**	**Advantages**	**Disadvantages**
Ultrasonic Sensors	• volume • vehicle presence • lane occupancy • speed • count • can be combined with other technologies for expanded capabilities	• multiple lane operation	• limited by extreme air turbulence • can be sensitive to temperature • some models require a device for each lane of detection
Passive Acoustic Array Sensors	• used for over-roadway applications such as bridges • volume • lane occupancy • average speed • vehicle presence	• multiple lane operation	• limited by strong winds, heavy snowfall, precipitation • cold temperatures can affect count ability • loud vehicles in adjacent lanes can cause false calls • not recommended for slow moving or stop-and-go traffic

Sources: The Vehicle Detector Clearinghouse, FHWA, 2007
Traffic Detector Handbook: Third Edition-Volume 1, FHWA, 2006

The literature review revealed studies discussing the performance of different vehicle detection technology types and sensor products as listed in Table 3.

Table 3: Technology Types and Products

Magnetometer	**Video**	**Microwave**
• Sensys • Canoga • Microloops	• Autoscope Solo Terra • Traficon Traficam • Iteris Vantage Edge 2 • Peek Unitrak	• Wavetronix SmartSensor HD • Wavetronix SmartSensor Advance • RTMS
Infrared	**Passive Acoustic Array**	**Combined Technologies**
• TIRTL	• SmarTek SAS-1 • SmartSonic TSS-1	• ASIM DT 272 • ASIM TT 262

Source: Survey conducted by University of Manitoba Transport Information Group, 2011

The literature did not identify a single superior detector; however, it highlighted strengths and weaknesses of different technology types and products in different applications. The issues identified in the literature review aided in selecting conditions used for analysis in this research. The following summarizes the literature findings:

- For the performance of video detection lighting is the main concern, where night periods have more detection problems due to detection by vehicle headlights only. During day time, glare and shadows have been a concern. (Medina, et al., 2009)
- Snow in both day and night significantly impact the performance of video detectors, with Peek Unitrak, Autoscope Solo Pro, and Iteris Vantage Edge 2 placing over 50 percent false calls at both stop bar and advanced detection locations (Medina, et al., 2009).
- The Wavetronix SmartSensor Advance detector, used for advanced detection, was found to be better at detecting gaps in the stream of traffic than video detection systems and provides good dilemma zone protection. Also, it is not affected by light or weather conditions. However, it produces over-counting of vehicles due to double detection of larger vehicles, turning volumes, and standing queues (Middleton, et al., 2009).
- Occlusion is a concern for side or overhead mounted sensors, where larger vehicles can block the detection of other vehicles in adjacent lanes or vehicles behind the larger vehicle (The Vehicle Detector Clearinghouse, 2007).
- Medina et al. (2008) and Medina et al. (2009) evaluated the performance of Image Sensing Systems-Autoscope Solo Pro (version 8.13) , Peek Unitrak (version 2.2), and Iteris Edge 2 vehicle detection systems (VDS) at both advanced and stop bar detection areas under various configuration changes, illumination conditions, windy conditions, and adverse weather conditions. The three devices were tested under

five illumination conditions: dawn, sunny morning (long shadows), cloudy noon, dusk, and night. Detection errors were the lowest in cloudy noon illumination conditions. Missed calls increased for only one VDS at the stop bar and there were only minor changes in the advance locations (Medina, et al., 2009).

- Medina et al. (2008) and Medina et al. (2009) studied the effects of various adverse weather conditions and found that the video detector’s performance was not greatly impacted under daytime light fog or rain conditions without wind, but were significantly impacted by dense fog and snow in daytime, and snow and rain in night time.
- Microwave radar technologies are typically insensitive to harsh weather conditions at the relatively short ranges encountered in traffic management applications (U.S. Federal Highway Administration, 2006).
- Environmental factors can significantly impact the capabilities and performance of non-intrusive technologies. Sensors have the tendency to work well under certain conditions and poorly under others (Associated Engineering, 2010).
- In congested flow count accuracy decreases, with video detection devices under counting by ten to 25 percent, as speed decreases (Middleton & Parker, 2002).

Information gained from the literature review was used in conjunction with the results of the jurisdictional survey, to help aide in the selection of technologies for this research. The following section describes information obtained from the jurisdictional survey.

2.2. JURISDICTIONAL SURVEY

As a part of this research a survey was distributed to 299 jurisdictions in Canada and United States (U.S.) to identify their preferred advanced vehicle detection product, products currently in testing, and products other than the preferred, which have provided positive results regarding detection, counting and classifying. An expanded list of survey responses are included in Appendix B.

The survey included 221 Canadian jurisdictions and 78 U.S. jurisdictions. The survey was conducted over a two week period from July 28, 2011 to August 12, 2011. Approximately 12 percent (39 of 299) of the surveyed jurisdictions replied to the survey; of these, 22 responses provided an answer for their preferred advanced vehicle detection product (other than inductive loop sensors).

Each jurisdiction was asked for information on their experiences with vehicle detection technologies, including the make and model of detector used, the number of intersections with vehicle detectors in use, whether the stop bar and advanced zones were being monitored and if the jurisdiction was using the classification capabilities of the device. Along with functionality at the stop bar and advanced zone, the jurisdictions were asked if they were using the sensitivity function for missed calls, or the selectivity function for false calls. Table 4 provides a summary of this information obtained from the summary. From this table it is notable that there were twelve jurisdictions using Autoscope Solo Terra, all of which used the sensitivity function at the stop bar. Also of note were the Iteris Vantage video detector and Wavetronix SmartSensor Matrix microwave radar sensor with two jurisdictions each using these products.

Table 4: Survey responses on preferred product functionality and performance

Technology type, manufacturer, model, and jurisdiction	Total signalized intersections	Intersection installations	Stop bar detection			Advanced detection			Vehicle counting			Vehicle classification	
			Used in jurisdiction	Sensitivity	Selectivity	Used in jurisdiction	Sensitivity	Selectivity	Used in jurisdiction	Sensitivity	Selectivity	Used in jurisdiction	Accuracy (percent)
Magnetometer – Sensys													
Owen Sound, ON	22	4	+	● green	● blue	▬	--	--	▬	--	--	▬	--
Vancouver, BC	821	21	▬	--	--	▬	--	--	+	--	--	▬	--
Video – Autoscope Solo Terra													
Township of Langley, BC	90	71	+	● green	● blue	▬	--	--	+	● blue	● blue	--	--
Columbus, OH	1000	50	+	● green	● green	✖	--	--	--	--	--	--	--
Vernon, BC	34	8	+	● green	● green	▬	--	--	--	--	--	▬	--
Essex County, ON	42	3	+	--	--	▬	--	--	▬	--	--	▬	--
Region of Halton, ON	165	20	+	● green	● green	✖	--	--	+	--	--	✖	--
Okotoks, AB	17	14	+	● green	● blue	▬	--	--	+	● green	● orange	▬	--
Region of Durham, ON	550	10	+	● green	● green	▬	--	--	+	● green	--	▬	95
Kelowa, BC	106	45	+	● green	● green	▬	--	--	+	● green	● green	▬	95
Lethbridge, AB	120	10	+	● blue	● blue	--	--	--	--	--	--	--	--
Milton, ON	36	5	--	--	--	+	● blue	● blue	--	--	--	--	--
Greater Sudbury, ON	115	4	+	● green	● green	+	--	--	▬	--	● green	▬	--
Oakville, ON	324	30	+	● green	● green	+	● green	● green	▬	--	--	▬	--
Video – Iteris Vantage													
Lansing, MI	--	20	--	● blue	● blue	+	● blue	● green	▬	--	--	▬	--
Orlando, FL	465	36	+	● green	● green	--	--	--	▬	--	--	--	--
Video – Naztec													
Newark, NJ	450	11	+	--	--	▬	--	--	▬	--	--	▬	--
Video – Traficon Traficam													
Greater Sudbury, ON	115	4	+	● green	● green	+	--	--	▬	--	● green	▬	--
Microwave – Wavetronix SmartSensor Matrix													
New Glasgow, NS	16	6	+	● green	● green	✖	● green	● green	+	--	--	--	80
Mississauga, ON	512	1	+	● green	● green	--	--	--	--	--	--	--	--
Microwave – MS Sedco TC26B													
R.M. of Wood Buffalo, AB	41	14	+	--	--	--	--	--	--	--	--	--	--
LED with 3D optical sensor – Tomar Strobecom II													
Peterborough, ON	119	60	--	--	--	+	--	--	--	--	--	--	--

+ represents that the function of the product is used

✖ represents that the function of the product is available but not used due to unsatisfactory performance

▬ represents that the function of the product is available but not used due to reasons other than unsatisfactory performance

-- represents no response given for the question

● green > 95 percent | ● blue 85 – 95 percent | ● orange 75 – 85 percent | ● red < 75 percent

Source: Survey conducted by University of Manitoba Transport Information Group, 2011

2.3. SELECTION OF SENSOR TECHNOLOGIES FOR FIELD TEST

Interviews were conducted with vendors of the 10 products identified in the jurisdictional survey as preferred or being tested at the time of the survey. Specific product information, including cost, capabilities, installation and maintenance requirements, and upgraded products was obtained from the vendor interviews. While the environmental scan considered intrusive technologies along with non-intrusive, the technologies meeting all of the needs of the City of Winnipeg were non-intrusive. Table 5 presents the 10 considered sensor products and associated information on functionalities and cost obtained from vendor interviews. The products were ranked high, medium, or low for recommended field testing based on the following criteria that met the needs of the City of Winnipeg:

- Two or more jurisdictions identified the product as a preferred product or undergoing testing
- Literature was available on the field testing of the product
- The product provides wireless capabilities
- The product provides remote viewing capabilities
- The product provides two or more functionalities (i.e. count, detection, classification)

Table 6 provides the latest upgrades to the Autoscope, Traficon, and MS Sedco sensor products. The selected products based on the set criteria are: Autoscope Encore video, Iteris Vantage Edge 2 video, Aldis Gridsmart video, Wavetronix Smartsensor, and Sensys Wireless magnetometers. Autoscope, Iteris, and Wavetronix agreed to participate in the research.

Table 5: Vendor information on preferred products and products currently being tested

Tab number	Recommendation rating	Technology, manufacturer, model	Functionality: Stop bar detection	Functionality: Advanced detection	Functionality: Counting	Functionality: Classification	Functionality: Speed	Capital cost* (CAD)	System life (years)	# of detection zones	Wireless capability	Remote Viewing
		Magnetometer										
1	High	Sensys VDS 240	+	+	+	+	+	--	10	1	yes	no
		Video										
2	High	Autoscope Solo Terra	+	+	+	+	+	19,700	10	100	yes	yes
3	High	Iteris Vantage	+	+	+	+	+	20,000	15	24	yes	yes
4	Low	Naztec colour camera						--				
5	Medium	Traficon Trafficam	+	+	+	+	+	--		8	yes	no
6	High	Aldis Gridsmart	+	+	+	+	+	18,200	12	24	yes	yes
		Microwave										
7	High	Wavetronix Smartsensor Matrix	+		+			24,000	10	16	yes	no
8	Low	MS Sedco TC26B	+	+				4,400	12	1	no	no
		LED										
9	Low	Tomar Strobecom II	Pre-emption					3,500	17	1	no	no
10	Low	LeddarTech Leddar d-tec	+					22,100		4	no	no

+ represents that the product has the capability

-- no information provided

*Capital cost is the cost for stop bar detection at a 4-leg intersection with 2 lanes on each leg.

Source: Vendor survey conducted by University of Manitoba Transport Information Group, 2011

Table 6: Vendor information on new upgraded products

Tab number	Recommendation rating	Technology, manufacturer, model	Functionality: Stop bar detection	Functionality: Advanced detection	Functionality: Counting	Functionality: Classification	Functionality: Speed	Capital cost*(CAD)	System life (years)	# of detection zones	Wireless capability	Remote Viewing
		Video										
11		Autoscope ENCORE	+	+	+	+	+	19,700		100	yes	yes
11		Traficon X-stream	+	+	+	+	+	--		24	yes	yes
		Microwave										
11		MS Sedco Intersector	+	+	+			22,600	12	8	yes	yes

+ represents that the product has the capability

-- no information provided

*Capital cost is the cost for stop bar detection at a 4-leg intersection with 2 lanes on each leg.

Source: Vendor survey conducted by University of Manitoba Transport Information Group, 2011

3. METHODOLOGY FOR THE FIELD TEST

This Chapter discusses the methodology developed and applied to the field test to evaluate the performance of each selected vehicle detection sensor. The field test was designed based on the literature review and interviews conducted with experienced personnel in this area of research. The field test design comprises five components: site selection, installation and data collection process, assessed conditions, sample size and evaluation methodology.

3.1. SITE SELECTION

The selected site for the field test was the intersection of Bishop Grandin Blvd and St. Mary's Rd, Winnipeg, Manitoba. This intersection is representative of a location where the City of Winnipeg intends to install vehicle detection technologies in the future. The intersection was selected based on the following criteria and characteristics:

- Typical larger intersection, consisting of two through lanes and two left-turn only lanes.
- Urban traffic conditions, with congestion for both the morning and afternoon peak periods and lower volumes with free flow conditions in off-peak periods.
- Used by a variety of modes, motorized and non-motorized.
- Relatively high speed limit of 80 km/h on approach.
- Inductive loop detectors currently installed at the intersection for stop bar and advance detection to be used to establish ground truth. Ground truth refers to the actual number of vehicles passing through a zone. Ground truth can be established using a known high sensitivity device, or with manual identification.

The intersection layout is shown in Figure 1. The eastbound approach of Bishop Grandin Blvd was monitored with the detection technologies to capture the effects of glare during sunset, as well as the effect of shadows during both sunrise and sunset. This approach has an Average Weekday Daily Traffic (AWDT) of 24,350 vehicles per day.

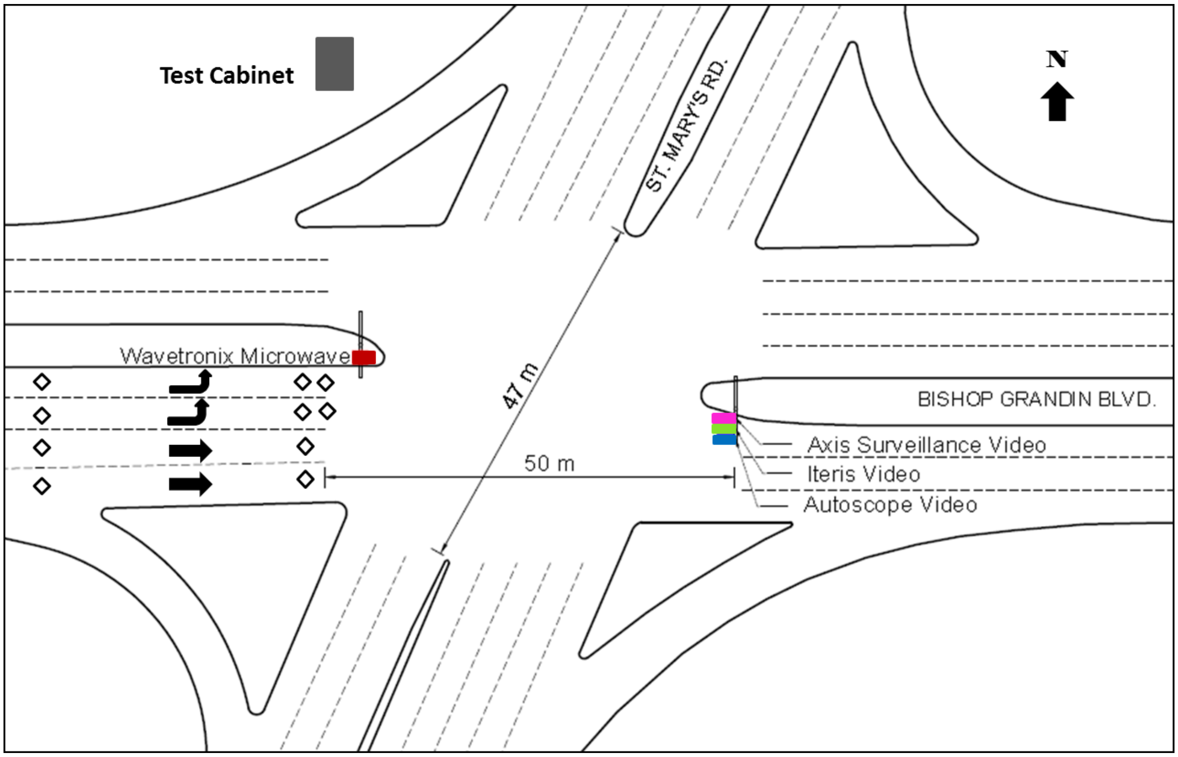


Figure 1: Field Test Intersection
(Not to scale)

3.2. SENSOR INSTALLATION AND DATA COLLECTION PROCESS

The vehicle detection sensors were installed with full supervision of the manufacturer or distributor representatives. Each sensor representative was provided a two-day period to install and calibrate the sensors, as well as provide training to the City of Winnipeg and University of Manitoba personnel on the installation, maintenance, and operation of the sensors. Axis network video cameras were also installed for ground truth surveillance of traffic at the intersection, allowing manual verification of detection errors.

The Iteris (referred to as *Iteris far*) and Autoscope video sensors and the Axis surveillance camera were mounted on a 10.7 metre (35 ft.) joint use pole on the davit arm, aligned between the eastbound through and left-turn lanes. The Iteris and

Autoscope video sensors were mounted at a height of approximately 12.2 metres (40 ft.) and 11.3 metres (37 ft.), respectively, in order to detect the advance locations. Figure 2 shows the mounting configurations of the overhead video vehicle detection sensors.

Figure 2: Overhead-mounted video detection sensors (*Iteris far* and Autoscope) and surveillance camera

An additional Iteris video sensor, referred to as *Iteris near*, was installed on the approach median, looking downward onto the stop bar traffic in a side-mounted configuration. The *Iteris near* configuration is shown in Figure 3

Since video sensors count and classify vehicles by identifying the gaps between vehicles, the downward facing configuration (*Iteris near*) was installed to evaluate whether the enhanced view of vehicle gaps resulted in improved count performance relative to the overhead forward facing configuration (*Iteris far*).

The microwave Wavetronix SmartSensor was also installed on the approach median, in a side-mount configuration. The sensor was initially mounted on the shaft at the typical recommended height of 4.6 metre (15 ft.). However, through observation of the detection performance, occlusion was noticed in the lanes further from the sensor. Therefore, the sensor was moved further away from the stop bar and mounted on the traffic signal Y-davit arm pole at a higher, at approximately 6.1 metres (20 ft.).

Figure 3: Side-mounted detection sensors *Iteris near* and microwave Wavetronix

The sensors were not controlling the intersection, however, the inputs from each device were being recorded to verify and compare their detection performance relative to the inductive loop sensors. The inputs from all detection zones were scanned every 10th of a second, similar to a standard Type 170 traffic signal controller. A customized data collection methodology was designed by City of Winnipeg personnel to allow the use of one data-logger to record detection inputs from multiple monitoring zones of multiple sensors. This saved significant cost and saved space in the signal controller cabinet. The count and classification data were provided by the sensor's own capability and storage methods using each sensor's specific software provided by the manufacturers.

To maximize the use of existing data-loggers on hand, and to ensure that all input measurements were taken at the same time due to differences in sensor clock times, digital-to-analog conversion boards were designed. Rather than reading the digital "1" or "0" measurement, each input gave a specific resistance value which was converted to the digital equivalent. This saved memory and reduced the number of data loggers and additional clock synchronizing required otherwise.

3.3. CONDITIONS USED FOR ANALYSIS

Four categories of conditions were determined for assessment based on issues identified in the environmental scan: adverse weather conditions, illumination conditions, wind conditions and traffic conditions.

Table 7 lists the conditions grouped by type, with condition parameters outlined.

Within the condition categories of weather, illumination, wind and traffic, specific conditions were identified for evaluation. In the weather category of conditions there were eight conditions defined reflecting four weather scenarios (clear, rain, snow and fog); each condition was evaluated during both day and night conditions. To limit the effect of wind speed on sensor performance segments selected for analysis were restricted to those with wind speeds less than or equal to 15 km/hr for all weather condition evaluations. Clear conditions were evaluated to measure sensor performance during optimal conditions.

Similar to the weather conditions, the illumination conditions used in the analysis were restricted to those with no wind (wind speed was restricted to less than or equal to 15 km/hr); this was done as a controlled parameter to limit the effects of environmental factors besides illumination conditions. Analyzed segments were also limited to those with adverse weather conditions.

To determine the effect of shadows and glare, illumination conditions were assessed at dawn (no glare, potential head light and light standard halos), cloudy noon (no shadows or glare - ideal conditions for video sensors), sunny afternoon (potential shadows), dusk (sunset glare) and night (head light and light standard halos).

Table 7: Condition Descriptions

Condition Criteria	Description	Wind Boundary Lower (km/hr)	Upper (km/hr)	Wind Class	Weather	Time Boundary Lower	Upper	Time
Weather Conditions								
1	no wind, clear, day	0	15	Low	No Adverse	+dawn	-dusk	Day
2	no wind, clear, night	0	15	Low	No Adverse	+dusk	-dawn	Night
3	no wind, rain, day	0	15	Low	rain	+dawn	-dusk	Day
4	no wind, rain, night	0	15	Low	rain	+dusk	-dawn	Night
5	no wind, snow, day	0	15	Low	snow	+dawn	-dusk	Day
6	no wind, snow, night	0	15	Low	snow	+dusk	-dawn	Night
7	no wind, fog, day	0	15	Low	fog	+dawn	-dusk	Day
8	no wind, fog, night	0	15	Low	fog	+dusk	-dawn	Night
Illumination Conditions								
9	no wind, no adverse weather, noon, cloudy	0	15	Low	Cloudy	11:00	13:00	Lunch
10	dawn, no wind, no adverse weather	0	15	Low	No Adverse	-dawn	+dawn	Dawn
11	sunny afternoon, no wind	0	15	Low	Clear	13:00	-dusk	Afternoon
12	dusk, no wind, no adverse weather	0	15	Low	No Adverse	-dusk	+dusk	Dusk
13	night, no wind, no adverse weather	0	15	Low	No Adverse	+dusk	-dawn	Night
Wind Conditions								
15	wind light to moderate, no adverse weather, sunny afternoon	15	30	Med	Clear	13:00	-dusk	Afternoon
16	wind light to moderate, no adverse weather, night	15	30	Med	No Adverse	+dusk	-dawn	Night
17	wind light to moderate, no adverse weather, cloudy, noon	15	30	Med	Cloudy	11:00	13:00	Lunch
18	wind moderate to strong, no adverse weather, sunny afternoon	30	200	High	Clear	13:00	-dusk	Afternoon
19	wind moderate to strong, no adverse weather, night'	30	200	High	No Adverse	+dusk	-dawn	Night
20	wind moderate to strong, no adverse weather, cloudy, noon	30	200	High	Cloudy	11:00	13:00	Lunch
Traffic Conditions								
21	no wind, no adverse weather, a.m. peak	0	15	Low	No Adverse	7:00	9:00	AMpeak
22	no wind, no adverse weather, p.m. peak	0	15	Low	No Adverse	15:00	18:00	PMpeak
23	no wind, no adverse weather,free flow, day	0	15	Low	No Adverse	9:00	15:00	FreeFlow
24	no wind, no adverse weather, free flow, night	0	15	Low	No Adverse	+dusk	-dawn	Night

Note 1: Condition 14 was removed from the research because while it emphasized wind conditions, and condition 9 emphasized illumination conditions, the same results were used for both. Condition 14 was eliminated because of this redundancy; as a result it does not appear in this table or elsewhere in the report.

Note 2:Wind Class refers to the wind speed segmentation outlined for the purposes of this research. Low refers to a wind speed of less than or equal to 15 km/hr. Medium refers to wind speeds between 15 and 30 km/hr. High refers to wind speeds of 30 km/hr or more.

Note 3: + and – signs in the Time Boundary columns indicate one hour greater (+) or one hour less (-) than the listed time.

The concern with the effect of wind speed on vehicle detection was the potential oscillation of detection sensors mounted higher than eight metres (26.2 ft) in the air. Associated with the oscillation were also increased effects of shadows, glare and lighting halos.

The average wind speed for Winnipeg is 17.63 km/hr based on the yearly average for 2008-2012 (Environment Canada, n.d.). The wind speed parameters for wind condition analysis for this research, were defined as follows:

- For this research "no wind" was defined as wind speed less than or equal to 15 km/hr.
- For this research "low to moderate wind" was defined as wind speed greater than 15 km/hr and less than or equal to 30 km/hr.
- For this research "strong wind" was defined as wind speed greater than or equal to 30 km/hr.

Six wind conditions were identified by wind speed category: no wind, light to moderate wind and moderate to strong wind, each evaluated in sunny afternoon conditions, cloudy noon conditions and night conditions. In addition to defining wind speeds for each condition, all wind conditions were stipulated with having no adverse weather conditions, such as rain, fog and snow

Traffic conditions assessed for this research involved free-flow and peak period conditions for both daytime and nighttime, and were also restricted to no wind (wind speed less than or equal to 15 km/hr). Peak period conditions were assessed for both the morning and afternoon peak hours to determine if sun glare affected the detection performance.

3.4. SAMPLE SIZE

3.4.1. Sample Size for Sensitivity Analysis at the Stop Bar and Advance Detection Zones

The sensitivity of a vehicle detection sensor is a measure of the device's ability to successfully detect vehicles in the detection zone. The detection device is either successful and senses the vehicle or fails and misses the call.

$$Sensitivity = \frac{number\ of\ vehicles\ sensed\ by\ device\ being\ tested}{number\ of\ ground\ truth\ calls}\ \%$$

Each instance of a vehicle present in the detection zone can be interpreted as Bernoulli trial, and the binomial probability distribution represents the discrete probability distribution for the number of successes obtained in a series of individual Bernoulli trials (a Bernoulli experiment).

For the purposes of making statistical inferences for evaluating and comparing detector performance, it is helpful to apply a continuous approximation to the discrete data, using the proportion of successes (p, in this case, sensitivity) as the variable of interest. The normal approximation, based on the Central Limit Theorem is the simplest, but does not work well under extreme probabilities because the proportion of successes is non-negative with an upper bound of one (Moore, et al., 2012) . The literature review and results of the jurisdictional survey for this research indicated that the three devices being evaluated in this research were expected to perform with a high sensitivity (greater than 90 percent) (The Vehicle Detector Clearinghouse, 2007), so the Normal approximation is not used. Instead, the Wilson approximation and corresponding methods for calculating confidence intervals, developed by Edwin Bidwell Wilson (1927) were selected for use in this research when evaluating the sensitivity performance of the selected detection devices because this approximation performs well for extreme probabilities (Wilson, 1927).

The experimental design includes forecasting a sample size required to produce meaningful confidence intervals for evaluation – intervals that are sufficiently narrow and with a sufficiently high confidence level. The design forecasted the required sample size (n = number of ground truth calls/number of Bernoulli trials) using the Wilson binomial confidence interval formula (shown below) to calculate the number of required ground truth calls for statistical significance (n), using the following parameters:

- A success rate of 80 percent (p=0.8); this was a reasonable assumption due to the expected higher success rate the devices (The Vehicle Detector Clearinghouse, 2007). As the formula below reveals, with a higher actual success rate and the sample size held constant, the confidence interval width will decrease.

- The desired confidence level is 90 percent confidence level (Z = 1.645 for 90 percent confidence). In other words, the research aims to conclude that there is at 90 percent probability that the true sensitivity falls within the sensitivity confidence interval.

- The desired maximum confidence interval width (C) for the device sensitivity is ± 2 percent. .

$$\mathrm{C} = \frac{\mathrm{Z}\sqrt{\frac{p(1-p)}{n} + \frac{Z^2}{4n^2}}}{1 + \frac{1}{\mathrm{n}}\mathrm{Z}^2}$$

Wilson Binomial Confidence Interval Formula

When entering the parameters described above (p=0.8; Z = 1.645; C=0.02) the estimated required sample size (number of ground truth calls/number of Bernoulli trials) is n = 1080. This sample size is required for each of the weather, wind, traffic and illumination conditions was 1080. Here forward, “n” will be referred to as ground truth calls.

3.4.2. Sample Size for Count Analysis

Count performance was evaluated based on percent error for data collected in time intervals, therefore a cumulative normal distribution function was used. To determine the sample size (n), the standard deviation (σ) was assumed. Based on literature, count and classification performance of the tested sensors (or previous models of the sensors) typically have worst case of 10 percent standard deviation.

Count data for nighttime hours, after 00:00 and before 05:00, were very low making statistically significant comparisons of Miovision Technologies. Miovision Technologies is a company located in Kitchener, Ontario that manages data for engineering projects; for this research Miovision Technologies was contracted to provide ground truth data for the count analysis in fifteen minute intervals. Weekend hours could not be used for the count comparison as volume information for the test intersection was available in Average Weekday Daily Total (AWDT). The limited available hours led to an insufficient amount of ground truth data available to evaluate count for each condition in a statistically significant way. For this reason a sampling of weekday hours was taken and analyzed for count accuracy. The size of the sample counts was dictated by project constraints described above and research funding constraints. Within the project constraints a sample of 232 bins (a bin refers to a count interval of fifteen minutes), or 58 hours were evaluated. Using a cumulative normal distribution with a standard deviation of 10 percent, this related to a 99.9 percent confidence interval with ± 2 percent error evaluated per sensor.

3.5. EVALUATION METHOD

The sensors were installed on March 9, 2012. Sensor data and video surveillance recording was collected continuously between March 9 and December 31, 2012. From the nine months of collected data, selected time segments were evaluated to meet the sample size requirements of 1080 calls per condition for each condition listed in Section 3.3.

This vehicle detection research evaluates the ability of the sensor to detect the presence of a vehicle in the test zone, or sensitivity. Missed calls decrease the sensor's sensitivity performance. Selectivity is also a measure of a sensor's ability to identify vehicles in the zone of interest. Selectivity refers to the number of "false calls" detected by sensors. Low selectivity can reduce the operational efficiency of an intersection by extending or calling an unnecessary phase. Ideally, the most suitable vehicle detection sensor will allow safe and efficient traffic movement by minimizing both missed and false calls. (Rhodes, et al., 2005) Sensor selectivity was not analyzed in this research due to resource and reliability constraints from manual video review of ground truth data.

In this research, the sensors were tested for stop bar and advance detection sensitivity, and vehicle count accuracy, depending on the capability of the sensor. During the detection function of a sensor once a call is placed (i.e. a vehicle is detected) the sensor remains on during the entire time the vehicle remains in the detection zone. For vehicles passing through the zone at high speed this may mean a detection of several tenths of a second. When a vehicle is stopped and waiting in the zone due to traffic congestion or a red light, the call lasts for the entire duration of the time in the zone. During the count function of a vehicle detector the sensors detect the vehicle once, on and then off, and do not remain on during the entire time the vehicle remains in the detection zone. Due to this fundamental difference in functioning it was essential to test for both vehicle detection and count in assessing a vehicle detection device.

Since detection sensitivity refers to the sensor's ability to detect vehicles within each configured zone, any vehicle not detected in a zone within a set time threshold was considered a "missed call" and reduced the detector's sensitivity rating (i.e., accuracy level). Medina (2008) used a two second time threshold for detection. The time threshold was set at three seconds for this research. The additional one second was allotted due to potential human response delay in the manual video review required. Missed calls are of great concern for traffic safety and must be minimized. When a vehicle is missed and a necessary phase is not placed, a dilemma zone problem may occur or vehicles may intentionally run red lights if their demand is not served at an appropriate time. The dilemma zone refers to the distance before an intersection when a motorist must decide to proceed at their current speed and continue through the intersection before the red phase of the signal or slow down and stop at the anticipated red phase. A missed vehicle in detection may result in a prolonged red phase creating a problem.

The sensor sensitivities were evaluated separately for individual zones and on an aggregate level across all lanes. The aggregate analysis of the traffic data was expected to provide higher accuracy levels, since per lane performance varies due to location of lane and lane configurations (Zhang, et al., 2007). The required ground truth calls for statistically significant results were 1080; this was based on the number of calls across the four tested lanes of the intersection, not on a per lane basis. The detection performance of sensors on an aggregate level was adequate for traffic signal timing, since a call in either one of the through lanes or left-turn lanes provide a call or extension of a phase. The by-zone analysis for stop bar detection and advanced detection analysis is provided in *Appendix C* and *Appendix D*, respectively, for additional information.

3.5.1. Stop Bar Detection

The following section discusses the general detection zone layout used in the field test. Four zones were defined at the stop bar, numbered 26 through 29, from North (median lane) to South (curb lane). Each stop bar zone was monitored by the three tested sensors (Autoscope video, Iteris video, and Wavetronix microwave). Figure 4 shows the field test intersection layout with detection zones. In Figure 4, Zones 26 through 29 indicate placement of the inductive loops at or before the stop bar; in reality the zone 26 through 29 loops were located past (East) of the stop bar, this resulted in the stop bar loops not being able to be used as ground truth for testing the detectors' sensitivities.

The stop bar detection performance was evaluated using manual video review as the base condition. The reason manual video review was used was that the original placements of the stop bar loop sensors were ahead of the stop bar, which resulted in vehicles stopping prior to the loops and not being detected. Instead of loop detection, video surveillance was used to verify the presence of vehicles at the stop bar to ground truth. Each hour of data required two to three hours of manual video review. This resulted in over 500 hours of manual video review and a total of 34,324 ground truth calls identified over all conditions.

A macro was developed to compare each sensor's detection performance to the manual video review. When the macro identified a detection call in the loop sensor data, it evaluated the corresponding detection status for Autoscope and Iteris video within a 3.0 second time interval to determine whether the test sensors had also detected the vehicle. If at least one detection was identified by the macro during the 3.0 second time interval, it was assumed that the test sensor did not miss the call. Although false calls may have occurred, the manual video review used for this research could not accurately and consistently identify false calls in a way that would be replicable in future research. Based on several hours of manual video review it was decided that 3.0 seconds was a reasonable time for the sensors to detect a vehicle, any time beyond this did not regularly result in a detection call.

3.5.2. Advance Zone Detection

The advance detection zones were located approximately 109 metres (358 feet) from the stop bar; with the left turning lanes starting at approximately 30.5 metres (100 feet) prior to the advanced zones. Traffic lane changing manoeuvers occur prior to reaching the detection zones and therefore did not affect advanced detection results. There were four advanced zone detection zones, numbered 21 through 24, from North (median lane) to South (curb lane), as shown in Figure 4. Each advanced zone was monitored by Autoscope video and Iteris video sensors. The Matrix sensor did not have advance zone detection capability. The right turning lane was not monitored since it is not controlled by the intersection traffic signals.

Inductive loop sensors were used as ground truth for advanced detection. However, due to wiring complications of the advanced loops, it was only possible to use data from zones 23 and 24, the through lanes. A macro was developed to compare each sensor's detection performance to the inductive loop detection data. When the macro identified a detection call in the loop sensor data, it evaluated the corresponding detection status for Autoscope and Iteris video within a 3.0 second time interval to determine whether the test sensors had also detected the vehicle. The detection data recorded in one tenth of a second interval. If at least one, one-tenth of a second was identified as a call by the macro during the 3.0 second time interval; it was assumed that the test sensor did not miss the call.

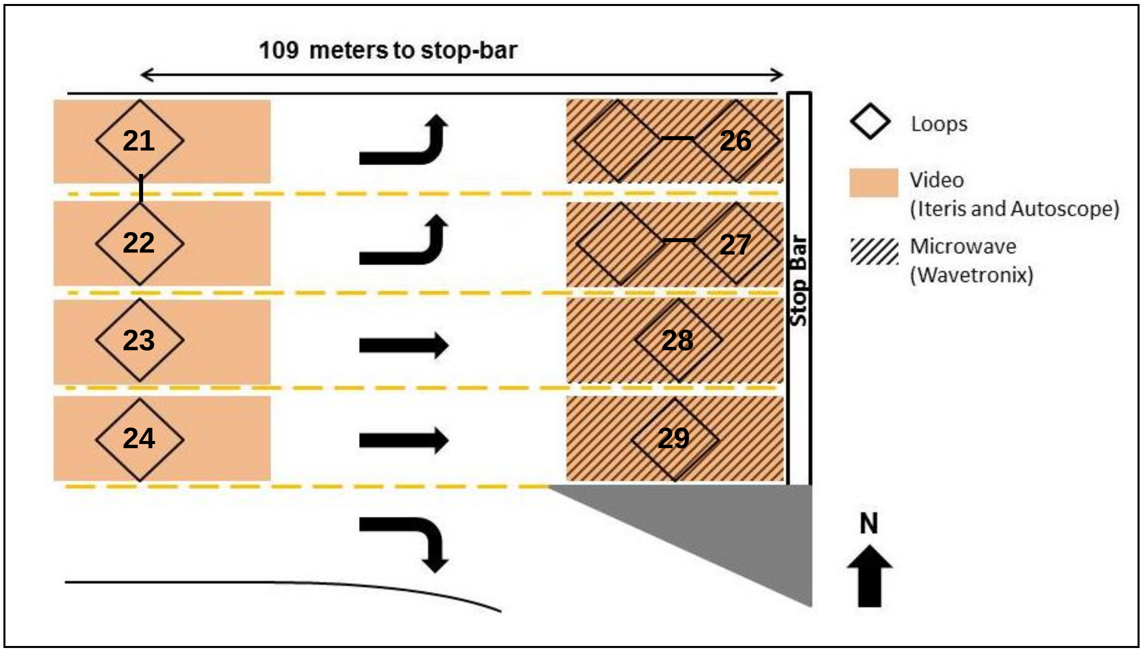


Figure 4 : Field Test Intersection Zone

Each selected half hour segment of data was processed by the macro separately. The macro took approximately 4 hours to process each half hour segment, taking a total of 180 hours for advanced zone analysis. This research did not review all conditions for advanced zone due to time and data constraints. It was decided, in consultation with the City of Winnipeg Engineers that the six best performing conditions and the six worst performing conditions from the stop bar analysis would be analyzed for advanced zone detection. The analysis resulted in a total of 23,927 advance zone ground truth detection calls.

3.5.3. Testing for Statistical Significance of Differences in Sensitivity

Once the sensitivity of each sensor was calculated the differences in sensitivity were compared to determine if the difference in sensitivity between the sensors was significant for a particular condition. For each condition for both the stop bar and advance zone analysis, three comparisons were made: Autoscope sensitivity to Matrix sensitivity, Autoscope sensitivity to Iteris sensitivity and Iteris sensitivity to Matrix sensitivity. To determine if the difference between the sensitivity of each pair was statistically significant Wilson's estimate (also known as the Plus Four Confidence Interval for Comparing Two Estimates) was used. Continuing with the 90 percent confidence level with a ±2% error (as established when calculating the ground truth call requirement), a null hypothesis that no difference in proportions existed and an alternate hypothesis that there was a difference in proportions, the probability of the results of this test correctly rejecting or failing to reject the hypotheses would be 90 percent; this is Type I error. A Bonferroni correction could have been applied to the data to reduce the Type I error to 3.33 percent (from ten percent), but this would have likely introduced Type II error. To favour a balance between Type I and Type II error a Bonferroni correction was not applied (Moore, et al., 2012).

3.5.4. Vehicle Counting

Count data was collected from Autoscope video and two Iteris video sensors, using Miovision Technologies video count data as ground truth. Count data could not be collected for the Wavetronix microwave sensor due to functionality problems with the sensor. These problems could not be resolved in time for the data collection. The two Iteris video sensors were installed in different locations and configurations: (1) overhead configuration, facing the oncoming traffic in the eastbound approach (also used for vehicle detection), referred to as *Iteris far* and (2) side-mount configuration, facing downward onto the stop bar lanes, referred to as *Iteris near*. The two mounting configurations were tested to evaluate the effect on count performance. Video sensors count and classify vehicles based on identifying the gap between vehicles; therefore the Iteris Near camera was expected to perform better than *Iteris far*.

As ground truth, Miovision Technologies processed 58 hours of video data in 15-minute intervals (total of 232 fifteen-minute intervals). The selected intervals were from weekdays, occurring between 6:00 am and midnight in order to get statistically significant hourly volumes.

4. ANALYSIS AND RESULTS

This chapter presents the results of the analysis for the following: (1) stop bar detection sensitivity performance of the Autoscope video, *Iteris far* video, and Wavetronix microwave sensors, (2) advance detection sensitivity of the same three sensors; and (3) count performance of the Autoscope video, *Iteris near* video, and *Iteris far* video sensors. Detection analysis was performed as a function of varying weather, illumination, wind, and traffic conditions as outlined in Chapter 3.

4.1. STOP BAR DETECTION ANALYSIS

The sensitivity of the Autoscope video, *Iteris far* video, and Wavetronix microwave sensors was analyzed at the four stop bar zones as a function of weather, illumination, wind, and traffic conditions. Analysis for each condition required 1080 ground truth calls for a 90 percent confidence interval, as determined in Section 3.4. Table 8 lists the conditions evaluated for the stop bar analysis along with the number of ground truth calls analyzed for each condition.

4.1.1. Sensitivity as a function of Weather

The stop bar sensitivity was analyzed as a function of clear, rain, fog, and snow weather conditions during both daytime and nighttime. Weather condition data was selected for wind speeds of 15 km/hr or less, limiting the effects of wind during measurement. A total of 9158 daytime and 4108 nighttime ground truth calls were identified for these conditions by manual video review.

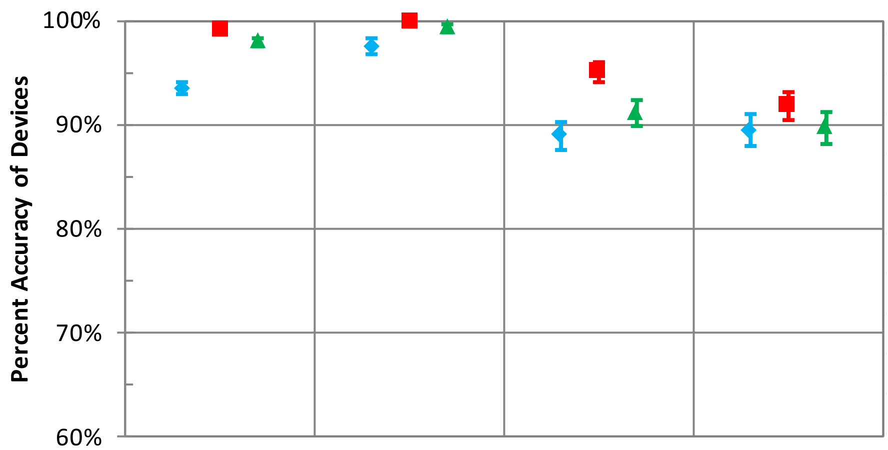
Figure 5 shows the sensitivity with the confidence interval limits for each of the three sensors under different weather conditions (clear, rain, snow, and fog) during daytime conditions. Figure 6 shows the same information, but for nighttime conditions.

The sensitivity of the three sensors during daytime ranged from 99.9 percent (for Iteris during rain) to 89.0 percent (for Autoscope during snow). Nighttime weather conditions performed similarly with the maximum sensitivity achieved by Iteris during fog with 99.6 percent, and minimum sensitivity of 79.2 percent with Autoscope during snow.

Table 8: Condition Numbers and Descriptions for Reference

Condition Criteria Condition #	Description	
Weather Conditions		Ground truth calls (n)
1	no wind, clear, day *base condition*	5222
2	no wind, clear, night *base condition*	1196
3	no wind, rain, day	1357
4	no wind, rain, night	466
5	no wind, snow, day	1460
6	no wind, snow, night	1338
7	no wind, fog, day	1119
8	no wind, fog, night	1108
Illumination Conditions		
9	no wind, no adverse weather, noon, cloudy *base condition*	1169
10	dawn, no wind, no adverse weather	1181
11	sunny afternoon, no wind	2055
12	dusk, no wind, no adverse weather	1403
13	night, no wind, no adverse weather	1196
Wind Conditions		
15	wind light to moderate, no adverse weather, sunny afternoon	1346
16	wind light to moderate, no adverse weather, night	1127
17	wind light to moderate, no adverse weather, cloudy, noon	1213
18	wind moderate to strong, no adverse weather, sunny afternoon	1201
19	wind moderate to strong, no adverse weather, night'	1095
20	wind moderate to strong, no adverse weather, cloudy, noon	1513
Traffic Conditions		
21	no wind, no adverse weather, a.m. peak	1162
22	no wind, no adverse weather, p.m. peak	1156
23	no wind, no adverse weather, free flow, day	3045
24	no wind, no adverse weather, free flow, night	1196

All three sensors, Autoscope, Iteris, and Matrix, performed with high sensitivity during clear weather conditions during both day and nighttime conditions, with 93.4, 99.1, and 97.9 percent accuracy levels during daytime and 93.6, 99.2, and 99.2 percent accuracy levels at nighttime, respectively.



Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	4880	1323	1299	1001
	Sensitivity	93.45 ± 0.57%	97.49 ± 0.73%	88.97 ± 1.36%	89.45 ± 1.53%
Iteris	# of vehicles detected	5178	1355	1388	1027
	Sensitivity	99.16 ± 0.21%	99.85 ± 0.26%	95.07 ± 0.95%	91.78 ± 1.37%
Matrix	# of vehicles detected	5114	1347	1331	1004
	Sensitivity	97.93 ± 0.33%	99.26 ± 0.43%	91.16 ± 1.23%	89.72 ± 1.51%
Ground Truth	n	5222	1357	1460	1119

Figure 5: Sensor Sensitivity as a Function of Daytime Weather Conditions with No Wind for All Zones (Evaluated Conditions 1, 3, 5, 7)

Base conditions for the MN-DOT study, although cloudy daytime, not clear, were at sensitivities of 100 percent, over 2070 calls. Nighttime base conditions for both studies were the same. Nighttime, base condition sensitivity performance for MN-DOT study was 100.0 to 92.7 percent over 2180 calls.

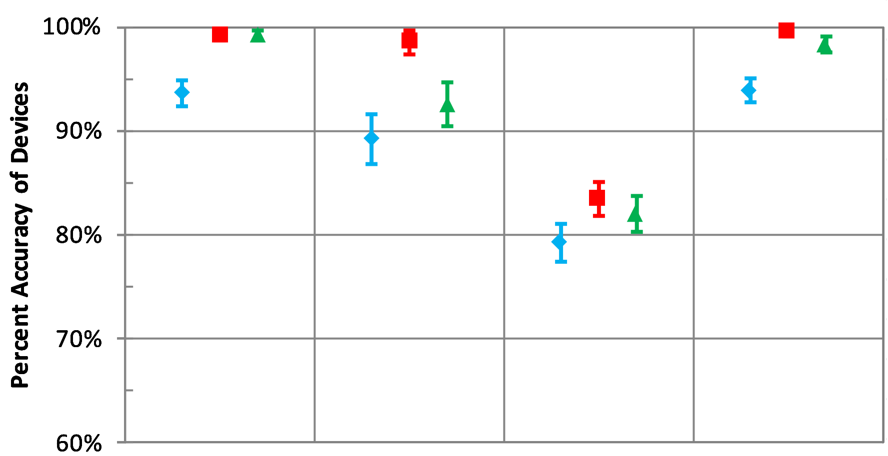
Rain did not affect the performance of the sensors during daytime, with sensitivities increasing in all three sensors; however, the accuracy levels of Autoscope and Matrix during nighttime were reduced by 4.3 and 6.7 percent, respectively, relative to the clear conditions, to 89.3 and 92.5 percent sensitivity. Rain conditions during daytime and nighttime had minimal effect on Iteris.

The nighttime rain condition, clear, no wind, had 466 calls; less than the required 1080 calls required for statistical significance. While the analysis was not statistically significant with 466 calls sensitivity was calculated for general comparison. The sensitivity of the sensors during nighttime rain varied from 89.3 to 98.5 percent. Nighttime rain events with no wind were limited during the data collection period due to an unusually dry spring and summer followed by an early winter.

Rain conditions in the MN-DOT study showed no change in sensitivity with each detector performing at 100.0 percent in daytime conditions, and two of three detectors performing at 100.0 percent in nighttime conditions. The third detector, Peek, performed at 94.4 percent. Daytime rain conditions for the Medina study were based on 1180 ground truth calls. Nighttime rain conditions for the MN-DOT study were based on 1593 ground truth calls for the rain condition and 1538 ground truth calls for the base condition.

Snow conditions reduced the accuracy levels of all three sensors during both daytime and nighttime conditions, with the greatest effect during nighttime conditions compared to all other weather conditions. During daytime conditions a reduction in sensitivity of 4.5 percent for Autoscope, 4.1 percent for Iteris, and 6.8 percent for Matrix was found. During nighttime snow conditions sensitivity decreased by of 14.4, 15.7, and 17.2 percent accuracy levels for Autoscope, Iteris, and Matrix, respectively. Autoscope was the most impacted by snow conditions in both daytime and nighttime conditions compared to the other two sensors.

In the MN-DOT study snow during daytime decreased sensitivity by 1.6 percent in one sensor, 0.2 percent in another and no impact in the third sensor. Nighttime snow conditions in the MN-DOT study had no decrease in sensor performance for two of the three sensors. The third sensor, Peek, decreased in sensitivity by 7.3 percent.



Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	1119	416	1059	1040
	Sensitivity	93.56 ± 1.19%	89.27 ± 2.41%	79.15 ± 1.83%	93.86 ± 1.21%
Iteris	# of vehicles detected	1186	459	1117	1103
	Sensitivity	99.16 ± 0.49%	98.5 ± 1.09%	83.48 ± 1.68%	99.55 ± 0.41%
Matrix	# of vehicles detected	1186	431	1097	1089
	Sensitivity	99.16 ± 0.49%	92.49 ± 2.08%	81.99 ± 1.74%	98.29 ± 0.68%
Ground Truth	n	1196	466	1338	1108

Figure 6: Sensor Sensitivity as a Function of Nighttime Weather Conditions with No Wind for All Zones (Evaluated Conditions 2, 4, 6, 8)

Fog during daytime had similar impact as snow on detector sensitivity, with a decrease in accuracy levels of approximately 4.0, 7.4, and 8.2 percent for Autoscope, Iteris, and Matrix, respectively. However, fog during nighttime had no impact on the performance levels compared to clear nighttime conditions; Autoscope and Iteris each performance 0.3 to 0.4 percent better, respectively. Matrix performed with 0.9 percent less sensitivity. When factoring in the percent error, these results are negligible.

In the MN-DOT study the data for fog was classified as light fog and dense fog. During dense fog the video devices in the MN-DOT study went into “fail safe” mode placing constant calls. Devices for this research were not configured for fail safe mode. When reviewing results of light fog from the MN-DOT study, the sensors’ sensitivity was not impacted by light fog during the daytime. Fog conditions during nighttime were not analyzed by the MN-DOT study.

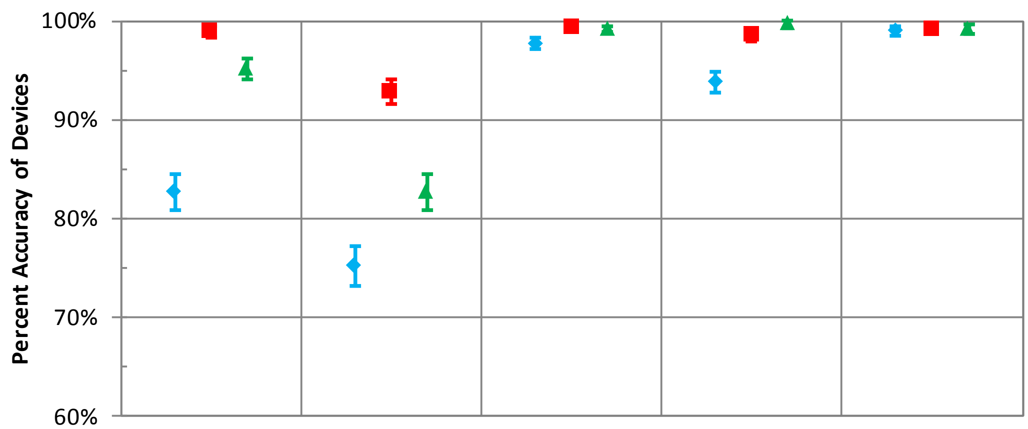
In summary, all three sensors performed with sensitivities of 79 percent or greater. In seventeen of 24 sensitivity calculations the devices performed at greater than 90 percent sensitivity. Autoscope performed the poorest during clear conditions (baseline) and was affected the most by rain, fog, and snow weather conditions compared to the other two sensors. The Iteris sensor, while generally being comparable to the Matrix sensor, had the highest sensitivity levels and was least impacted by the different weather conditions. Snow conditions had the highest effect on sensor performances, resulting in accuracy levels between 79.2 and 95.1 percent for the three sensors in both day and night conditions with no wind.

4.1.2. Sensitivity as a Function of Illumination

The stop bar detection performance was analyzed as a function of varying illumination conditions to assess the effects of glare and shadows on sensor performance. The analyzed lighting conditions were cloudy noon (baseline), dawn, sunny afternoon (long shadows), dusk, and night. Cloudy noon was identified in literature ((Medina, et al.,

2009) as being the ideal lighting conditions for video sensors, and was therefore the baseline condition.

Illumination condition data was collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, in order to limit the effects of wind and weather during measurement. A total of 7004 ground truth calls were identified for these conditions by manual video review. Figure 7 shows the accuracy levels and error margins for each of the three sensors under the different illumination conditions.



Device		Noon	Dawn	Afternoon	Dusk	Night
Autoscope	# of detected vehicles	967	888	2008	1316	1119
	Sensitivity	82.72 ± 1.83%	75.19 ± 2.08%	97.71 ± 0.56%	93.8 ± 1.07%	99 ± 0.52%
Iteris	# of detected vehicles	1156	1096	2043	1382	1186
	Sensitivity	98.89 ± 0.55%	92.8 ± 1.26%	99.42 ± 0.31%	98.5 ± 0.57%	99.16 ± 0.49%
Matrix	# of detected vehicles	1113	977	2038	1398	1186
	Sensitivity	95.21 ± 1.05%	82.73 ± 1.82%	99.17 ± 0.35%	99.64 ± 0.33%	99.16 ± 0.49%
Ground Truth	n	1169	1181	2055	1403	1196

Figure 7: Sensor Sensitivity as a Function of Illumination Conditions with No Wind and No Adverse Weather for All Zones (Evaluated Conditions 9, 10, 11, 12, 13)

The accuracy of the three sensors ranged from 75.2 percent (for Autoscope during dawn) to 99.6 percent (for Matrix during dusk). For the base condition (i.e., cloudy at noon), Iteris and Matrix performed with 98.9 and 95.2 percent sensitivity, respectively. At the base condition Autoscope had lower sensitivity of 82.7 percent; factors causing this difference in performance could not be identified.

Base conditions for the MN-DOT study, noon cloudy were at sensitivities of 100 percent, over 2070 calls.

Dawn lighting conditions had the most effect on detection sensitivity for all three sensors. Autoscope showed the least sensitivity at 75.2 percent. Iteris and Matrix performed with sensitivities of 92.8 and 82.7 percent, respectively. No external factors could be identified as adversely affecting the performance of the devices, indicating that dawn lighting conditions, specifically the transition from darkness to light adversely affects the performance of these video detection devices. Medina said “During the transition from night to day time, particularly at the early stage of dawn when daylight is the lowest and vehicles have their headlights on detection seemed to be more difficult…” (Medina, et al., 2009). In the MN-DOT study, detectors experienced no decrease in sensitivity, all performing at 100.0 percent; it must be noted that in the MN-DOT study that there were only 257 dawn calls for comparison to base conditions.

Sunny afternoon conditions were selected as a condition of evaluation for illumination as a time of day when shadows would be longest. Autoscope, Iteris and Matrix performed at 97.7, 99.42, and 99.2 percent sensitivities, respectively. The difference in performance with base, cloudy noon condition increased for and Matrix, and remained very similar for Iteris; indicating minimal effect of shadows during sunny conditions on detector sensitivity. In the MN-DOT study, the sunny condition for long shadows was in the morning. In the MN-DOT study sensor sensitivity was unaffected, remaining at 100.0 percent in two conditions and decreased in the remaining detector by 0.4 percent, decreasing sensitivity to 99.6 percent.

Dusk lighting conditions, unlike dawn conditions, had no negative impact on device sensitivity. For Autoscope, sensitivity increased by 11.1 percent, for Iteris sensitivity decreased by 0.4 percent and for Matrix sensitivity increased by 4.4 percent. In the MN-DOT study, two sensors experienced no decrease in sensitivity remaining at 100.0 percent. The remaining sensor decreased by 8.2 percent to a sensitivity of 91.8 percent.

Nighttime lighting conditions produced increased in sensitivity in all three detectors. Autoscope increased from 82.7 percent to 99.0 percent, Iteris increased from 98.9 to 99.2 percent and Matrix increased from 95.2 to 99.2 percent. In the MN-DOT study sensor sensitivity was unaffected, remaining at 100.0 percent in two conditions and decreased in the remaining detector by 10.9 percent, decreasing sensitivity to 89.1 percent.

Overall, Iteris was the least affected by the different lighting conditions, maintaining an sensitivity of greater than 92.0 percent. Matrix performed similarly to Iteris under the different illumination conditions, except during the dawn condition resulting in approximately 10.0 percent lower accuracy level than Iteris, at 82.7 percent. Results of the illumination conditions indicates less sensitivity during the base, noon, cloudy condition indicating that the tested sensor are less affected by shadows, and lighting transitions and are more affected by less difference in pixilation in the monochromatic setting of cloudy noon conditions.

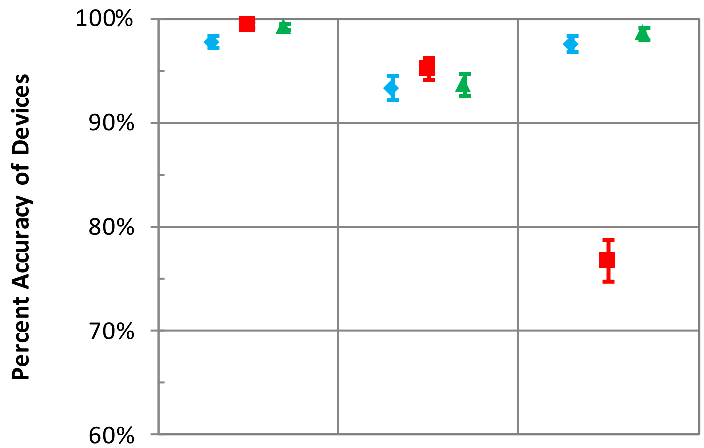
4.1.3. Sensitivity as a Function of Wind

The stop bar detection performance was analyzed as a function of low (less than 15 km/hr), moderate (between 15 and 30 km/hr), and strong (greater than 30 km/hr) wind conditions for sunny daytime, cloudy noon, and nighttime lighting conditions. This allowed the evaluation of a combination effects on sensor performance. The low wind condition was established as the baseline condition for all three lighting conditions, when compared with moderate and strong conditions within each illumination condition.

Wind condition data was only collected for no adverse weather conditions, in order to limit the effects of weather during measurement. A total of 4602 sunny daytime, 3895 cloudy noon, and 3418 nighttime ground truth calls were identified for these conditions using manual video review. Figure 8, Figure 9, and Figure 10 show the sensitivity and percent error for each of the three sensors under the different wind speed conditions, for sunny daytime, cloudy noon, and nighttime conditions, respectively.

The MN-DOT study also analyzed the effect of wind speed on sensor performance. In that study, wind conditions were labeled as windy and no wind, with no parameters of wind speed defined. The conditions analyzed for that study were cloudy noon and sunny daytime conditions, no nighttime analysis was conducted. Throughout the MN-DOT study no change in sensitivity was noted for the assessed conditions.

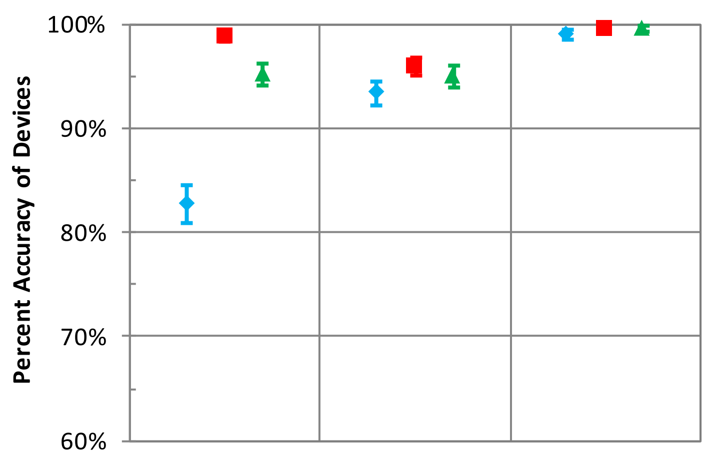
As Figure 8 shows under the sunny daytime lighting condition, the sensitivity of the three sensors ranged from 76.7 percent (for Iteris during strong wind) to 99.4 percent (for Iteris during low wind). Under the ideal condition of low wind for sunny daytime conditions, all three sensors performed with sensitivity levels between 97.8 and 99.4 percent. The three sensors performed with less sensitivity in moderate wind conditions with sensitivity reduced by 4.4 for Autoscope, 4.3 percent for Iteris and 5.6 percent for Matrix relative to their baseline conditions. Strong wind conditions did not have an effect on Autoscope and Matrix from the base condition; however, Iteris was significantly affected with a decrease in performance of 22.7 percent for a sensitivity of 76.7 percent. Autoscope and Iteris were anticipated to perform with less sensitivity as wind speed increased. Autoscope and Iteris were mounted at 11.3 metres (40 feet) and 12.2 metres (35 feet) above the ground; making them susceptible to oscillation during increased wind. It was not anticipated that the sensors would be less sensitive during moderate wind conditions and increase in sensitivity during strong wind conditions (Autoscope and Matrix).



Device		Low	Moderate	Strong
Autoscope	# of detected vehicles	2008	1256	1171
	Sensitivity	97.71 ± 0.56%	93.31 ± 1.14%	97.5 ± 0.77%
Iteris	# of detected vehicles	2043	1280	921
	Sensitivity	99.42 ± 0.31%	95.1 ± 0.99%	76.69 ± 2.02%
Matrix	# of detected vehicles	2038	1260	1183
	Sensitivity	99.17 ± 0.35%	93.61 ± 1.11%	98.5 ± 0.62%
Ground Truth	n	2055	1346	1201

Figure 8: Sensor Sensitivity as a Function of Wind Speed during Sunny Daytime Conditions for All Zones (Evaluated Conditions 11, 15, 18)

Figure 9 shows that under the cloudy noon lighting condition, the sensitivity of the three sensors ranged from 82.7 percent (for Autoscope during low wind) to 99.6 percent (for Matrix during strong wind). Under the ideal condition of low wind Autoscope's sensitivity was 82.7 percent, Iteris' sensitivity was 98.9 percent and Matrix's sensitivity was 95.2 percent. Autoscope's lower accuracy level under ideal conditions could not be attributable to a specific cause; the poorer performance may be reflective of the random sampling of data segments. All three sensors performed similarly under moderate wind conditions, with Iteris and Matrix resulting in slightly decreased sensitivity relative to the baseline conditions. The sensitivity of Autoscope increased from baseline conditions by 10.7 percent. With the lower than anticipated performance of Autoscope during baseline conditions the device performance during the other evaluated conditions may be more reflective of overall performance. Strong wind conditions did not have an effect on sensor performance under cloudy noon conditions, with all sensors having accuracy levels greater than 99.0 percent. Performance of the devices was not as anticipated for this condition set.



Device		Low	Moderate	Strong
Autoscope	# of vehicles detected	967	1133	1499
	Sensitivity	82.72 ± 1.83%	93.4 ± 1.19%	99.07 ± 0.44%
Iteris	# of vehicles detected	1156	1164	1506
	Sensitivity	98.89 ± 0.55%	95.96 ± 0.95%	99.54 ± 0.34%
Matrix	# of vehicles detected	1113	1152	1507
	Sensitivity	95.21 ± 1.05%	94.97 ± 1.05%	99.6 ± 0.32%
Ground Truth	n	1169	1213	1513

Figure 9: Sensor Sensitivity as a Function of Wind Speed during Noon Cloudy, Daytime Conditions for All Zones (Evaluated Conditions 9, 17, 20)

Under the nighttime lighting condition, the accuracy of the three sensors ranged from 84.3 percent (for Autoscope during moderate wind) to 99.2 percent (for all three sensors during low wind), shown in Figure 10.

Under the ideal condition of low wind, all three sensors performed with sensitivity of greater than 99 percent. Moderate wind reduced sensitivity in Autoscope by 14.7 percent, for a moderate wind at night sensitivity of 84.3 percent. Similarly for Iteris and Matrix, moderate wind reduced sensitivity by 10.9 percent and 12.6 percent, respectively for sensitivity of Iteris at 88.3 percent and 86.6 percent for Matrix.

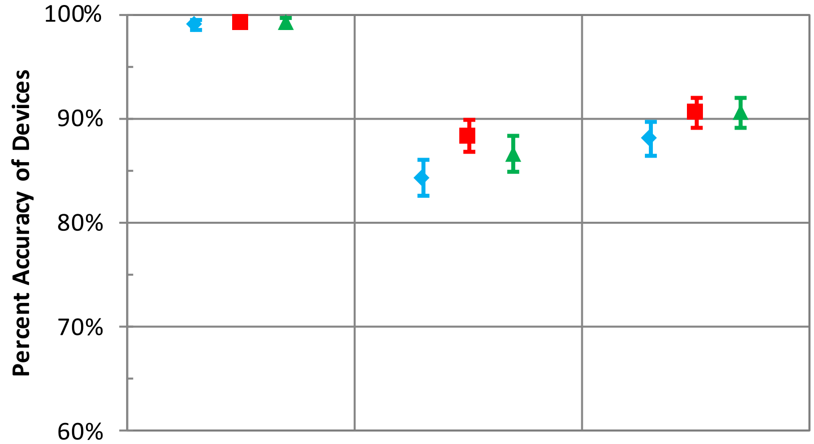
For strong wind, sensitivities for all three devices increased over moderate conditions, but were decreased from base conditions. For Autoscope the decrease in sensitivity from low wind speed to strong wind was 11.1 percent, for a sensitivity of 88.0 percent. For Iteris the decrease in sensitivity from low wind speed to strong wind was 8.6 percent for a sensitivity of 90.6 percent and for Matrix the decrease in sensitivity from low wind speed to strong wind was 8.7 percent for a sensitivity of 90.5 percent.

Wind speed affected sensor performance, with moderate wind speeds of fifteen to 30 km/hr presenting the greatest change in sensitivity.

4.1.4. Sensitivity as a Function of Traffic

The stop bar detection performance was analyzed as a function of morning peak, afternoon peak, and free flow day and night traffic conditions. The free flow daytime condition was identified as the baseline condition.

Traffic condition data was only collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, in order to limit the effects of wind and weather during measurement. A total of 6559 ground truth calls were identified for these



Device		Low	Moderate	Strong
Autoscope	# of vehicles detected	1119	950	963
	Sensitivity	99 ± 0.52%	84.29 ± 1.79%	87.95 ± 1.63%
Iteris	# of vehicles detected	1186	995	992
	Sensitivity	99.16 ± 0.49%	88.29 ± 1.59%	90.59 ± 1.47%
Matrix	# of vehicles detected	1186	976	991
	Sensitivity	99.16 ± 0.49%	86.6 ± 1.68%	90.5 ± 1.47%
Ground Truth	n	1196	1127	1095

Figure 10: Sensor Sensitivity as a Function of Wind Speed during Nighttime Conditions for All Zones (Evaluated Conditions 13, 16, 19)

conditions by manual video review. Figure 11 shows the sensitivity and error margins for each of the three sensors under the traffic conditions. The MN-DOT study referred to in other sections of this chapter did not include traffic conditions analysis. No other study of traffic condition sensitivity performance of video detection devices was found.

The sensitivity of the three sensors ranged from 87.1 percent (for Autoscope during am peak) to 99.6 percent (for Iteris during pm peak). Iteris and Matrix sensors were the least affected by different traffic conditions with minimum sensitivity levels of 98.4 and 94.2 percent, respectively during morning peak traffic conditions. Autoscope was the most affected by the am peak and free flow day traffic with less than 90 percent sensitivity. Autoscope's performance under pm peak was similar to that of Iteris and Matrix.

During the base condition, free flow day, the devices performed with sensitivities of 89.6 percent (Autoscope), 99.0 percent (Iteris) and 96.9 percent (Matrix). During morning peak hours, sensitivity performance for Autoscope decreased by 2.5 percent to 87.1 percent. Iteris sensitivity decreased by 0.5 percent to 98.5 percent and Matrix performance decreased by 2.7 percent to 94.2 percent for morning peak conditions.

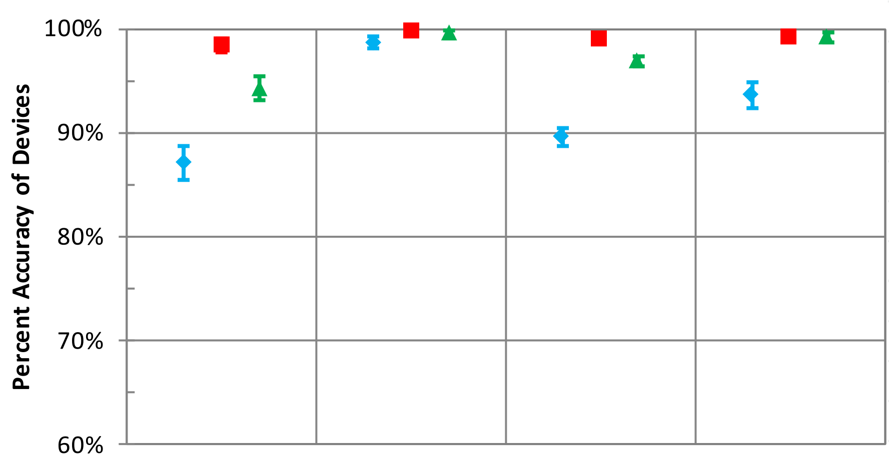
For afternoon peak conditions, all sensors increased in sensitivity by 9.0 percent (Autoscope), by 0.7 percent (Iteris) and 2.6 percent (Matrix); no explanation for this increase in sensitivity could be found in external causes or in the literature findings.

During nighttime traffic conditions, again, sensitivity increased over base conditions. For Autoscope sensitivity increased by 3.9 percent, for Iteris sensitivity increased by 0.2 percent and for Matrix, sensitivity increased by 2.3 percent. No explanation for increase in sensitivity during nighttime conditions could be found in external causes or in the literature findings.

Traffic condition analysis resulted in lower sensitivities for Autoscope with sensitivities ranging from 98.6 percent to 87.1 percent. Iteris and Matrix showed minimal deviation in sensitivity in the various traffic conditions.

4.1.5. Sensitivity Differences, Selecting the Best Performing Device

An objective of this research was to select a vehicle detection device which is particularly suited to the weather, wind, illumination and traffic conditions of Winnipeg, MB. Table 9 presents a summary of the sensitivity performance of each detector for the 24 weather, illumination, wind and traffic conditions of this research.



Device		a.m. peak	p.m. peak	Free flow day	Free flow night
Autoscope	# of vehicles detected	1012	1140	2729	1119
	Sensitivity	87.09 ± 1.63%	98.62 ± 0.61%	89.62 ± 0.91%	93.56 ± 1.19%
Iteris	# of vehicles detected	1144	1152	3013	1186
	Sensitivity	98.45 ± 0.64%	99.65 ± 0.37%	98.95 ± 0.32%	99.16 ± 0.49%
Matrix	# of vehicles detected	1095	1150	2950	1186
	Sensitivity	94.23 ± 1.15%	99.48 ± 0.42%	96.88 ± 0.53%	99.16 ± 0.49%
Ground Truth		1162	1156	3045	1196

Figure 11: Sensor Sensitivity as a Function of Traffic Conditions with No Wind and No Adverse Weather for All Zones (Evaluated Conditions 21, 22, 23, 24)

Table 9 also indicates if the difference in performance between each of the detector is statistically significant. As mentioned in section 3.5.3 the Plus Four Confidence Interval for Comparing Two Estimates was used to compare the differences in sensitivity between the devices for statistical significance.

For example, in Table 9, for condition one: daytime, clear conditions, Autoscope had 93.45 percent sensitivity, Iteris had 99.16 and Matrix had 97.93 percent. When comparing Autoscope to Iteris, the difference of 93.45 percent to 99.16 percent is a statistically significant difference according to the Plus Four Confidence Interval for

Comparing Two Estimates. Similarly, no statistical difference in the comparison for Autoscope with Matrix and Iteris with Matrix was found.

Table 9: Differences in Sensor Sensitivities Compared for Statistical Difference for Stop Bar Analysis

Condition		Sensitivity			Significant Difference		
Condition #	Description	Autoscope	Iteris	Matrix	Autoscope to Iteris	Autoscope to Matrix	Iteris to Matrix
Weather Conditions (no wind)							
1	clear, day	93.45	99.16	97.93	Yes	Yes	Yes
2	clear, night	93.56	99.16	99.16	Yes	Yes	-
3	rain, day	97.49	99.85	99.26	Yes	Yes	Yes
4	rain, night	89.27	98.50	92.49	Yes	No	Yes
5	snow, day	88.97	95.07	91.16	Yes	Yes	Yes
6	snow, night	79.15	83.48	81.99	Yes	Yes	No
7	fog, day	89.45	91.78	89.72	Yes	No	No
8	fog, night	93.86	99.55	98.29	Yes	Yes	Yes
Illumination Conditions (no wind, no adverse weather)							
9	noon, cloudy	82.72	98.89	95.21	Yes	Yes	Yes
10	dawn	75.19	92.80	82.73	Yes	Yes	Yes
11	sunny afternoon	97.71	99.42	99.17	Yes	Yes	No
12	dusk	93.80	98.50	99.64	Yes	Yes	Yes
13	night	99.00	99.16	99.16	No	No	-
Wind Conditions (no adverse weather)							
15	light to moderate, sunny afternoon	93.31	95.10	93.61	Yes	No	No
16	light to moderate, night	84.29	88.29	86.60	Yes	No	No
17	light to moderate, cloudy, noon	93.40	95.96	94.97	Yes	No	No
18	moderate to strong, sunny afternoon	97.50	76.69	98.50	Yes	Yes	Yes
19	moderate to strong, night	87.95	90.59	90.50	Yes	Yes	No
20	moderate to strong, cloudy noon	99.07	99.54	99.60	No	Yes	No
Traffic Conditions (no wind, no adverse weather)							
21	morning peak	87.09	98.45	94.23	Yes	Yes	Yes
22	afternoon peak	98.62	99.65	99.48	Yes	Yes	No
23	free flow, day	89.62	98.95	96.88	Yes	Yes	Yes
24	free flow, night	93.56	99.16	99.16	Yes	Yes	-

Note: "-" in the Significant Difference column indicates that the sensors being compared performed with the same sensitivity for that particular condition.

When comparing sensitivities be percentage only, over all conditions, Iteris performs with better sensitivity in seventeen of 24 conditions; additionally, Iteris and Matrix perform with the same sensitivity in three of the conditions. When factoring in the statistical significance of the differences in sensitivities, Iteris and Matrix perform with no statistically significant difference in nine of the seventeen instances described above. Autoscope also does not perform with statistically significant differences in sensitivity in two conditions.

4.2. ADVANCE ZONE DETECTION ANALYSIS

The overall detection performance of the Autoscope video, and *Iteris far* video sensors were analyzed for the two through lanes for advance zones as a function of weather, illumination, wind, and traffic conditions. Resource limitations on the research did not allow for assessing each of the 24 defined conditions as completed with the stop bar analysis. Upon completion of the stop bar analysis the six best performing conditions and the six worst performing conditions were analyzed for advanced zone performance. This was decided jointly with Traffic Signals Engineering from the City of Winnipeg.

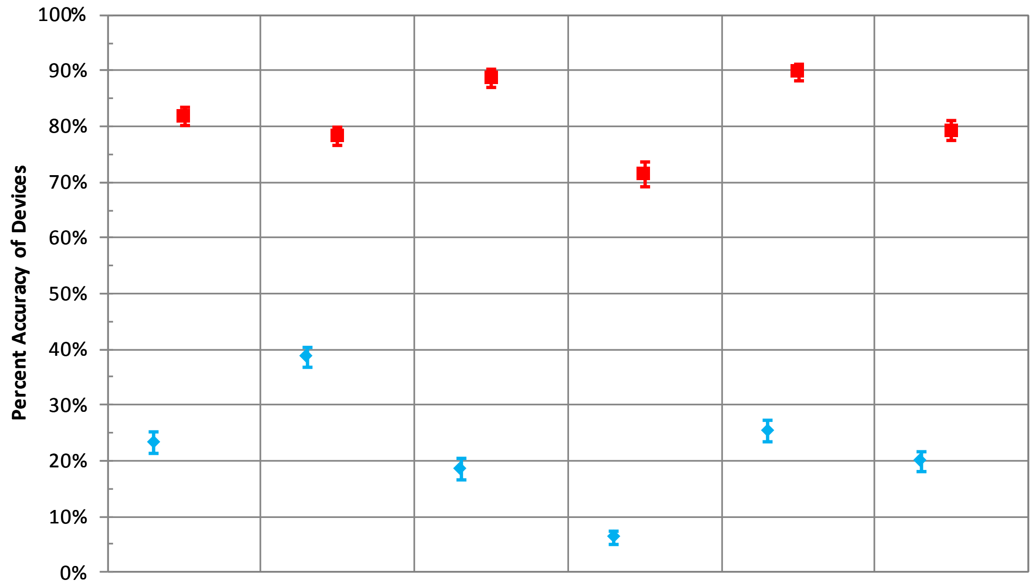
4.2.1. Sensitivity for Conditions Performing Well in Stop bar Analysis

The six best performing conditions from the stop bar analysis were:

- Weather: daytime rain (Condition 3)
- Illumination: sunny afternoon (Condition 11)
- Illumination: dusk (Condition 12)
- Illumination: night (Condition 13)
- Wind: Moderate to strong wind during cloudy noon (Condition 20)
- Traffic: p.m. peak (Condition 22)

A total of 8138 ground truth calls were identified for the six conditions. Figure 12 shows the accuracy levels and error margins for each sensor under the six defined conditions.

The sensitivity of the Autoscope sensor ranged from 6.26 percent for nighttime illumination conditions to 38.65 for sunny afternoon illumination, as shown in Figure 13. Once results of the analysis of Autoscope sensitivity were reviewed a further investigation into the operation of the device at the test site followed. The Autoscope device worked only intermittently during the test. Results from this test cannot be used to determine regular device performance.



Device		Weather, rain, day	Illumination, sunny afternoon	Illumination, dusk	Illumination, night	Wind, strong, noon, cloudy	Traffic, p.m. peak
Autoscope	# of vehicles detected	304	758	197	72	317	279
	Accuracy	23.24 ± 1.93%	38.65 ± 1.81%	18.45 ± 1.96%	6.26 ± 1.2%	25.3 ± 2.03%	19.97 ± 1.77%
Iteris	# of vehicles detected	1070	1534	946	822	1124	1106
	Accuracy	81.8 ± 1.76%	78.23 ± 1.54%	88.58 ± 1.62%	71.42 ± 2.2%	89.7 ± 1.43%	79.17 ± 1.79%
Ground Truth	n	1308	1961	1068	1151	1253	1397

Figure 12: Sensor Sensitivity for Advanced Zone Detection Performance for Conditions Performing Well in Stop bar Analysis

The accuracy of the Iteris sensor ranged from 89.7 percent during p.m. peak traffic to 71.4 percent during nighttime illumination. When compared with stop bar sensitivity performance, Iteris performed 9.8 percent to 27.7 percent, or 17.9 percent on average, less sensitively in the advance zone. This difference is attributable to having two zones rather than four for testing as well as the likelihood that the device was not properly configured for advance detection as was the case with Autoscope.

4.2.2. Sensitivity for Conditions Performing Poorly in Stop Bar Analysis

The six worst performing conditions from the stop bar analysis were:

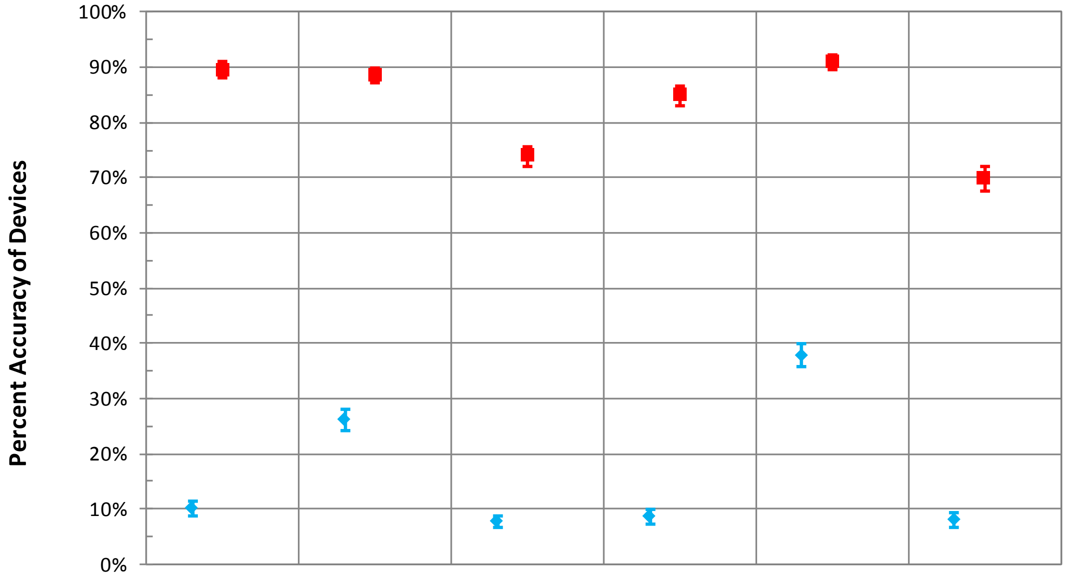
- Weather: snow during nighttime (Condition 6)

- Illumination: cloudy noon (Condition 9)
- Illumination: dawn (Condition 10)
- Wind: light to moderate wind at nighttime (Condition 16)
- Wind: moderate to strong wind during sunny afternoons (Condition 18)
- Traffic: a.m. peak (Condition 21)

A total of 8188 ground truth calls were identified for these conditions. Figure 13 shows the accuracy levels and error margins for each sensor under the six defined conditions.

Autoscope's sensitivity ranged from 37.78 percent during moderate to strong winds at sunny afternoons to 7.67 percent during dawn illumination conditions. Again, due to the malfunction of the Autoscope device, results from this test cannot be relied upon to reflect the actual performance of the device.

Iteris' sensitivity improved for two conditions over the stop bar performance: weather during nighttime snow conditions (increase of 6.0 percent to 89.5 percent) and strong winds during sunny afternoon (increase of 14.2 percent to 90.9 percent). For the remaining conditions, the sensitivity of Iteris decreased by 10.3 percent to 28.6 percent for sensitivities ranging from 92.9 percent to 98.9 percent.



Device		Weather, snow, night	Illumination, noon, cloudy	Illumination, dawn	Wind, moderate, night	Wind, strong, sunny afternoon	Traffic, a.m. peak
Autoscope	# of vehicles detected	136	368	124	94	589	94
	Sensitivity	10.18 ± 1.37%	26.01 ± 1.92%	7.67 ± 1.1%	8.51 ± 1.4%	37.78 ± 2.02%	8.13 ± 1.34%
Iteris	# of vehicles detected	1196	1253	1194	938	1417	807
	Sensitivity	89.52 ± 1.39%	88.55 ± 1.4%	73.84 ± 1.8%	84.89 ± 1.78%	90.89 ± 1.21%	69.81 ± 2.23%
Ground Truth	n	1336	1415	1617	1105	1559	1156

Figure 13: Sensor Sensitivity for Advanced Zone Detection Performance for Conditions Performing Poorly in Stop bar Analysis

4.3. COUNT ANALYSIS

The overall count performance of Autoscope video and Iteris video, near and far, was analyzed through comparison with ground truth counts. Ground truth counts were established through video review conducted by Miovision Technologies using video from the test intersection. As mentioned in section 3.5.4, Miovision Technologies provides vehicle count ground truth vehicle counts using manual video review. Traffic counts were selected from March 10 through May 30, 2012. Time intervals of one hour (provided in 15 minute intervals) for counts were randomly selected to represent different times of day and a random sampling of various weather, wind, illumination and traffic conditions.

Analyzed counts were taken from Monday through Friday, from 06:00 to 23:00. Further, due to low traffic volumes during overnight, counts from 00:00 to 05:00 were not considered as counts could not be compared in a statistically meaningful way, due to very low traffic volumes during these times. A total of 76 hours of traffic counts were analyzed with a total of 67,256 ground truth vehicles. Analysis was based on percent error of each device with respect to the ground truth count for each respective hour.

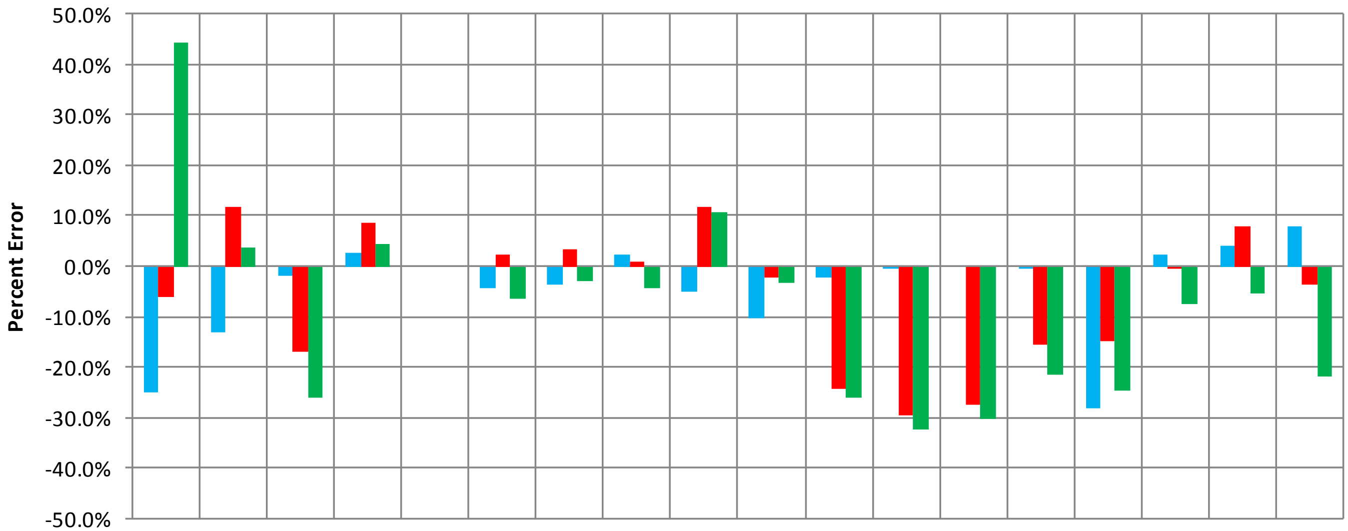
Counts were provided to Miovision Technologies in 15-minute intervals and then combined for one hour counts.

Figure 14 shows the hourly percent difference from ground truth for each device for the count analysis. Percent difference was calculated in the same way that sensitivity was calculated for the detection tests.

$$Percent\ Difference = \{1 - \frac{number\ of\ vehicles\ counted\ by\ device\ being\ tested}{number\ of\ ground\ truth\ calls\ provided\ by\ Miovision}\}\ 100\%$$

In Figure 14 a negative sign indicates under counting and a positive sign indicates over counting with respect to ground truth. In terms of magnitude of counts on an hourly basis, due to sampling the data randomly, some hours have one hourly (four fifteen-minute counts) while others have up to six hourly counts represented. For this reason percent difference from ground truth is analyzed, but comparison with hourly average daily traffic (ADT) cannot be made.

For Autoscope, percent difference varied from under counting by 28.3 percent to over counting by 7.8 percent. Iteris Far varied in percent error from under counting by 29.5 percent to over counting by 11.9 percent. Iteris Near varied in percent error from under counting by 32.6 percent to over counting by 44.2 percent. These results are contrary to the findings of SRF Consulting in the NIT – Phase II Evaluation of Non-Intrusive



Device		600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300
Autoscope	# of detected vehicles	240	3128	2443	1523	n/a	9077	10630	2419	3714	6404	7328	5363	3843	2214	2565	849	795	1380
	%Difference from Ground Truth	-25.2%	-13.3%	-1.8%	2.5%	n/a	-4.4%	-3.6%	2.3%	-5.2%	-10.5%	-2.3%	-0.3%	0.0%	-0.3%	-28.3%	2.3%	4.2%	7.8%
Iteris Far	# of detected vehicles	301	4037	2068	1612	n/a	9708	11390	2381	4377	6998	5673	3793	2790	1872	3043	825	822	1232
	%Difference from Ground Truth	-6.2%	11.9%	-16.9%	8.5%	n/a	2.2%	3.3%	0.7%	11.7%	-2.2%	-24.4%	-29.5%	-27.4%	-15.7%	-14.9%	-0.6%	7.7%	-3.8%
Iteris Near	# of detected vehicles	463	3745	1836	1549	n/a	8898	10679	2260	4333	6926	5544	3626	2671	1745	2690	766	722	999
	%Difference from Ground Truth	44.2%	3.8%	-26.2%	4.2%	n/a	-6.3%	-3.1%	-4.4%	10.6%	-3.2%	-26.1%	-32.6%	-30.5%	-21.4%	-24.8%	-7.7%	-5.4%	-22.0%
Ground Truth	n	321	3609	2488	1486	n/a	9499	11022	2364	3917	7157	7504	5378	3843	2220	3575	830	763	1280

Figure 14: Hourly Count Analysis Showing Percent Error

Note 1: n/a indicates no data available, this was a result of the random sampling process

Note 2: as a result of the random sampling of counts there was no count data represented from 10:00 to 11:00

Technologies for Traffic Detection (2002), where overhead devices over counted less than side mounted devices.

The greatest percent errors were found in the hours from 06:00 to 08:00 and from 16:00 to 20:00. These results were consistent with the results from Middleton and Parker (2002), where count accuracies were shown to decrease in time of congested flow. Lower percent errors occur from 11:00 through to 16:00. Iteris, both near and far, consistently under counted vehicles from 16:00 to 20:00, this time range encompasses the afternoon peak period; this is also consistent with Middleton and Parker's findings (2002). Autoscope had less undercounting during the afternoon peak period with undercounting ranging from -0.3 to -2.3 percent from 16:00 to 19:00. Undercounting for Autoscope then increased significantly to -28.3 percent during the 20:00 hour: however, no explanation for this could be determined. As congestion increases, sensors under count due to problems with occlusion; not being able to delineate the space between vehicles. From a traffic operations perspective, under counting presents a problem in planning future infrastructure, estimating roadway wear as well as, daily signal timing this is because with higher than anticipated traffic volumes, infrastructure will not be planned to accommodate the needed level of service, roadways will wear faster and signal timing will not provide an adequate level of service.

4.4. LIMITATIONS OF THIS RESEARCH AND LESSONS LEARNED

This research had several limitations, some of which were known at the start of the project, some developed as the research progressed.

4.4.1. Installation and Calibration of Equipment

There were several challenges with equipment, installation and calibration, beginning with the placement of the inductive loops at the stop bar. The loops were inadequately installed past the stop bar; leaving vehicles stopped at the stop bar undetected. Not having the loops functioning at the stop bar necessitated manual video review of over 500 hours to establish ground truth for the stop bar analysis. This problem took away resources from other elements of this research.

The calibration and alignment of the video detection technologies was not done to ensure proper functioning for advance zone detection. Medina et al. (2008) found that further alignment, was required after several months of operation to ensure optimum operation of devices. Vendor and City of Winnipeg crews did not perform a secondary alignment for the research test intersection, leaving sources of device performance inadequacies in question.

During installation of all equipment, clocks on each device, the ground truth video camera and the control cabinet were not synchronized by the vendors. Along with no synchronization at the beginning of the research, each clock drifted at different rates. Clock synchronization should have been completed on a regular basis by the City of Winnipeg. This lack of synchronization resulted in possible introduced error when comparing ground truth to device performance.

For Matrix, there were not enough units provided by the vendor to test the device for advance zone detection. During installation, the vendor also could not get the count function working on the device, making testing Matrix for count accuracy impossible during this research.

4.4.2. Equipment Performance

In the advance zone, the inductive loops used for ground truth were found to be miss labeled in the City of Winnipeg control cabinet. Two of four advance zones did not have loops working, decreasing the number of zones available for analysis.

4.4.3. Available Resources

This research was a project conducted to aid the City of Winnipeg in selecting vehicle detection devices for use in Winnipeg. The City of Winnipeg required that the project be completed by March 31, 2013. Due to the tight timeline of the project, combined with the need to review over 500 hours of video, the first restriction was in the confidence level for each analysis. To decrease the number of ground truth calls required, the confidence level was decreased from the more common 95 percent level to the 90 percent level. The decrease in the confidence level makes this research more difficult to assess when compared to other similar studies, as most research is conducted at the 95 percent confidence level. The manual video review for the stop bar analysis resulted in more than 500 hours of video review, draining time away from other portions of the research such as analysis of the advance zone. The decreased analysis for the advance zone lead to comparing only the most significant (best and worst) weather, illumination, wind and traffic conditions found in the stop bar analysis, rather than all 24 conditions defined for this research. The intention of the research was to conduct an analysis of each weather, illumination, wind and traffic condition as done for the stop bar analysis at the 90 confidence with two percent error level of 1080 ground truth calls. Financial constraints of the project did not allow for sufficient ground truth segments to be analyzed by Miovision for the count analysis. The intention of the count analysis was to establish a 90 confidence level with a 2 percent error count, 96 bins (fifteen-minute intervals) for each weather, illumination, wind and traffic condition as outlined in the stop bar analysis.

4.5. OPPORTUNITIES FOR FUTURE SIMILAR RESEARCH

There are many ways to expand and strengthen this research, including the following:

- re-aligning the equipment after several months of operation to ensure optimal performance
- synchronizing all devices to the same time at installation and on a regular basis
- statistically significant count analysis for each condition by zone for both stop-bar and advanced zones, at the 95 percent confidence level
- re-conducting the detection analysis for stop-bar zone using inductive loops for ground truth
- re-conducting the advanced zone detection with all zones included
- expanding the advanced zone detection to all conditions
- expanding the count analysis to a statistically significant level for each hour of the day
- expanding the count analysis to a statistically significant level for each condition

5. CONCLUSIONS AND RECOMMENDATIONS

This research analyzed vehicle detection devices for use in Winnipeg. The research consisted of an environmental scan, sensor selection, field test design, stop bar detection analysis, advanced zone detection analysis and vehicle count analysis. The tested sensor products were: (1) Matrix Wavetronix SmartSensor (microwave), (2) Autoscope Encore (video), and (3) Iteris Vantage Edge 2 (video) sensors.

5.1. FIELD TEST

The intersection selected for the field test was Bishop Grandin Blvd and St. Mary's Rd in Winnipeg, Manitoba. This intersection has high traffic volume (24 350 AWDT in each direction), high speed limit (80 km/hr). The three devices were tested on the four eastbound lanes of Bishop Grandin Blvd. The four lanes consisted of two left turn lanes and two through lanes. Data and video collection was conducted from March through December, 2012.

Twenty-four conditions were identified for testing. The four major categories for these conditions were: weather, illumination, wind, and traffic. The conditions were defined to isolate temporal and climate conditions specific to Winnipeg. For the stop bar and advance detection analysis the Wilson binomial formula for accuracy was used to determine that 1080 calls per condition were for ground truth at a 90 percent confidence level with two percent error.

The field test was designed to compare data collected by the vehicle detection devices with ground truth provided by a mounted video camera and in pavement loop sensors located at the stop bar and advanced zone. Due to the location of the loop detectors at the stop bar, ground truth had to be established by manual video review. More than 500 hours of manual video review resulted in 34,324 ground truth calls.

For advanced zone detection analysis four zones were located across the lanes of the test intersection. Due to some difficulties in data transmission, only the through lanes of the intersection were analyzed. The in pavement loops were used as ground truth for comparison with device data.

5.2. RESEARCH FINDINGS

From the literature review several findings were confirmed during this research:

- The literature indicates that *environmental factors can significantly impact the capabilities and performance of non-intrusive technologies. Sensors have the tendency to work well under certain conditions and poorly under others.* Results from this research showed that environmental factors can have significant impacts. Daytime snow and fog conditions resulted in a decrease in accuracy of 4.0 to 8.2 percent. Nighttime snow conditions resulted in an accuracy decrease of 4.0 to 14.4 percent. There was no measureable decrease in this research with nighttime fog events. Nighttime rain conditions resulted in a substantial decrease in accuracy of 4.7 percent for Autoscope and a 6.7 percent decrease for Matrix.

- The literature indicated *that the performances of video detection systems are impacted by any environmental condition that reduces visibility. Lighting is the main concern, where night periods have more detection problems due to detection by vehicle headlights only. During day time, glare and shadows have been a concern.* The research found that for environmental factors impacting reduced visibility such as adverse weather, the video detection devices (Autoscope and Iteris) were negatively impacted by rain and snow. For illumination conditions the video detection devices were negatively impacted by dawn illumination conditions only.

Table 10 shows a summary of each of the assessed conditions for the stop bar zone and advanced zone detection analysis. In 20 conditions Iteris performed with the highest accuracy; of these 20 conditions, Matrix performed as well in three conditions (2, 13, 24). For two conditions, strong wind at cloudy noon (condition 20) conditions and strong wind at night (condition 19), Matrix performed best. Iteris' weaker performance is attributable to its high mounting height. For advanced zone detection, there were 12 analyzed conditions. In 11 of 12 conditions Iteris out performed Autoscope. For nighttime illumination conditions (condition 13), Autoscope performed best.

For this research ground truth counts were compared with, Autoscope, *Iteris Far* and *Iteris Near* counts. Ground truth for the count analysis was established by video review by Miovision Technologies. Seventy-six hours of count data were reviewed and included 67,256 vehicles. Count data varied in accuracy, both over and undercounting. *Iteris Far* performed the most accurately overall in terms of absolute error.

The detection devices performed best from 11:00 to 16:00. These five hours daily have moderate traffic flow and no problems relating to shadows, and nighttime detection, accounting for their strong performance.

In consideration of adverse weather, wind, illumination and traffic conditions in Winnipeg. Iteris performed with a higher accuracy and more consistently in stop bar zone, and advance zone sensitivity analysis. For counting performance, Autoscope counted more accurately than Iteris. Additional count analysis on a by condition basis in a statistically significant way is needed to confirm the outcomes of the count analysis.

Table 10: Best Performing Device Summary for Stop bar and Advanced Zone Detection

Condition Criteria		Stop-bar Detection Analysis	Advanced Zone Detection Analysis
Weather Conditions	description		
1	clear, day	Iteris	-
2	clear, night	Iteris/Matrix	-
3	rain, day	Iteris	Iteris
4	rain, night	Iteris	-
5	snow, day	Iteris	-
6	snow, night	Iteris	Iteris
7	fog, day	Iteris	-
8	fog, night	Iteris	-
Illumination Conditions			
9	noon, cloudy	Iteris	Iteris
10	dawn	Iteris	Iteris
11	sunny afternoon	Iteris	Iteris
12	dusk	Matrix	Iteris
13	night	Iteris/Matrix	Autoscope
Wind Conditions			
15	moderate, sunny afternoon	Iteris	-
16	moderate, night	Iteris	Iteris
17	moderate, cloudy, noon	Iteris	-
18	strong, sunny afternoon	Matrix	Iteris
19	strong, night	Iteris	-
20	strong, cloudy, noon	Matrix	Iteris
Traffic Conditions			
21	a.m. peak	Iteris	Iteris
22	p.m. peak	Iteris	Iteris
23	free flow, day	Iteris	-
24	free flow, night	Iteris/Matrix	-

This research provided information for the City of Winnipeg to aid in selecting an appropriate vehicle detection technology for use in Winnipeg's climate and traffic conditions. Besides the final outcomes of this research, much was learned about conducting testing vehicle detection technologies. Research planning, project management and the needed resources for this type of project are now better understood for future research.

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7. APPENDICES

A. LITERATURE REVIEW

A.1 Intrusive sensor technologies

A brief overview of the principles, stated capabilities, and limitations of intrusive technologies is described here. For more information, readers can consult the *Traffic Detector Handbook* (Klein, et al., 2006), or *A Summary of Vehicle Detection and Surveillance Technologies used in Intelligent Transportation Systems* (Mimbela & Klein, 2007).

An intrusive sensor is one that is either:

- embedded in the pavement of the roadway,
- embedded in the subgrade of the roadway, or
- taped or otherwise attached to the surface of the roadway.

All intrusive technologies have safety implications; personnel safety is a concern when these technologies must be installed or have maintenance conducted. For example, on congested freeways and arterials, volumes may be high at all times, not providing a window for safe installation. Traffic lanes are sometimes needed to be temporarily closed to provide safety for personnel during installation. Lane closures result in traffic disruptions; disruptions can be minimized if installation or maintenance are done during new construction or when the roadway will be closed for other reasons such as resurfacing. Roadway geometrics can make it difficult to obtain accurate counts using intrusive technologies, including geometries where there is significant lane changing or where vehicles do not follow a set path in making turns. Weaving sections can pose a problem because vehicles may be double-counted or missed altogether; this can be particularly problematic in urban areas (Klein, et al., 2006).

A.1.1 Inductive Loop Detectors

A.1.1.1 Principles of Operation

Inductive loops are the most common detector technology in use (Klein, et al., 2006). They are comprised of two main parts; one or more turns of insulated loop wire embedded in the pavement and an electronics unit housed in the controller cabinet as shown in Figure 15.

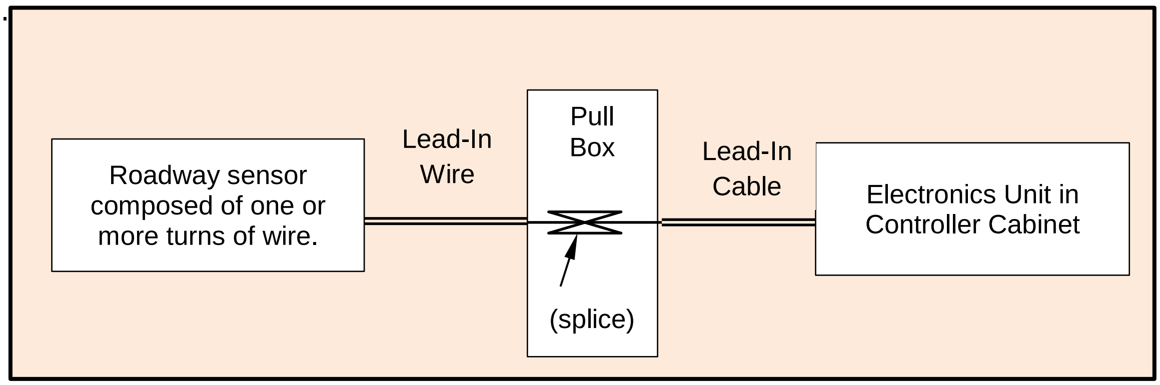


Figure 15: Inductive-loop detector system.

The electronics unit contains an oscillator and amplifiers that excite the embedded wire loop. When a vehicle passes over the wire loop or stops within the area enclosed by the loop, the metal in the vehicle causes a reduction in inductance and an increase in oscillator frequency. The electronics unit interprets this change in inductance and determines that a vehicle is present when the frequency change exceeds the threshold set by the sensitivity setting.

Conventional loop detectors are installed by cutting the loop shape in the pavement, laying the loop wire in the slot, and then covering the loop with sealant. The size, shape, and configuration of the loop vary depending on the specific application. Alternative installations include trenched-in loops installed below the pavement and encasing the loop wire in a plastic sleeve before placing in the saw-cut.

A.1.1.2 Application and Uses

Inductive loop detectors provide data for vehicle passage, presence, count, and occupancy. High frequency excitation models can provide classification data. Loops cannot directly measure speed, however speed can be determined using a two-loop speed trap or a single loop detector and an algorithm whose inputs are loop length, average vehicle length, time over the detector, and number of vehicles counted. Some newer versions of loops can classify vehicles by identifying different frequencies for specific metal portions from the undercarriage of vehicles.

A.1.1.3 Advantages of Inductive Loop Detectors

Inductive loop detectors are a mature technology, and in most cases are sufficiently accurate if properly installed and maintained. Because they are such a mature technology, transportation professionals are very familiar with the operational and maintenance needs of loops. Their flexible design makes them suitable for a wide variety of applications. Loops are generally insensitive to inclement weather conditions such as rain, fog, and snow. They are often the common standard for obtaining accurate occupancy measurements and provide the best accuracy for count data as compared with other commonly used technologies. Newer inductive loop detector electronics units and loop configurations are capable of vehicle classification.

A.1.1.4 Disadvantages of Inductive Loop Detectors

Installation and replacement of loops represent a significant cost when traffic control, motorist delay, and increased crash risk during installation and maintenance are considered. When loops are installed using a saw-cutting procedure the pavement is weakened and improper installation can decrease pavement life. Multiple loops are usually required to monitor a particular location.

A.1.2 Magnetic Detectors

A.1.2.1 Principles of Operation

Magnetic detectors (commonly referred to as an induction or search coil magnetometer) sense vehicles by measuring the change in the flux lines of the earth's magnetic field caused by vehicles metallic components.

These devices contain a single coil winding around a permeable, magnetic rod. The detector generates a voltage when a ferromagnetic object distorts the Earth's magnetic field. These detectors generally require a minimum speed (usually 5 to 8 km/h) to detect a vehicle because they measure a change in the magnetic field with respect to time.

A.1.2.2 Application and Uses

Magnetic detectors are simple, inexpensive, rugged devices that are only capable of a single pulse output. They are commonly used for traffic-actuated signal control or to count vehicles. Magnetic detectors can be installed in a nonferrous conduit and bored under the roadway, cored into the roadway or mounted under bridges. These detectors provide volume, lane occupancy, and speed data based on the detection zone size and an assumed vehicle length.

A.1.2.3 Advantages of Magnetic Detectors

Magnetic detectors are well suited for cold weather areas where deteriorated pavement and frost break wire loops. They are generally insensitive to inclement weather conditions such as rain, fog, and snow. Compared to loops they are less susceptible to traffic stress. Some models can be installed under the roadway without a need for pavement cuts, however, this requires boring under the roadway.

A.1.2.4 Disadvantages of Magnetic Detectors

Installation of magnetic detectors requires pavement cut, coring, or boring under the roadway and thus requires lane closure during installation. Because these detectors can only detect vehicles moving faster than a minimum speed, they cannot detect stopped vehicles.

A.1.2.5 Previous Studies

Cheung et al. (2009) evaluated the performance of wireless magnetic sensors downstream of a signalized intersection. During a 2 hour test, 332 vehicles were observed and the magnetic sensor had a detection rate of 99 percent (100 percent if motorcycles are excluded), and average vehicle length and speed estimates that were approximately 90 percent.

Middleton et al. (2009) evaluated detector technologies for application in Texas traffic signal systems. Global Traffic Technologies (GTT) magnetometers were installed underneath a bridge just prior to an intersection and detections were tested against recorded video data to assess detection accuracy. When compared to a base count of 327 vehicles counted by researchers watching recorded video data the GTT magnetometers over counted vehicles by as much as 5 to 7 percent. It was discovered that very slow moving or stopped vehicles (usually trucks) caused a “drop out” to occur; the detector would then re-detect the vehicle, resulting in the over-count. Researchers noted that the presence detection area at the stop line was small and that placing two magnetometers per location would be necessary to provide sufficient detection width.

A.1.3 Magnetometer

A.1.3.1 Principles of Operation

Fluxgate magnetometers operate similar to magnetic detectors; however they measure disturbances in both the vertical and horizontal components of the Earth’s magnetic field.

The two-axis fluxgate magnetometer is composed of a primary winding, two secondary windings, and a high permeability, soft magnetic core. One of the secondary windings in a two-axis fluxgate magnetometer senses the vertical component of a vehicle signature, while the other, offset by 90 degrees, senses the horizontal component of the signature. The horizontal axis of the magnetometer is usually aligned with the traffic flow direction to provide in-lane presence detection. Fluxgate magnetometers measure the passage of a vehicle when operated in the pulse output mode and in the presence mode they give a continuous output as long as either the horizontal or vertical signature exceeds a detection threshold.

A.1.3.2 Application and Uses

Magnetometers are used for vehicle presence detection and counting, similar to inductive loops. Typical applications are for signal control, vehicle presence detection on bridge decks and viaducts where inductive loops are disrupted by the steel support structure or weaken the existing structure, and temporary installations in freeway and surface street construction zones. Multiple magnetometers sharing a common signal processor have the potential to locate, track, and classify vehicles in a multilane scenario using a row of above-ground sensors.

A.1.3.3 Advantages of Magnetometers

Magnetometers provide a benefit over magnetic detectors because they can identify stopped vehicles in addition to performing the other capabilities of magnetic detectors. Compared to inductive loops, magnetometers survive longer in crumbly pavements and require fewer linear feet of saw cut. Magnetometers can detect two vehicles separated by a distance of a foot which potentially makes the magnetometer as accurate as or better than the inductive loop detector at counting vehicles. They can hold the presence of a vehicle for a considerable length of time and do not exhibit crosstalk interference. Some models can transmit data over a wireless frequency link.

A.1.3.4 Disadvantages of Magnetometers

Installation and maintenance require pavement cuts or boring which require lane closure, and can decrease pavement life when improperly installed. Models with small detection zones require multiple units for full lane detection. Magnetometers are not a good locator of the perimeter of the vehicle because there is an uncertainty of about ± 45 cm; therefore two closely spaced magnetometer sensors are preferred for determining occupancy and speed in a traffic management application.

A.1.3.5 Previous Studies

Day et. al. (2010) conducted a five day analysis of a Sensys Networks Inc. wireless magnetometer at two left-turn pockets of an actuated, coordinated signalized intersection. They found that this detection technology provided “extremely similar performance” to inductive loop detectors. During 240 hours of ground truthed data the magnetometer had 15 false calls and 44 events where the product was stuck on until another vehicle arrived. The authors also tested magnetometer spacing and reported that blind spots were found to lead to a large number of missed calls when positioned at 15 foot spacing and recommend that an 8 foot spacing of the sensors adjacent to the stop bar be used to minimize missed calls.

The California Center for Innovative Transportation (CCIT) (Margulici, et al., 2006) evaluated the performance and effectiveness of Sensys Networks Inc. wireless magnetometers on freeways. Data was collected from four wireless sensors for two weeks, from 05:00 to 22:00 each day. CCIT reported that it takes less than 15 minutes per sensor to complete an installation. Based on calibration data from inductive loop detectors, the detection events were considered to be approximately 95 percent valid, compared to six video samples lasting five minutes each, the detection events were considered to be approximately 98 percent valid. Motorcycles were undercounted and, some double counting occurred during heavy congestion.

ARRB Consulting conducted tests on battery, temperature and humidity, durability, detection zone, and transmission range performance of the Sensys magnetometer. They reported that “The overwhelming positive results from all laboratory tests lead to the conclusion that the research move on to Stage 2 of the research – controlled field tests” (p. 56). However, the magnetometer failed the humidity test and it is recommended that tests be conducted in wet-weather field scenarios.

The Illinois Center for Transportation (Medina, et al., 2009) evaluated Sensys Networks Inc. wireless magnetometers detection performance at a signalized intersection with three approaching lanes. The study period was 52 hours and there were approximately 11,000 vehicles detected across the three lanes at the stop bar zone and an advance zone. At the stop bar zones, false calls occurred on all three zones and the proportions ranged from 13.5 percent to 19.6 percent. There were only six missed calls and these were mostly observed for motorcycles. Two stuck-on and three dropped calls were reported. At the advance zones, false calls varied between 0.7 and 2.4 percent. Missed calls ranged from 0.9 to 10 percent. Most missed calls were due to vehicles travelling between lanes, but motorcycles and some vehicles were missed while travelling straight over the sensors. No stuck-on or dropped calls were observed at advance zones.

Medina et al. (2011a) then evaluated detector performance at the same installation and test location in winter conditions (25 hours of data) and rain (20 hours of data). At the stop bar zones, the overall frequency of false calls due to vehicles in the adjacent lanes ranged from 7.7 to 15.4 percent per lane in the winter data and between 2.6 and 6.2 percent in the rain data. There were seven stuck-on calls, two missed calls, and no dropped calls. At the advance zones, frequency of missed vehicles ranged between 0.4 and 5.4 percent in the winter condition, and between 0.8 and 9.7 percent in the rain condition. False calls ranged on average from 1 to 4 percent. No stuck-on calls or dropped calls were found at the advance zones.

A third research project was completed by Medina et al. (2011b) to evaluate the sensors' performance one year after the initial installation. Results did not show any significant changes one year after the system was in use, except for a decrease in the frequency of false calls due to vehicles in adjacent lanes (from a range of 5.6 -7.6 percent, to a range of 0.8 - 2.4 percent).

Middleton et al. (2009) evaluated detector technologies for application into Texas traffic signal systems. Global Traffic Technologies (GTT) magnetometers were installed underneath a bridge just prior to an intersection and detections were tested against recorded video data to assess detection accuracy. Sensys Networks magnetometers were installed and compared to data collected from inductive loops; recorded video data was then used to explain discrepancies. The report indicates that the Sensys magnetometers over count from 3 to 8 percent and that the largest source of false calls was caused by a communication interruption between the magnetometers and the Sensys Networks Access Point. The researchers also stated that Sensys software systems raised some concerns. They stated "Based on the TTI (Texas Transport Institute) experience compared to vendor statements, the software does not fully accomplish the manufacturer's intended purposes and needs considerable work. TTI experienced difficulty getting all the communication elements to function as intended, and that difficulty rendered the system completely useless without technical support" (p. 54).

A.1.4 Piezoelectric

A.1.4.1 Principles of Operation

Piezoelectric material converts kinetic energy to electrical energy. When a vehicle passes over a detector, the piezoelectric material generates a voltage proportionate to the force or weight of the vehicle. However, the material only generates a voltage when the forces are changing so the initial charge will decay if the force remains constant.

A.1.4.2 Application and Uses

Piezoelectric sensors can provide data for vehicle counts, vehicle classification, speed, and vehicle weight. They have the ability to classify vehicles by axle count and spacing. A multiple-sensor configuration is required to measure vehicle speeds. "Piezoelectric sensors are mainly used for traffic data collection and weight enforcement" (Martin, et al., 2003).

A.1.4.3 Advantages of Piezoelectric

Piezoelectric sensors can differentiate individual axles with a high degree of accuracy. They provide more information than inductive loops in the form of improved speed accuracy, and the ability to determine the classification of a vehicle based on weight and axle spacing while being only marginally more expensive on an installed cost basis.

A.1.4.4 Disadvantages of Piezoelectric

The disadvantages of these sensors are similar to those of inductive loops sensors in that they include disruption of traffic for installation and repair, failures associated with installation in poor road surfaces, and use of substandard installation procedures.

Resurfacing of roadways and repairs can require the reinstallation of these sensors. Piezoelectric sensors can also be sensitive to pavement temperature and speed.

A.1.4.5 Previous Studies

No literature was found discussing the application or accuracy of piezoelectric sensors with respect to vehicle detection for applications considered in this research.

A.2 Non-Intrusive sensor technologies

Non-intrusive sensors are ones that are mounted either above the roadway surface or adjacent to the roadway and are therefore not embedded in or on the pavement. Non-intrusive technologies have many advantages in providing historical and real-time traffic data compared to the traditional in-roadway vehicle sensor technology.

They cause minimal disruption to normal traffic operations during installation, operation, and maintenance and thus can be deployed more safely than conventional detection methods. In addition to ease of installation and maintenance, there is preference for this technology to also provide ease of data transmission and have the capability of classifying vehicles and speeds. They also have lower life-cycle costs and comparable levels of data accuracy to traditional intrusive technologies.

Some common issues of non-intrusive technologies include (Associated Engineering, 2010):

- Vehicles observed from beside or above are sometimes hidden from the view of the sensor by a larger vehicle;

- Environmental impacts can significantly affect the capabilities and performance of the technology. Sensors have the tendency to work well under certain conditions and poorly under others;

- Often cannot collect data according to FHWA's 13-category vehicle classification system.

A.2.1 Video Image Processor

A.2.1.1 Principles of Operation

A video image processor (VIP) system consists of one or more cameras, a microprocessor-based computer for digitizing and analysing imagery, and software for interpreting the images and converting them into traffic flow data. The algorithms used in VIP are designed to detect objects identified as automobiles, trucks, buses, motorcycles, and bicycles, by examining variations in color shading of groups of pixels between successive frames and ignoring gray level or color variations in the stationary background and variations caused by weather conditions, shadows, daytime or night-time artifacts (Klein, et al., 2006).

The detection process of a VIP system is illustrated in Figure 16. The firmware (camera) runs real-time algorithms for image formatting and data extraction.

The video imagery is commonly digitized and stored in a computer where algorithms are then used to extract spatial and temporal features in each detection zone. Integrated video imaging vehicle detectors (VIVD) have integrated the camera unit with the image processor into one device unit (Anzai, et al., 2005).

The series of thresholds in the algorithms used at the vehicle detection stage segregate the data that will be passed on to the rest of the algorithms for classification, identification, and tracking. False vehicles may be identified at the detection stage, but an actual vehicle is only recorded once the data has successfully passed through all algorithms (The Vehicle Detector Clearinghouse, 2007).

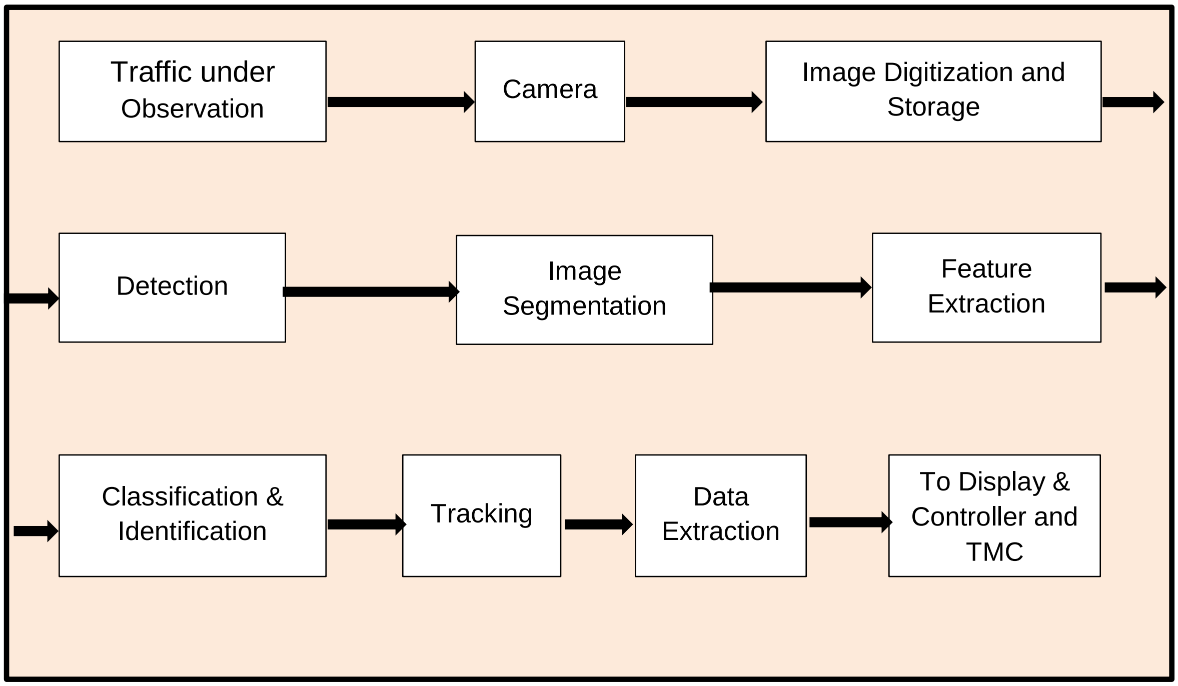


Figure 16: Procedure for Image Processing for Vehicle Detection

The image is divided into smaller areas, typically individual vehicles, through Image segmentation. The image pixels are then analysed for feature extraction and where a sufficient number of pre-determined characteristics are identified, a vehicle is declared present and its flow characteristics are calculated. Video Image Processors that have tracking capabilities estimate vehicle trajectories by time trace of vehicle positions to provide lane change and turning movement.

A.2.1.2 Application and Uses

Video image processing (VIP) is able to automatically analyze a traffic scene through the analysis of black and white or color imagery gathered by cameras to classify vehicles by length and determine vehicle presence, volume, lane occupancy, and speed for each class and lane. Some VIPs can track vehicles and have the ability to register turning movements and lane changes (U.S. Federal Highway Administration, 2006).

One camera can provide detection over several lanes, while multiple cameras can be used in one VIP system to extend the area of detection. VIP cameras mounted on the side of a roadway require a higher mounting height of 9.14 to 15.24 metres (30 to 50 ft.) relative to a camera mounted in the middle of a roadway 6.10 metre (20 ft.). As the mounting height of the camera decreases, the error of measurement of speed increases (The Vehicle Detector Clearinghouse, 2007).

A.2.1.3 Advantages of Video Image Processors

Video technology can provide a wide range of traffic information in addition to the conventional data, such as dwell time, lane change, incident detection, and origin-destination information, and also provide surveillance information (Kranig, et al., 1997).

VIP signal processing algorithms have the ability to identify shadows, illumination changes, reflections, inclement weather, and camera motion from wind or vehicle-induced vibration (The Vehicle Detector Clearinghouse, 2007). However, false identifications still exist, with different video sensor products using different algorithms.

A VIP system is generally cost-effective for a traffic view requiring many detection zones and provides more flexibility in the installation location, such as on bridges.

A.2.1.4 Disadvantages of Video Image Processors

Depending on the VIP product and the algorithm used, some limitations include vulnerability to viewing obstructions, inclement weather, shadows, vehicle projection into adjacent lanes, occlusion, camera motion caused by strong winds, day to night transition, vehicle/road contrast, water, salt grime, icicles, and cobwebs on camera lens. Proper setup and calibration is essential to achieving satisfactory performance in poor lighting conditions, such as headlight glare on wet pavement, poor vehicle-road contrast, and low angle sunlight.

Installation and maintenance of video devices is much more involved than other types of technologies. In addition, for optimum performance of a side mounted configuration a mounting height of 15.24 metres (50 ft.) or greater may be required (The Vehicle Detector Clearinghouse, 2007).

A.2.1.5 Previous Studies

Yu et. al. (2009) tested the accuracy and reliability of the Autoscope Rack Vision Terra length-based classification using a five vehicle classification scheme (motorcycles, light duty vehicles, single unit trucks, articulated trucks, and multi-unit trucks). During one test the overall classification accuracy was 90 percent during daytime but only 61 percent during nighttime conditions. The classification accuracy was affected by bright light (glare) such as direct or reflected sunlight in the morning or artificial light such as car headlamps at night, shadows from surrounding obstacles (e.g. trees, and buildings) and weather variation. They concluded that the sensor may be incapable of discerning motorcycles from light duty trucks and a simplified classification scheme using 2 to 3 classes may be more suitable. In comparison to the other two tested sensor technologies in this study, the TIRTL active infrared sensor provided the most reliable classification under ideal conditions while the SmartSensor HD microwave radar device had the poorest classification performance.

Medina et. al. (2008) and Medina et. al. (2009) evaluated the performance of Image Sensing Systems-Autoscope Solo Pro (version 8.13) , Peek Unitrak (version 2.2), and Iteris Edge 2 video detection systems (VDS) at both advanced and stop bar detection areas under various configuration changes, illumination conditions, windy conditions, and adverse weather conditions. The results from each condition effects are published in separate volumes (Volume 1-4) and the summary is provided below.

After preliminary analysis of the three detectors from the initial setup, the manufacturers/distributors made changes to the camera configurations to improve the detector's performance. Configuration changes were mainly made to the Peek and Autoscope with minor changes to the Iteris video detection zones and other detection properties. It was found that in general, dropped and missed calls decreased at stop bar locations during night-time, however false calls increased during both day and night-time. It was concluded that there are trade-offs between false, missed, and dropped calls, and that even after improvements made to the detector the performance of the detector must continue to be monitored for occurrence of different error types (Medina, et al., 2008).

The three devices were tested under five illumination conditions: dawn, sunny morning (long shadows), cloudy noon, dusk, and night. Detection errors were the lowest in cloudy noon illumination conditions, with the main cause of errors being the image of tall vehicles falling on the adjacent lane generating false calls. The results indicated that low illumination and shadows increased false calls and stuck on calls. However, missed calls increased for only one VDS at the stop bar and there were only minor changes in the advance locations (Medina, et al., 2009),

The effect of windy conditions was evaluated for the three devices. The authors reported that wind affected day time performance mostly in sunny conditions where false calls notably increased. These increases were caused mostly due to vehicles on the adjacent lane placing false calls that flickered on and off when the camera image moved because of the wind (Medina, et al., 2009).

The effects of various adverse weather conditions were also evaluated. It was found that the video detector's performance was not greatly impacted under daytime light fog or rain conditions without wind, but were significantly impacted by dense fog and snow in daytime, and snow and rain in night time. During dense fog the Autoscope and Iteris placed constant calls due to loss of image contrast (13 percent and 75 percent error, respectively), while the Peek significantly increased its missed calls. Snow in daytime and night time resulted in over 50 percent false calls for all three devices, with limited effects on missed, stuck-on, and dropped calls. Peek video had the worst performance at both stop bar and advanced locations during snow at day and night conditions (up to 91 percent at day and 87 percent at night) (Medina, et al., 2009).

Chitturi (2007) evaluated the accuracy of the Iteris Edge 2 and Autoscope SoloPro for traffic counting at stop bar and advanced locations approximately 250 feet away. They found that during cloudy daytime conditions advance counts provided significantly lower error than stop bar counts and at night there was an increase in errors for both locations.

Rhodes et. al. (2006) evaluated the Autoscope (version 8.10), Peek UniTrak (version 2), and Iteris Vantage (Camera CAM-RZ3) stop bar VDS at signalized intersections. They conducted two 48 hour tests four months apart which showed that all three detectors had a moderate to high number of missed and false calls, the accuracy of all three systems degraded with time, and it appeared that a recalibration was necessary to maintain their performance. The Econolite Autoscope produced the most false calls with the least number of missed calls. In contrast, the Peek had the highest number of missed calls; however was the least susceptive to headlight effects. The Iteris had the best performance in the first test but had a significant degradation over time and required recalibration.

Rhodes et. al. (2005) evaluated the performance of the Econolite Solo Pro on four approaches of an intersection, installed at the vendor recommended camera position of

60 feet from the strain pole (vendor recommended location) and at the less optimal positions of 36 and 48 feet from the strain pole, for less expensive options. Data analysis over a 24 hour period showed that the video detection produced statistically significant more false detections and missed detections than inductive loop detectors on most phases. A small incremental increase in performance was observed when the camera was mounted at the recommended 60 feet rather than 36 feet.

The Minnesota Department of Transportation (DOT) in cooperation with SRF Consulting Group Inc. (2002) tested the performance of the Traficon Video Image Processor and the ISS Autoscope Solo. Three people were required to complete the camera installation; two to mount and aim the camera and a third to provide calibration. The cameras were mounted at a height of 32 feet and monitored two lanes of traffic, however the vendor indicated the sensor would perform better if it were mounted higher and further away from the intersection. Data was collected for one day with both cameras monitoring two lanes. Test data for the Traficon camera revealed that the sensor over-counted vehicles in the right turn lane by 17 percent and undercounted vehicles in the through lane by 13 percent. The Autoscope camera over-counted vehicles in the right turn lane by 18 percent and there was a 19 percent absolute difference in the through lane. Overall, the two detectors performed well with no significant difference in performance, installation, calibration, or reliability between the two sensors.

Grenard (2001) evaluated the accuracy of vehicle counts using Econolite Autoscope and Peek Video Trak 905 video systems in Indiana. It was found that although the Autoscope counts were closest to the observed counts; neither provided accurate presence detection for turning movement counts and during less than optimal conditions such as high wind, fog, and rain. Under worst-case conditions the missed calls were approximately 16 and 20 percent, and generated false calls more than 40 percent of the time. The main concern was identified as nighttime detection where vehicles often caused early detection calls due to the headlights, thereby extending the effective detection zone and reducing efficiency of the signal. Missing or dropping calls of vehicles past the stop bar due to not detecting the headlights out of the detection zone were a concern. A major shortcoming of video detection was cited as its inability to provide dilemma zone detection. Subsequent to this study, a consensus of video detection vendors recommended lighting the intersection, raising the camera height from 30 to 40 ft, and locating cameras in optimal positions along the projection of the lane line separating the left-turn and the through lanes (Rhodes, et al., 2005). Extending the detection zone past the stop bar may also help for stop bar vehicle detection at night.

A.2.2 Microwave Radar

A.2.2.1 Principles of Operation

Microwave radar technology is used for vehicle detection by transmitting microwave signals and receiving echoes from targeted objects within its range of frequency coverage. Microwave is the transmitted energy with a wavelength ranging between 1 and 30 cm, equivalent to 1 GHz and 30 GHz. The transmitted microwave wavelengths for traffic data collection in the U.S. regulated by The Federal Communications Commission (FCC) are typically near 10.5, 24.0, and 34.0 GHz (The Vehicle Detector Clearinghouse, 2007).

There are two types of microwave radar sensors used in traffic management applications: (1) continuous wave (CW) Doppler radar and (2) frequency modulated continuous wave (FMCW).

The CW Doppler sensor transmits a signal that is constant in frequency with respect to time. This type of sensor detects moving vehicles and determines their speed from the change in frequency of the reflected signal caused by the moving vehicle.

In contrast, the FMCW radar sensor transmits a frequency that is constantly changing with respect to time and can detect the presence of motionless vehicles. The radar device divides the field of view of each lane into smaller zones referred to as range bins. The speed of vehicles is estimated from the time difference corresponding to a vehicle arriving at the leading edge of two range bins over the distance between the range bins (The Vehicle Detector Clearinghouse, 2007).

A.2.2.2 Application and Uses

The radar sensor can be mounted over the center of a lane to monitor a single lane of traffic or at the side of a roadway to monitor traffic across several lanes.

The type of traffic data received by microwave radar depends on the type of wavelength transmitted. The CW Doppler radar can detect vehicles in motion only, from the change in the reflected signal frequency. They can be used for direction dependent vehicle detection, measurement of vehicular volume and speed, and data for the activation and extension of green signal phases.

The FMCW radar can detect motionless vehicles and is used to control left turn signals, provide real-time volume, monitor traffic queues, and collect occupancy and speed data (multi-zone models only) (The Vehicle Detector Clearinghouse, 2007).

A.2.2.3 Advantages of Microwave Radar

This technology is typically insensitive to harsh weather conditions at the relatively short ranges encountered in traffic management applications. It also has the ability of multiple lane operation and direct speed measurement (U.S. Federal Highway Administration, 2006).

A.2.2.4 Disadvantages of Microwave Radar

The Doppler sensors cannot detect stopped (motionless) vehicles unless equipped with an auxiliary sensor. It has been found that the Doppler sensor has poor counting performance at intersections (Kranig, et al., 1997).

A.2.2.5 Previous Studies

Yu et. al. (2009) tested the accuracy and reliability of the Wavetronix Smartsensor HD length-based classification using a five vehicle classification scheme (motorcycles, light duty vehicles, single unit trucks, articulated trucks, and multi-unit trucks). They reported that the classification of each vehicle JR class was inadequate for practical uses. Accuracy generally degraded from nearer lanes to farther lanes and missed and double counts increased during congested periods. The SmartSensor HD microwave radar device had the poorest classification performance in comparison to the other two tested sensor technologies in this study, the TIRTL active infrared sensor and the Autoscope video.

Middleton et al. (2009) tested the Wavetronix SmartSensor Advance to determine its capabilities for providing dilemma zone protection to motorists. It was found that the detector is better at detecting gaps in the stream of traffic than video detection systems. The data analysis indicated an average decrease of 4.81 percent in red-light-running within the first 2 sec after the onset of red and an average increase of 0.67 percent in red-light-running between 2 to 4 sec after red start on phase 2 when using the SS-200 detector compared to video detection. The authors report that the detector is not affected by light or weather conditions and causes little to no traffic disruption during installation.

They describe the user interface to be intuitive, and that the software to setup and configure the detection zones and enter data elements was easy to use while providing real-time visual feedback on sensor operation.

Sharma et al. (2008) compared the performance of the Wavetronix Advance detector as a type of wide area detector (WAD) to loop detectors as a type of point detectors, in terms of dilemma zone protection. In theory, a WAD significantly benefits dilemma zone protection by detecting the actual position and speed of every vehicle in the dilemma zone instead of using extrapolated values. The test was conducted with 100 passing vehicles. It was found that the WAD generated a large number of false calls for vehicle entrance and exit on turning traffic and standing queues, however it performed satisfactorily on tracking the vehicle's position and speed. Overall, the detector showed considerable potential for dilemma protection with some improvements for the detection and tracking accuracy.

Kotzenmacher et al. (2005) tested the EIS Remote Traffic Microwave Sensor (RTMS) and the Wavetronix SmartSensor on a freeway location. They were found to provide reliable three-class classification. This finding is in contrast to the Yu et al. (2009) study stated previously, where the SmartSensor was tested for a five-class classification scheme. It was found adverse weather such as rain or snow had no impact on both sensor's performance, however severe weather conditions such as extreme heavy precipitation or snow may have an impact.

Edgar (2002) tested a Remote Traffic Microwave Sensor (RTMS) manufactured by Electronic Integrated Systems, Inc. to evaluate its capabilities to function as a viable detection device at a signalized intersection. The device was installed in between two signalized intersections on a bridge structure at 105 meters from both intersections for a period of 4 weeks, and provided “extension” and “call” functions for the signal controller. The data showed the microwave detector undercounted the loop detectors by an average of 5.7 percent; however it is not believed to be significant enough to affect proper operation of the signal controller. Some potential errors may be due to undercounting small vehicles hidden by larger vehicles in adjacent lanes, motorcycles, tailgating traffic with spacing less than 1.7 meters, and vehicles not travelling in lanes, and over counting due to slow moving traffic, and vehicles changing lanes.

A.2.3 Infrared Sensors

A.2.3.1 Principles of Operation

Infrared technology is used for signal control, volume, speed, and class measurements, and pedestrian detection. The sensor converts the reflected or emitted energy into electrical signals which is processed in real-time for the detection of vehicles. Two types of infrared technology are used for traffic applications: active and passive.

Active infrared sensors transmit multiple low energy laser beams to a target area on the pavement and measure the time for the reflected signal to return the sensor. The reduction in time for the signal return measures the presence of a vehicle.

Passive infrared sensors do not transmit energy of their own; rather they detect emitted energy from vehicles, road surfaces, and other objects in their field of view, and the atmosphere. They can be designed to receive emitted energy at any frequency. When a vehicle enters the sensor’s monitoring area, the change in the emitted energy is used to detect the vehicle. The emissivity difference between the road and vehicle and the temperature difference between the road and the atmosphere are the measuring factors (The Vehicle Detector Clearinghouse, 2007).

A.2.3.2 Application and Uses

Active infrared sensors, depending on the device, have the capability of detecting volume, presence, density, length, speed, and number of axles. Some sensors have the ability to classify 11 types of vehicles and are used on toll roads. Multiple units can be installed at the same intersection without signal interference from one another.

Passive infrared sensors with single detection zones measure volume, presence, lane occupancy and speed (with multi-zone sensors). Multi-zone sensors can also measure speed and classify by length, where one device can replace the functionality of two inductive loops.

A.2.3.3 Advantages of Infrared Sensors

Active infrared sensors transmit multiple beams for a more accurate measurement of vehicle position, speed, and class (The Vehicle Detector Clearinghouse, 2007). Multi-zone passive infrared sensors can also measure speed. Side-mounted models can detect multiple lanes.

A.2.3.4 Disadvantages of Infrared Sensors

Infrared sensors require periodical lens cleaning due to dirt and road grime accumulating on the lens; this requires a lane closure. Also, the near sided sensors are limited by occlusion.

Glint or glare from sunlight may cause confusing signals. The sensors may also have reduced sensitivity to vehicles in inclement weather conditions. Atmospheric particulates and inclement weather that cause water concentrations such as fog, haze, and rain, or other obscurants such as smoke and dust can scatter or absorb energy that should be directed to the sensor. As a rule of thumb, there is a high probability that the sensor will detect the vehicle if a human observer can see the vehicle under the same conditions. (The Vehicle Detector Clearinghouse, 2007)

A.2.3.5 Previous Studies

Yu et al. (2009) tested the accuracy and reliability of the TIRTL active infrared axle-based classification. The TIRTL provided adequate accuracy for FHWA classification scheme based on axle count and separation, best performance relative to the other two tested sensors (Autoscope video and SmartSensor microwave); however, the equipment is required to be deployed on flat pavements without pronounced crowns to provide positive performance.

A.2.4 Ultrasonic Sensors

A.2.4.1 Principles of Operation

Most ultrasonic sensors transmit pulse waves of sound energy with frequencies between 25 and 50 KHz and provide vehicle presence, occupancy, speed, and count information. The sensor measures the time it takes for the pulse wave in the area of detection to be transmitted and reflected back to the sensor. When a distance other than that to the road surface is measured, a vehicle is detected. The received ultrasonic energy is converted into electrical energy and analyzed by signal processing electronics.

Some ultrasonic sensors use the Doppler principle with constant frequency waves rather than the pulse waveform for the measurement of speed. However, these devices are more expensive.

A.2.4.2 Application and Uses

Doppler ultrasonic sensors can detect volume, presence, and speed while pulsed ultrasonic sensors can detect volume, presence, classification, and occupancy (Ngo-Quoc & Zhu, 2003) . They can be used in combination with other sensor technologies to enhance presence and queue detection, vehicle counting, and height and distance discrimination (The Vehicle Detector Clearinghouse, 2007).

The range measuring, pulse ultrasonic sensors can be mounted looking downward onto the roadway or from the side perpendicular to the vehicles. An automatic pulse frequency control is implemented to allow the detection of high speed vehicles by reducing the time repetition period as much as possible. A pulse is transmitted immediately after the reflected signal from the road is received. A hold time is also built into the sensor to enhance vehicle detection, with values from manufacturers ranging between 115 ms to 10 s (The Vehicle Detector Clearinghouse, 2007).

A.2.4.3 Advantages of Ultrasonic Sensors

The installation of this device is non-intrusive and some models provide multiple lane detection.

A.2.4.4 Disadvantages of Ultrasonic Sensors

Ultrasonic sensors are limited by environmental conditions that inhibit the propagation of sound wave such as extreme air turbulence. Some models may be sensitive to temperature variation, while some models take into account the effects of temperature. Appropriate pulse repetition time is required for accurate vehicle counts, where large gaps between transmitted pulses may result in missed vehicle detection on medium to high speed roadways.

The models that provide single lane detection require a detection device for each lane of an intersection that must be mounted overhead above the lane, possibly posing an aesthetic problem.

A.2.4.5 Previous Studies

No literature was found discussing the application or accuracy of ultrasonic sensors.

A.2.5 Passive Acoustic Array Sensors

A.2.5.1 Principles of Operation

Acoustic sensors consist of an array of microphones that detect acoustic energy or audible sounds produced by vehicles passing through the detection zone, through the interaction of the vehicle's tires with the road and from a variety of sources within the vehicle. The increase in sound above the threshold from a vehicle entering the detection zone is identified by algorithms and a vehicle presence signal is generated. The speed of a vehicle is calculated through an algorithm based on an assumed vehicle length.

Acoustic sensors are equipped with two-dimensional array of microphones. Two types of acoustic sensors are available: SmartSonic and SAS-1. SmartSonic sensors measure the time delay between the arrival of sound at the upper and lower microphones when a vehicle is outside the detection zone. Once the vehicle is in the detection zone the sound is received immediately by both microphones. SAS-1 sensors are equipped with fully populated microphone array and adaptive spatial processing to form multiple zones that receive acoustic signals.

A.2.5.2 Application and Uses

The SmartSonic sensors are recommended for use on bridges and other roads where over-roadway technology is required. They can also be used where stop-and-go traffic is not present. The SAS-1 sensor provides data on volume, lane occupancy, and average speed for each lane over a period of time selected by the user. Vehicle presence is optionally available.

A.2.5.3 Advantages of Acoustic Sensors

The installation of these sensors is non-intrusive. They are insensitive to precipitation and some models provide multiple lane detection.

A.2.5.4 Disadvantages of Acoustic Sensors

Passive acoustic sensors are limited by environmental conditions that inhibit the propagation of sound wave such as strong winds and heavy snowfall or precipitation (Ngo-Quoc & Zhu, 2003). Cold temperatures may have an effect on the vehicle counting performance of the sensor. Loud vehicles, such as trucks, in adjacent lanes can result in false calls and some models are not recommended for slow moving vehicles in stop-and-go traffic.

A.2.5.5 Previous Studies

The city of Los Angeles tested the SmarTek SAS-1 sensor with a side-mounted overhead configuration. It was found that the sensor was relatively easy to install and demonstrated a high degree of accuracy and precision in vehicle detection. The detector’s count accuracy was found to be equal to loop detectors for a two- to three-lane roadway. Peak daily accuracy levels of 99.99 percent was found relative to loop detectors and 99.8 percent relative to adjusted true traffic volumes. The disadvantages were the requirement of manual calibration and the relatively high cost. (Middleton & Parker, 2002)

Kotzenmacher et al. (2005) in a MnDOT and SRF Consulting research, found that the SAS-1 sensor (along with the RTMS and SmartSensor microwave technologies) provided fairly reliable three-class classification.

The Minnesota Department of Transportation in cooperation with SRF Consulting Group Inc. (2002) tested the performance of the SmarTek SAS-1. They report that the sensor is easy to install and calibrate and the interface is user friendly while providing real-time and historic data. The sensor performed best when installed at a 45-degree angle to the roadway by allowing the sensor to receive the strongest acoustic signal. It was mounted side-fire at a height of 15 ft. Vehicle presence was evaluated at the intersection location by manually comparing the sensor output to vehicles observed approaching the intersection and was found to be 100 percent accurate during minimal testing. On the freeway location the sensor was observed to undercount vehicles during heavy congestion traffic, with the 24-hour count accuracy ranging from 6 to 12 percent at the vendor recommended location.

In the Phase 1 of the Minnesota DOT study (1996), the authors also tested the SmartSonic TSS-1 and found that this device over counted vehicles at intersection sites. The speed accuracy was ± 10 percent compared to loop detection.

A.3 Combined Technologies

In order to take advantage of the strengths of different sensors, vehicle detectors are developed with combination of different technologies in one device. The availability and experience with these multisensory non-intrusive technologies is limited. While the cost for the systems can be significant, they provide a means to overcome limitations associated with individual technologies. (Associated Engineering, 2010) ASIM Technologies have developed sensors that combine passive infrared detection with ultrasonic radar to provide enhanced accuracy for presence and queue detection, vehicle counting, and height and distance discrimination. (Ngo-Quoc & Zhu, 2003) They also developed the combination of passive infrared with Doppler radar sensor for presence and queue detection, vehicle counting, speed measurement, and length classification. The Doppler radar measures high to medium speeds while passive infrared measures vehicle count and presence. Their microprocessor control signal combines the signal from both detector parts to provide accurate vehicle detection information.

A.3.1 Passive Infrared/Ultrasonic

The Minnesota Department of Transportation (DOT) in cooperation with SRF Consulting Group Inc. (2002) tested the performance of the ASIM DT 272, an ultrasonic/passive infrared technology developed in Switzerland. This product provides single lane detection for short distances, maximum 11.89 metres (39 ft.) for horizontal and vertical detection and 6.10 metres (20 ft.) for diagonal side-fire mounting. The authors reported that the sensor performed effectively in a variety of configurations and that installation and calibration were simple. At the intersection installation, vehicle presence was evaluated by manually comparing the sensor output to vehicles observed approaching the intersection and was found to be 100 percent accurate during minimal testing.

A.3.2 Ultrasonic/passive infrared/Doppler Radar

The Minnesota Department of Transportation (DOT) in cooperation with SRF Consulting Group Inc. (2002) tested the performance of the ASIM TT 262 that combines three sensor technologies for detecting vehicles in a single lane of traffic on a freeway, facing downward from above the roadway. It was found that the sensor was easy to install and calibrate, taking approximately 30 minutes. The sensor can provide count, speed, presence, and classification. The sensor provided accurate speed and volume results at the freeway test site, with an absolute difference between sensor and loops of 4.4 percent at 6.40 metres (21 ft.) and 3 percent at 5.18 metres (17 ft.) mounting height for speed accuracy and 2.8 percent at 6.40 metres (21 ft.) and 4.9 percent at 5.18 metres (17 ft.) height for count accuracy. Overall, the detector showed excellent performance.

B. JURISDICTIONAL SURVEY

A part of this project was a survey was distributed to 299 jurisdictions in Canada and United States (U.S.) to identify their preferred advanced vehicle detection product, products currently in testing, and products other than the preferred, which have provided positive results regarding detection, counting and classifying.

The survey included 221 Canadian jurisdictions and 78 U.S. jurisdictions. The survey was conducted over a two week period from July 28, 2011 to August 12, 2011. Approximately 12 percent (39 of 299) of the surveyed jurisdictions replied to the survey; of these, 22 responses provided an answer for their preferred advanced vehicle detection product (other than inductive loop sensors); only those responses were included in the survey analysis.

Of the 39 responding jurisdictions, 22 responses (56%) specified the use of advanced vehicle sensors, seven responses (18%) specified the use of inductive loop detectors only, and seven responses (18%) indicated no use of sensors at signalized intersections in their jurisdiction. The survey identified eight unique products that are the preferred technology and two further unique products which are currently being tested (LeddarTech LED and Aldis Gridsmart video). Video is the most preferred technology (16 of 22 responses), with Autoscope Solo Terra video being the most preferred video technology with 12 of 16 respondents using it.

The survey questions were developed in consultation with engineering professionals from the City of Winnipeg Traffic Signals Branch. A draft survey was initially emailed to City of Winnipeg Traffic Signals Branch professionals on July 21 and a 5-day period was provided to receive feedback. The revised survey was then distributed by email to 221 jurisdictions in Canada selected from the Transportation Association of Canada (TAC) membership directory and 78 jurisdictions from the U.S. selected from the Institute of Transportation Engineers (ITE) membership directory. The survey targeted transportation professionals able to speak on behalf of the jurisdiction for which they are professionally responsible. The survey was conducted over a two week period from July 28, 2011 to August 12, 2011. Approximately 12 percent (39 of 299) of the surveyed jurisdictions replied to the survey. However, only 22 responses completed the survey for their preferred advanced vehicle detection product and are included in the survey analysis. Two responses did not identify the product used in their jurisdiction. Seven responses indicated that their jurisdiction used only inductive loops and seven responses indicated their jurisdiction does not use vehicle detection products.

The survey questions can be categorized into the following topics:

- General information about the jurisdiction
- Detection, counting, and classification functionality and performance of the preferred vehicle sensor product for new installations
- Other functionalities, installation and maintenance information, and problems of the preferred vehicle sensor product
- Other vehicle sensor products which have provided positive results, are currently in testing, or are no longer used for new installations.

A summary of the key findings from the survey is given in the following sections.

The 22 responses to the survey identified eight unique preferred vehicle sensor products for new installations. Video is the most preferred technology (16 of 22 responses) and the Autoscope Solo Terra is the most preferred video technology with 12 respondents using it.

Jurisdictions use these technologies for a variety of applications. **Table 11**shows the number of survey responses that use their preferred product for a particular application.

Table 11: Current and future applications of preferred product

	Total	Magnetometer, Sensys	Video, Autoscope Solo Terra	Video, Iteris Vantage	Video, Naztec	Video, Traficon Traficam	Microwave, Wavetronix Matrix	Microwave, MS Sedco TC26B	LED, Tomar Strobecom II
Survey Responses	**22**	**2**	**12**	**2**	**1**	**1**	**2**	**1**	1
Speed information	**8**	0	4	1	1	1	1	0	0
Remote real time video viewing	**11**	0	9	1	1	0	0	0	0
Signal pre-emption	**0**	0	0	0	0	0	0	0	0
Network interface to TMC	**11**	0	8	2	0	1	0	0	0
Pedestrian detection	**2**	0	2	0	0	0	0	0	0
Cyclist detection	**7**	0	6	0	0	0	1	0	0
Motorcycle detection	**7**	0	5	0	0	1	1	0	0

Source: Survey conducted by University of Manitoba Transport Information Group, 20

Table 11 reveals that half of the jurisdictions use their preferred product for remote real time video viewing and have a network interface to the traffic management center. None of the responding jurisdictions indicated that they used their product for signal pre-emption.

Table 12 presents responses on installation and maintenance for each jurisdictions preferred product. **Table 12** reveals the following:

- Product installation and maintenance is generally completed by a third party (11 of 22) or by the responding agency (8 of 22 responses).
- Most products (10 of 22 responses) require between 2.5 and 4 hours for installation.

- Maintenance (preventive or reactive) is most commonly conducted on an annual basis (9 of 22 responses).
- When maintenance is completed, responses indicate it generally requires between 0.5 and 1 hour (11 of 22).
- Product set-up was the most commonly cited (11 of 22 responses) problem encountered.
- Approximately half of responding jurisdictions use remote trouble-shooting (11 of 22) and remote diagnosis (10 of 22).

Table 13 shows the ambient conditions that impact the performance of the preferred product. Snow was the most commonly cited ambient condition as having an affect (8 of 22). Weather conditions were only identified to impact video sensors (Autsocope, Iteris, and Traficon) and one microwave sensor. Sensys magnetometers, Naztec video, Wavetronix microwave, and LED sensors are not identified by respondents as being impacted by weather conditions.

Table 14 lists products, other than the preferred products, which have been used by the responding jurisdiction and have provided positive results. Autoscope and Iteris video were identified by the most jursidictions (three jurisdictions each) as providing positive results, followed by Wavetronix microwave.

Table 15 lists products other than the preferred product which are currently being tested by the responding jurisdiction. Sensys magnetometers are the most popular sensors currently being tested, identified by three jurisdictions, followed by Aldis Gridsmart video and Wavetronix microwave sensors being tested by two jurisdiction each.

Table 12: Preferred product installation and maintenance responses

	Total	Magnetometer, Sensys	Video, Autoscope Solo Terra	Video, Iteris Vantage	Video, Naztec	Video, Traficon Traficam	Microwave, Wavetronix Matrix	Microwave, MS Sedco TC26B	LED, Tomar Strobecom II
Survey responses	**22**	**2**	**12**	**2**	**1**	**1**	**2**	**1**	**1**
Product installation and maintenance completed by:									
Own agency	**8**	1	6	1	0	0	0	0	0
Product supplier	**0**	0	0	0	0	0	0	0	0
Third party	**11**	0	6	0	0	1	2	1	1
Other	**3**	1	0	1	1	0	0	0	0
Approximate time needed for on-site setup and installation:									
Less than 2.5 hours	**2**	0	1	0	0	0	0	1	0
Between 2.5 and 4 hours	**10**	2	4	1	0	1	2	0	0
Between 4 and 8 hours	**7**	0	6	0	0	0	0	0	1
More than 8 hours	**3**	0	1	1	1	0	0	0	0
Approximate timeframe between maintenance (preventive or reactive):									
Weekly	**2**	0	2	0	0	0	0	0	0
Monthly	**1**	0	1	0	0	0	0	0	0
quarterly	**0**	0	0	0	0	0	0	0	0
Semi-annually	**6**	1	4	0	0	0	1	0	0
Annually	**9**	1	4	2	0	1	0	0	1
Other	**3**	0	1	0	1	0	1	0	0
Approximate time needed for on-site maintenance:									
Less than 0.5 hours	**4**	1	2	1	0	0	0	0	0
Between 0.5 and 1 hour	**11**	0	8	0	0	1	1	0	1
Between 1 and 2 hours	**4**	1	1	1	1	0	0	0	0
More than 2 hours	**1**	0	1	0	0	0	0	0	0
Most common problems encountered:									
Wiring	**3**	0	1	0	0	1	1	0	0
Hardware	**2**	0	1	0	0	0	0	0	1
Firmware	**4**	0	2	1	0	1	0	0	0
Set-up	**11**	1	7	1	1	1	0	0	0
Other	**7**	1	3	1	1	1	0	0	0
Remote troubleshooting and diagnoses:									
Problems are remotely trouble-shot	**11**	2	5	0	1	1	2	0	0
Problems are remotely diagnosed	**10**	2	5	0	1	1	1	0	0

Source: Survey conducted by University of Manitoba Transport Information Group, 2011

Table 13: Ambient condition impacts on preferred product performance

	Total	Magnetometer, Sensys	Video, Autoscope Solo Terra	Video, Iteris Vantage	Video, Naztec	Video, Traficon Traficam	Microwave, Wavetronix Matrix	Microwave, MS Sedco TC26B	LED, Tomar Strobecom II
Survey Responses	**22**	**2**	**12**	**2**	**1**	**1**	**2**	**1**	**1**
Ambient Temperature									
High temperature (above 30°C)	**0**	0	0	0	0	0	0	0	0
Low temperature (below 0°C)	**1**	0	1	0	0	0	0	0	0
Weather events									
Sunny	**4**	0	3	1	0	0	0	0	0
Cloudy	**0**	0	0	0	0	0	0	0	0
Rain	**3**	0	2	0	0	1	0	0	0
Snow	**8**	0	6	1	0	1	0	1	0
Twilight	**4**	0	4	0	0	0	0	0	0
Night time operation	**3**	0	3	0	0	0	0	0	0

Comments	
Autoscope Solo Terra	
Low temp	Condensation in the camera unit causes false calls.
Sunny	Problems if camera is low (pointing at horizon) and shielding from sun is not sufficient.
	Direct sunlight into camera whites it out.
	Glare causes problems.
	If aimed too high road glare can cause false calls. Re-aiming camera usually resolves issue.
	Sometimes does not go into a failsafe mode.
	Reflection from surface at night time during heavy snowfall causes problems
Rain	Sometimes does not go into a failsafe mode.
Snow	Heavy snowfall causes recall.
	Heavy snow or fog causes constant calling.
	Whiteouts cause problems.
	Snow gathers in front of the lens causing no calls.
Twilight	Dark vehicles and sudden change of light cause problems.
	Sun glare causes false or missed calls.
	Sometimes requires adjusting aim and/or settings, issue is usually false calls.
Night	Needed to add additional lumination.
	Headlights ahead of vehicles sometimes cause early detection.
	Missed calls increase.
Iteris Vantage	
Sunny	Rising or setting sun shining directly into the lens or moving shadows cause problems.
Snow	Causes missed calls.
Traficon Traficam	
Rain	Sometimes does not go into failsafe mode.
Snow	Sometimes does not go into failsafe mode.

Source: Survey conducted by University of Manitoba Transport Information Group, 2011

Table 14: Other products in use which have provided positive results

Technology type, manufacturer and model	Number of jurisdiction responses (number of intersections)
Magnetometer	
Sensys	1 (--)
Canoga Microloop	1 (--)
Video	
Autoscope Solo Terra	3 (8, 3, 1)
Iteris Vantage	3 (6, 2, 1)
Iteris Versicam	1 (2)
Aldis Optima	1 (1)
Microwave	
RTMS	1 (10)
Wavetronix Smart Sensor	2 (1,10)
Naztec Accuwave	1 (--)
-- represents that no response was given	

Source: Survey conducted by University of Manitoba Transport Information Group, 2011

Table 15: Other products which are currently being tested

Technology type, manufacturer and model	Number of jurisdiction responses (number of intersections)
Magnetometer	
Sensys	3 (44, 2, --)
Video	
Aldis Gridsmart	2 (2, 1)
Microwave	
Wavetronix Smart Sensor	2 (1, --)
MS Sedco TC26B	1 (2)
Sensys	1 (2)
LED	
LeddarTech Leddar d-tec	1 (1)
-- represents that no response was given	

Source: Survey conducted by University of Manitoba Transport Information Group, 2011

Each jurisdiction was asked for information on their experiences with vehicle detection technologies, including the make and model of detector used, the number of intersections with vehicle detectors in use, whether the stop bar and advanced zones were being monitored and if the jurisdiction was using the classification capabilities of the device. Along with functionality at the stop bar and advanced zone, the jurisdictions were asked if they were using the sensitivity function for missed calls, or the selectivity function for false calls. Table 4 provides a summary of this information obtained from the summary. From this table it is notable that there were twelve jurisdictions using Autoscope Solo Terra, all of which used the sensitivity function at the stop bar. Also of note were the Iteris Vantage video detector and Wavetronix SmartSensor Matrix microwave radar sensor with two jurisdictions each using these products.

Table 4 shows a summary of the survey responses. This matrix was used to help select an appropriate technology for testing in the vehicle detection study in Winnipeg. Jurisdictions use the identified technologies for a variety of applications. Half of the responding jurisdictions use their preferred product for remote real time video viewing and have a network interface to the traffic management center. None of the responding jurisdictions indicated that they used their product for signal pre-emption.

Table 16: Survey responses on preferred product functionality and performance.

Technology type, manufacturer, model, and jurisdiction	Total signalized intersections	Intersection installations	Stop bar detection: Used in jurisdiction	Stop bar detection: Sensitivity	Stop bar detection: Selectivity	Advanced detection: Used in jurisdiction	Advanced detection: Sensitivity	Advanced detection: Selectivity	Vehicle counting: Used in jurisdiction	Vehicle counting: Sensitivity	Vehicle counting: Selectivity	Vehicle classification: Used in jurisdiction	Vehicle classification: Accuracy (percent)
Magnetometer – Sensys													
Owen Sound, ON	22	4	✚	🟢	🔵	▬	--	--	▬	--	--	▬	--
Vancouver, BC	821	21	▬	--	--	▬	--	--	✚	--	--	▬	--
Video – Autoscope Solo Terra													
Township of Langley, BC	90	71	✚	🟢	🔵	▬	--	--	✚	🔵	🔵	--	--
Columbus, OH	1000	50	✚	🟢	🟢	✖	--	--	--	--	--	--	--
Vernon, BC	34	8	✚	🟢	🟢	▬	--	--	--	--	--	▬	--
Essex County, ON	42	3	✚	--	--	▬	--	--	▬	--	--	▬	--
Region of Halton, ON	165	20	✚	🟢	🟢	✖	--	--	✚	--	--	✖	--
Okotoks, AB	17	14	✚	🟢	🔵	▬	--	--	✚	🟢	🟠	▬	--
Region of Durham, ON	550	10	✚	🟢	🟢	▬	--	--	✚	🟢	--	▬	95
Kelowa, BC	106	45	✚	🟢	🟢	▬	--	--	✚	🟢	🟢	▬	95
Lethbridge, AB	120	10	✚	🔵	🔵	--	--	--	--	--	--	--	--
Milton, ON	36	5	--	--	--	✚	🔵	🔵	--	--	--	--	--
Greater Sudbury, ON	115	4	✚	🟢	🟢	✚	--	--	▬	--	🟢	▬	--
Oakville, ON	324	30	✚	🟢	🟢	✚	🟢	🟢	▬	--	--	▬	--
Video – Iteris Vantage													
Lansing, MI	--	20	--	🔵	🔵	✚	🔵	🟢	▬	--	--	▬	--
Orlando, FL	465	36	✚	🟢	🟢	--	--	--	▬	--	--	--	--
Video – Naztec													
Newark, NJ	450	11	✚	--	--	▬	--	--	▬	--	--	▬	--
Video – Traficon Traficam													
Greater Sudbury, ON	115	4	✚	🟢	🟢	✚	--	--	▬	--	🟢	▬	--
Microwave – Wavetronix SmartSensor Matrix													
New Glasgow, NS	16	6	✚	🟢	🟢	✖	🟢	🟢	✚	--	--	--	80
Mississauga, ON	512	1	✚	🟢	🟢	--	--	--	--	--	--	--	--
Microwave – MS Sedco TC26B													
R.M. of Wood Buffalo, AB	41	14	✚	--	--	--	--	--	--	--	--	--	--
LED with 3D optical sensor – Tomar Strobecom II													
Peterborough, ON	119	60	--	--	--	✚	--	--	--	--	--	--	--

✚ represents that the function of the product is used

✖ represents that the function of the product is available but not used due to unsatisfactory performance

▬ represents that the function of the product is available but not used due to reasons other than unsatisfactory performance

-- represents no response given for the question

🟢 > 95 percent | 🔵 85 – 95 percent | 🟠 75 – 85 percent | 🔴 < 75 percent

Source: Survey conducted by University of Manitoba Transport Information Group, 2011

The survey resulted in the following findings on the installation and maintenance of jurisdictions' preferred products:

- Product installation and maintenance is generally completed by a third party (11 of 22) or by the responding agency (8 of 22 responses).
- Most products (10 of 22 responses) require 2.5 - 4 hours to install.
- Maintenance (preventive or reactive) is most commonly conducted on an annual basis (9 of 22 responses).
- When maintenance is conducted it generally requires 0.5 - 1 hour (11 of 22 responses).
- Product set-up was the most commonly cited problem encountered (11 of 22 responses).
- Half of responding jurisdictions use remote trouble-shooting and 10 of 22 use remote diagnosis.

Respondents indicated that ambient conditions sometimes impact the performance of their preferred product; specifically sun glare, rain, snow, twilight and night operation. Autoscope Solo Terra video was identified the most as having issues with adverse weather, keeping in mind that it was selected by 12 out of 22 respondents as being the most preferred sensor. Snow was the most commonly cited ambient condition as having an adverse effect (8 of 22).

In addition to the most preferred product, jurisdictions were asked to identify a product they use that provides positive results as well as products currently being tested. Autoscope and Iteris video were identified by the most jurisdictions (selected by three jurisdictions each) as providing positive results, followed by Wavetronix microwave (selected by two jurisdictions). Sensys magnetometers are the most popular sensors currently being tested, identified by three jurisdictions, followed by Aldis Gridsmart video and Wavetronix microwave sensors being tested by two jurisdiction each.

The literature review revealed studies discussing the performance of different vehicle detection technology types and products as listed in

.

Table 17: Technology Types and Products

Magnetometer	Video	Microwave
• Sensys • Canoga • Microloops	• Autoscope Solo Terra • Traficon Traficam • Iteris Vantage Edge 2 • Peek Unitrak	• Wavetronix SmartSensor HD • Wavetronix SmartSensor Advance • RTMS
Infrared	**Passive Acoustic Array**	**Combined Technologies**
• TIRTL	• SmarTek SAS-1 • SmartSonic TSS-1	• ASIM DT 272 • ASIM TT 262

The literature did not identify a single superior detector; however, it highlighted strengths and weaknesses of different technology types and products in different applications. The issues identified in the literature aided in selecting the conditions used for testing in this study. The following lists related key findings from previously tested products:

- Magnetometers have high accuracy levels for vehicle detection and count (within 5% error), even on high volume urban freeways, stop-and-go traffic, and high truck presence.

- Environmental factors can significantly impact the capabilities and performance of non-intrusive technologies. Sensors have the tendency to work well under certain conditions and poorly under others.

- Video detection systems generally perform well (under 2 percent false calls) under ideal conditions (cloudy noon, no wind, and no rain) with an exception at the curb lane at both stop-bar and advanced locations, where significant false calls are placed due to shadows from larger vehicles in adjacent lanes.

- The performance of video detection systems are impacted by any environmental condition that reduces visibility. Lighting is the main concern, where night periods have more detection problems due to detection by vehicle headlights only. During day time, glare and shadows have been a concern.

- Snow in both day and night significantly impact the performance of video detectors, with Peek Unitrak, Autoscope Solo Pro, and Iteris Vantage Edge 2 placing over 50% false calls at both stop-bar and advanced detection locations.

- The Wavetronix SmartSensor Advance detector, used for advanced detection, was found to be better at detecting gaps in the stream of traffic than video detection systems and provides good dilemma zone protection. Also, it is not affected by light or weather conditions. However, it produces over-counting of vehicles due to double detection of larger vehicles, turning volumes, and standing queues.

- Occlusion is a concern for side or overhead mounted sensors, where larger vehicles can block the detection of other vehicles in adjacent lanes or vehicles behind the larger vehicle.

C. STOP BAR ANALYSIS

Appendix C provides the analysis for the stop bar detection performance of Autoscope video, *Iteris far* video, and Wavetronix microwave sensors for each of the four stop-bar zones. For the by-zone analysis, the number of ground-truth calls per device is significantly less than the 1080 calls required for statistical significance in the total device performance. Variation in ground-truth calls is caused by zone (lane) location in the intersection as well as traffic flow variation due to temporal and climate influences. Zones 26 and 27, the left-turning lanes will have less ground-truth calls than the through lanes, zones 28 and 29. Figure 3shows the test intersection configuration with the zones labeled. **Error! Reference source not found.** shows condition numbers and descriptions.

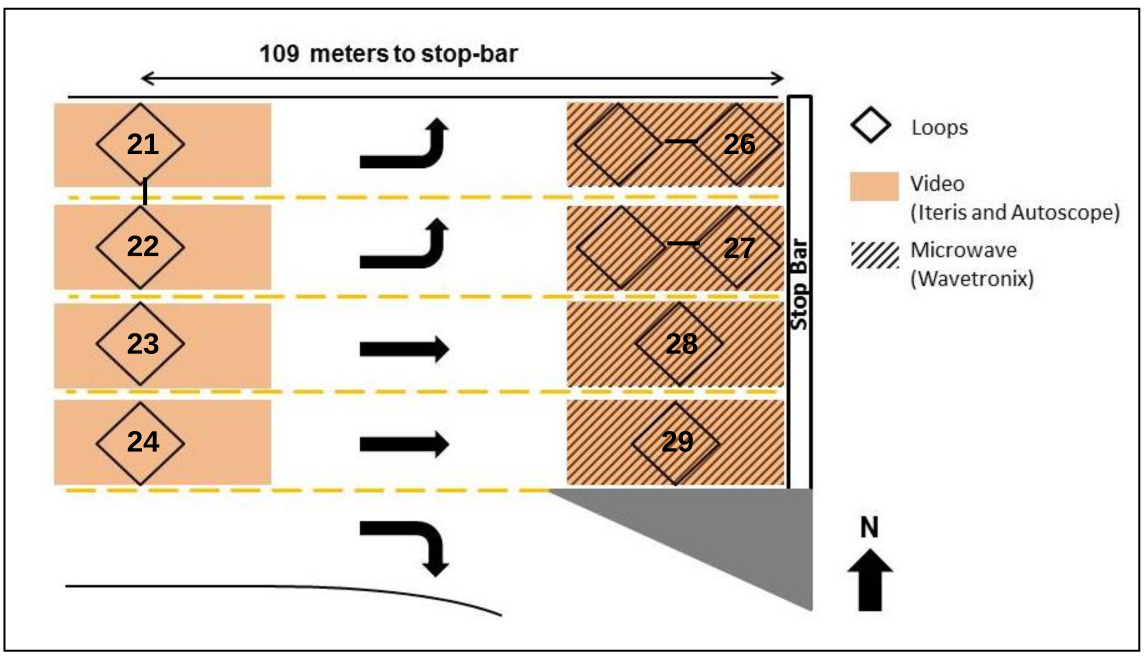


Figure 3: General detection zone layout at eastbound approach

Table 9: Condition Numbers with Descriptions

Condition #	Description
Weather Conditions	
1	no wind, clear, day
2	no wind, clear, night
3	no wind, rain, day
4	no wind, rain, night
5	no wind, snow, day
6	no wind, snow, night
7	no wind, fog, day
8	no wind, fog, night
Illumination Conditions	
9	no wind, no adverse weather, noon, cloudy
10	dawn, no wind, no adverse weather
11	sunny afternoon, no wind
12	dusk, no wind, no adverse weather
13	night, no wind, no adverse weather
Wind Conditions	
15	wind light to moderate, no adverse weather, sunny afternoon
16	wind light to moderate, no adverse weather, night
17	wind light to moderate, no adverse weather, cloudy, noon
18	wind moderate to strong, no adverse weather, sunny afternoon
19	wind moderate to strong, no adverse weather, night'
20	wind moderate to strong, no adverse weather, cloudy, noon
Traffic Conditions	
21	no wind, no adverse weather, a.m. peak
22	no wind, no adverse weather, p.m. peak
23	no wind, no adverse weather,free flow, day
24	no wind, no adverse weather, free flow, night

Note: Condition 14 was redundant with condition 9. Condition 14 does not appear in the above table or elsewhere in the report.

C.1 ZONE 26

Zone 26 is the left-turning lane next to the median (i.e. the north most lane of the intersection). For zone 26 ground truth calls varied from 1302 calls for clear, daytime conditions to 115 calls for nighttime, rain conditions. The location of zone 26, to the left of the video detection devices, Autoscope and Iteris, is a potential cause of the decrease in accuracy of the devices. The Matrix microwave device was mounted on a pole approximately two meters above ground level and performs best in zone 26 because there was no traffic between the sensor and the vehicles in the zone.

C.1.1 Sensitivity as a Function of Weather

The stop-bar detection performance was analyzed as a function of clear, rain, fog, and snow weather conditions during both daytime and nighttime. Weather condition data was collected for wind speeds of 15 km/hr or less, limiting the effects of wind during measurement. A total of 2404 daytime and 978 nighttime ground-truth calls were identified for these conditions by manual video review. Figure 4 and Figure 5 show the accuracy levels and error margins for each of the three sensors under different weather conditions (clear, rain, snow, and fog).

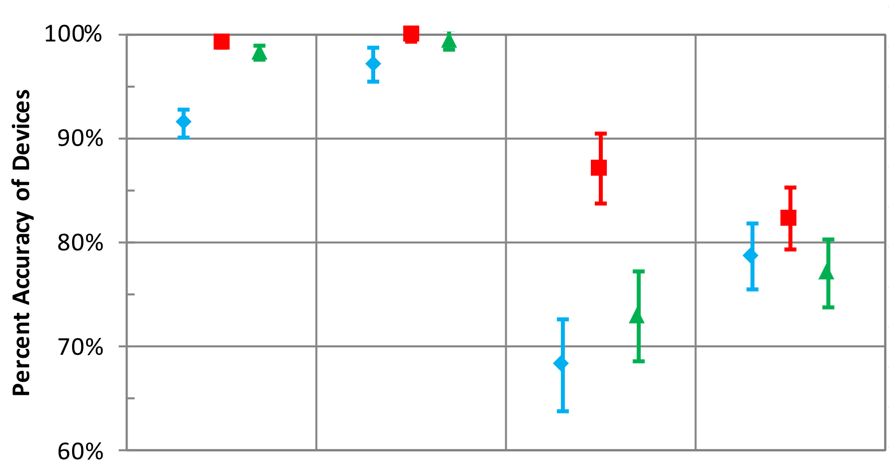
The accuracy of the three sensors during daytime ranged from 100.0 percent (for Iteris during rain) to 68.2 percent (for Autoscope during snow). Nighttime weather conditions performed similarly with the maximum accuracy achieved by Iteris and Martrix during clear conditions with 99.3 percent, and minimum accuracy of 55.2 percent with Autoscope during snow.

All three sensors, Autoscope, Iteris, and Matrix, performed at high accuracy levels under clear weather conditions during both day and nighttime conditions, with 91.4, 99.2, and 98.2 percent accuracy levels during daytime and 90.6, 99.3, and 99.3 percent accuracy levels at nighttime, respectively. Clear conditions were used as the baseline condition.

Performance of the sensors improved during daytime rain conditions; however, the accuracy levels of the all devices during nighttime were reduced by 6.1 percent for Iteris and 17.6 and 25.3 percent for Autoscope and Matrix relative to the clear conditions. The improvement in performance of all devices during daytime rain conditions may be attributable to several factors such as:

- the low volume counts used in the zone by zone analysis, produce significantly insignificant results

- results atypical to expected can appear due to anomalies in random sampling
- margins of error with by zone analysis are larger due to the smaller sample sizes

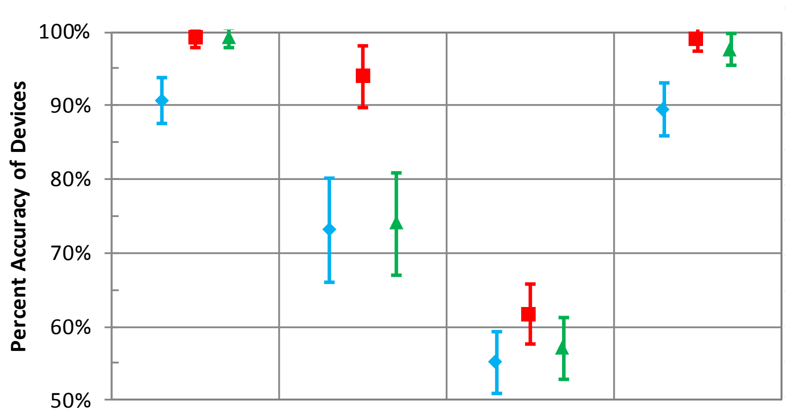


Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	1190	332	206	360
	Sensitivity	91.4 ± 1.29%	97.08 ± 1.68%	68.21 ± 4.46%	78.6 ± 3.19%
Iteris	# of vehicles detected	1291	342	263	377
	Sensitivity	99.16 ± 0.46%	100 ± 0.79%	87.09 ± 3.27%	82.31 ± 2.97%
Matrix	# of vehicles detected	1278	340	220	353
	Sensitivity	98.16 ± 0.65%	99.42 ± 1.03%	72.85 ± 4.27%	77.07 ± 3.27%
Ground Truth		1302	342	302	458

Figure 4: Daytime Weather Conditions (1, 3, 5, 7) for Zone 26

Snow conditions reduced the accuracy levels of all three sensors during both daytime and nighttime conditions, with the greatest effect during nighttime conditions compared to all other weather conditions, resulting in a reduction of 35.1, 37.7, and 42.3 percent accuracy levels for Autoscope, Iteris, and Matrix, respectively.

Fog during daytime had similar impact as snow on performance levels, with a decrease in accuracy levels of approximately 12.8, 16.9, and 21.1 percent for Autoscope, Iteris, and Matrix, respectively. Iteris performed slightly poorer in fog conditions compared to snow. However, fog during nighttime had little impact on the performance levels compared to clear nighttime conditions.



Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	241	84	214	187
	Sensitivity	90.6 ± 3.08%	73.04 ± 7.04%	55.15 ± 4.18%	89.47 ± 3.68%
Iteris	# of vehicles detected	264	108	239	207
	Sensitivity	99.25 ± 1.33%	93.91 ± 4.26%	61.6 ± 4.09%	99.04 ± 1.68%
Matrix	# of vehicles detected	264	85	221	204
	Sensitivity	99.25 ± 1.33%	73.91 ± 6.97%	56.96 ± 4.16%	97.61 ± 2.14%
Ground Truth		266	115	388	209

Figure 5: Nighttime Weather Conditions (2, 4, 6, 8) for Zone 26

In summary, although all three sensors performed well, Autoscope performed the poorest during clear conditions (baseline) and was affected the most by snow weather conditions compared to the other two sensors. The Iteris sensor, while generally being comparable to the Matrix sensor, had the highest accuracy levels and was least impacted by the different weather conditions. Iteris outperformed Matrix by 14.2 percent for daytime snow conditions. Nighttime snow conditions had the highest effect on sensor performances, resulting in accuracy levels between 55.2 and 61.9 percent for the three sensors.

C.1.2 Sensitivity as a Function of Illumination

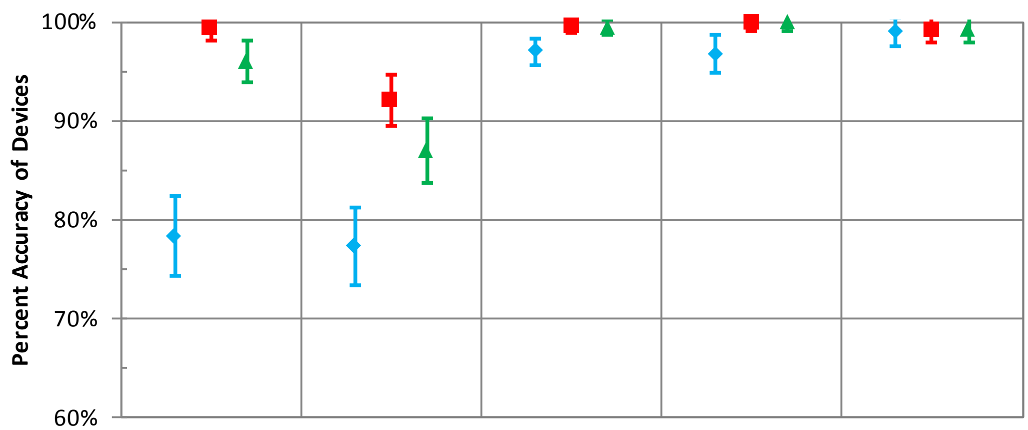
The stop-bar detection performance was analyzed as a function of varying illumination conditions to assess the effects of glare and shadows on sensor performance. The analyzed lighting conditions were cloudy noon (baseline), dawn, sunny afternoon, dusk, and night. Cloudy noon was identified in literature as being the ideal lighting conditions for video sensors, and was therefore the baseline condition.

Illumination condition data was collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, to limit the effects of wind and weather during measurement. A total of 1682 ground-truth calls were identified for these conditions by manual video review in zone 26. Figure 6 shows the accuracy levels and error margins for each of the three sensors under the different illumination conditions.

The accuracy of the three sensors ranged from 77.4 percent (for Autoscope during dawn) to 100.0 percent (for Matrix and Iteris during dusk). Under ideal conditions (i.e. cloudy noon), Iteris and Matrix performed well with 99.3 and 95.9 percent accuracy levels, respectively. However, Autoscope resulted in a lower accuracy of 78.3 percent, which could be due to other uncontrolled factors, as discussed in C.1.1.

All three sensors performed well under sunny afternoon, dusk, and night conditions with accuracy levels of over 96.8 percent. Dawn lighting conditions had the most effect on detection performance for all three sensors, with the highest effect on Autoscope resulting in the lowest accuracy level of 78.3 percent.

Overall, Iteris was the least effected by the different lighting conditions, maintaining an accuracy level of greater than 92 percent. Matrix generally performed similarly to Iteris under the different lighting conditions, except during the dawn condition resulting in approximately 5 percent lower accuracy level than Iteris, at 86.9 percent.



Device		Noon	Dawn	Afternoon	Dusk	Night
Autoscope	# of vehicles detected	231	243	483	299	241
	Sensitivity	78.31 ± 4.02%	77.39 ± 3.94%	96.99 ± 1.36%	96.76 ± 1.86%	99 ± 1.41%
Iteris	# of vehicles detected	293	289	496	309	264
	Sensitivity	99.32 ± 1.2%	92.04 ± 2.63%	99.6 ± 0.71%	100 ± 0.87%	99.25 ± 1.33%
Matrix	# of vehicles detected	283	273	495	309	264
	Sensitivity	95.93 ± 2.08%	86.94 ± 3.22%	99.4 ± 0.78%	100 ± 0.87%	99.25 ± 1.33%
Ground Truth		295	314	498	309	266

Figure 6: Illumination Conditions (9, 10, 11, 12, 13) for Zone 26

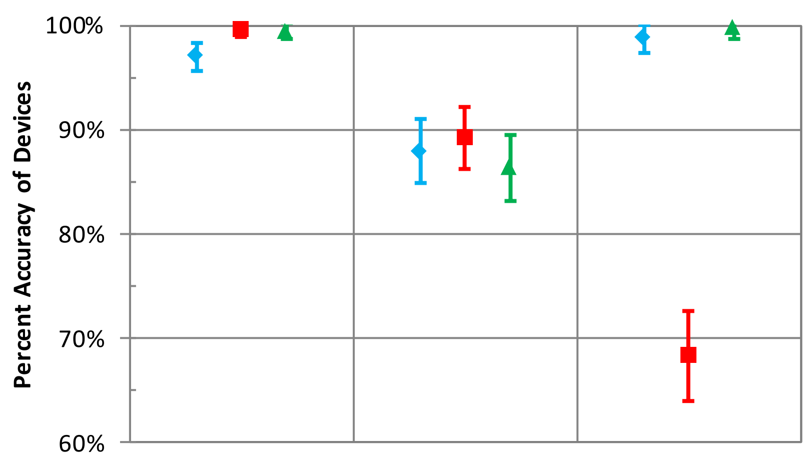
C.1.3 Sensitivity as a Function of Wind

The stop-bar detection performance was analyzed as a function of low (less than 15 km/hr), moderate (between 15 and 30 km/hr), and strong (greater than 30 km/hr) wind conditions for sunny daytime, cloudy noon, and nighttime lighting conditions. This allows the evaluation of combination effects on sensor performance. The low wind condition was identified as the baseline condition for all three lighting conditions.

Wind condition data was collected for no adverse weather conditions, to limit the effects of weather during measurement. A total of 1132 sunny daytime, 1023 cloudy noon, and 804 nighttime ground-truth calls were identified for these conditions by manual video review. Figure 7, Figure 8, and Figure9 how the accuracy levels and error margins for each of the three sensors under the different wind speed conditions, for sunny daytime, cloudy noon, and nighttime conditions, respectively.

During the sunny daytime lighting condition, the accuracy of the three sensors ranged from 68.3 percent (for Iteris during strong wind) to 99.7 percent (for Matrix during strong wind), shown in Figure 4. Under the ideal condition of low wind, all three sensors performed very well, with accuracy levels between 96.7 and 99.6 percent. All three sensors preformed slightly poorer under moderate wind conditions with accuracy levels reduced by 9.1 to 13.1 percent relative to their baseline conditions. Strong wind conditions didn't have an effect on Autoscope and Matrix, however, Iteris was significantly affected with a decrease in accuracy of 31.3 percent from low wind speed. Iteris was mounted at the highest height (40 feet) of the tested detection devices. Iteris was mounted on a mast arm pole making it highly susceptible to movement, especially vertical oscillation, by wind force.

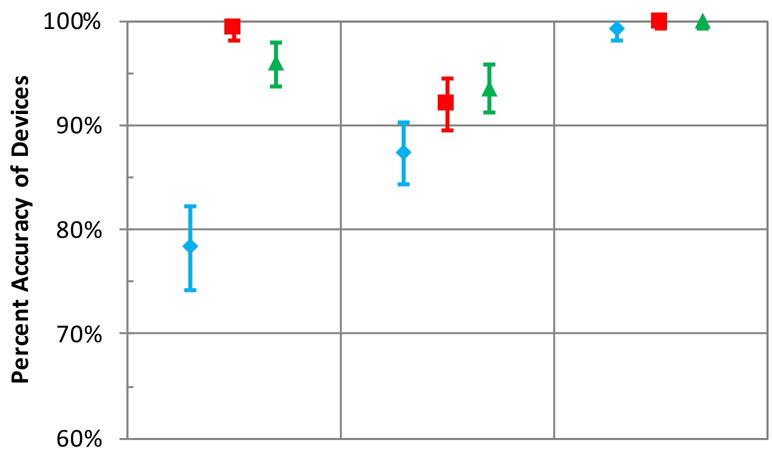
Under the cloudy noon lighting condition, the accuracy of the three sensors ranged from 78.3 percent (for Autoscope during low wind) to 100.0 percent (for Iteris and Matrix during strong wind), shown in Figure 8. During the ideal condition of low wind, the three sensors range in performance levels with Iteris at the highest accuracy level of 99.3 percent for and Autoscope at the lowest accuracy level of 78.3 percent.



Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	483	283	308
	Sensitivity	96.99 ± 1.36%	87.89 ± 3.08%	98.72 ± 1.35%
Iteris	# of vehicles detected	496	287	213
	Sensitivity	99.6 ± 0.71%	89.13 ± 2.95%	68.27 ± 4.38%
Matrix	# of vehicles detected	495	278	311
	Sensitivity	99.4 ± 0.78%	86.34 ± 3.23%	99.68 ± 1.01%
Ground Truth		498	322	312

Figure 7: Sunny, Daytime Wind Conditions (11, 15, 18) for Zone 26

Autoscope's lower accuracy level under ideal conditions could be due to other unidentified factors outside of the scope of the research. All three sensors perform similarly under moderate wind conditions, with Iteris and Matrix resulting in only slightly lower accuracy levels relative to the baseline conditions. However, the accuracy levels of Autoscope increased from baseline conditions by 9 percent which could be due the exceptionally low baseline accuracy level caused by other factors. Strong wind conditions did not have an effect on sensor performance under cloudy noon conditions, with all sensors having accuracy levels greater than 99 percent.



Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	231	297	385
	Sensitivity	78.31 ± 4.02%	87.35 ± 3.05%	99.23 ± 1%
Iteris	# of vehicles detected	293	313	388
	Sensitivity	99.32 ± 1.2%	92.06 ± 2.52%	100 ± 0.69%
Matrix	# of vehicles detected	283	318	388
	Sensitivity	95.93 ± 2.08%	93.53 ± 2.32%	100 ± 0.69%
Ground Truth		295	340	388

Figure 8: Noon Cloudy, Daytime Wind Conditions (9, 17, 20) for Zone 26

Under the nighttime lighting condition, the accuracy of the three sensors ranged from 79.9 percent (for Autoscope during strong wind) to 99.2 percent (for all Iteris and Matrix during low wind), shown in Figure 9.

Under the ideal condition of low wind, all three sensors performed with high accuracy levels of greater than 99 percent. Moderate and strong winds reduced the sensor's performance by approximately 14 to 19 percent.

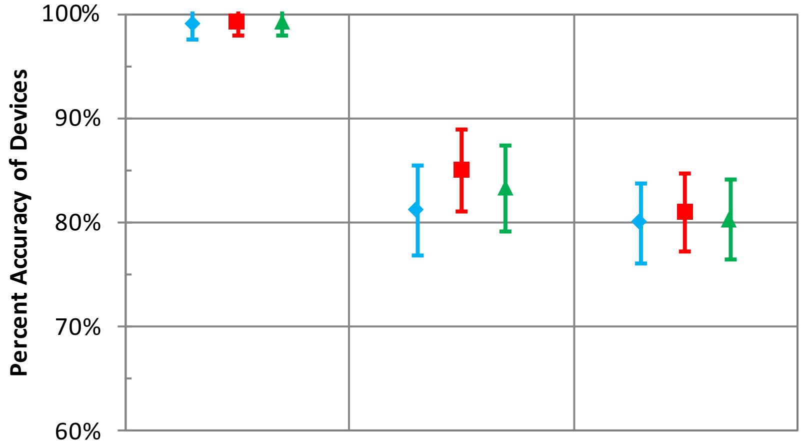
In summary, moderate winds had the highest effect on all three sensor's performances for noon cloudy and afternoon sunny conditions. During nighttime conditions, strong wind has the greatest effect on all three tested sensors. Iteris was the most effected by strong winds in sunny afternoon conditions due to its high mounted height, resulting in a 76 percent accuracy level. Aside from that, the highest reduction in accuracy levels was due to moderate winds during nighttime conditions, with a reduction of 10 to 15 percent accuracy. However under daytime conditions (i.e. cloudy noon and sunny daytime) wind did not significantly affect the sensor performances, with all three sensors resulting in greater than 93 percent accuracies.

C.1.4 Sensitivity as a Function of Traffic

The stop-bar detection performance was analyzed as a function of am peak, pm peak, and free flow day and night traffic conditions. The free flow daytime condition was identified as the baseline condition.

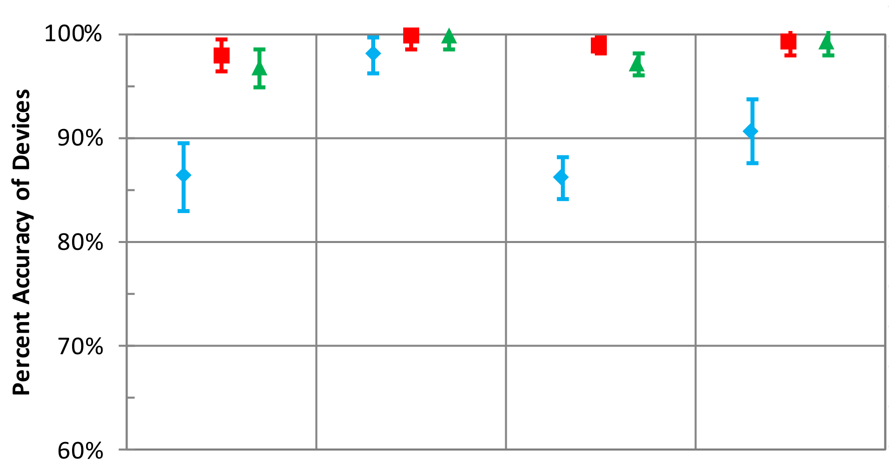
Traffic condition data was collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, to limit the effects of wind and weather during measurement. A total of 1647 ground-truth calls were identified for these conditions by manual video review. Figure 10 shows the accuracy levels and error margins for each of the three sensors under the different traffic conditions.

The accuracy of the three sensors ranged from 86.1 percent (for Autoscope during daytime free flow traffic) to 99.7 percent (for Iteris and Matrix during pm peak). Iteris and Matrix sensors were the least effected by different traffic conditions with accuracy minimum accuracy levels of 97.9 and 97.1 percent, respectively. Autoscope was the most affected by the am peak and free flow day traffic with approximately 86 percent accuracy levels. Autoscope's performance under pm peak was similar to that of Iteris and Matrix.



Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	241	194	239
	Sensitivity	99 ± 1.41%	81.17 ± 4.26%	79.93 ± 3.88%
Iteris	# of vehicles detected	264	203	242
	Sensitivity	99.25 ± 1.33%	84.94 ± 3.93%	80.94 ± 3.81%
Matrix	# of vehicles detected	264	199	240
	Sensitivity	99.25 ± 1.33%	83.26 ± 4.08%	80.27 ± 3.86%
Ground Truth		266	239	299

Figure 9: Nighttime Wind Conditions (13, 16, 19) for Zone 26



Device		a.m. peak	p.m. peak	Free flow day	Free flow night
Autoscope	# of vehicles detected	282	284	658	241
	Sensitivity	86.24 ± 3.21%	97.93 ± 1.65%	86.13 ± 2.08%	90.6 ± 3.08%
Iteris	# of vehicles detected	320	289	755	264
	Sensitivity	97.86 ± 1.54%	99.66 ± 1.08%	98.82 ± 0.73%	99.25 ± 1.33%
Matrix	# of vehicles detected	316	289	742	264
	Sensitivity	96.64 ± 1.82%	99.66 ± 1.08%	97.12 ± 1.05%	99.25 ± 1.33%
Ground Truth		327	290	764	266

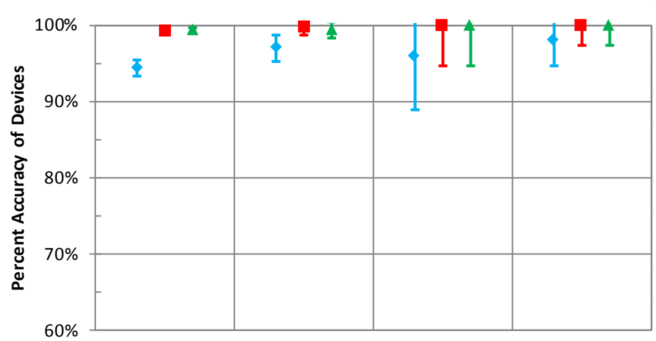
Figure 10: Traffic Conditions (21, 22, 23, 24) for Zone 26

C.2 ZONE 27

Zone 27 was the left-turning lane, one lane away from the median. During data review, there were some cases where zone 27 was not operating adequately to use for analysis, for this reason zone 27 has less ground-truth calls than predicted. As the lanes move further from the Matrix sensor there was increased risk of occlusion by a larger vehicle from a more northern lane over shadowing another vehicle and decreasing Matrix's sensitivity. Zone 27 moved one lane closer to the centre of the intersection, limiting the effects of angular detection problems for Autoscope and Iteris.

C.2.1 Sensitivity as a Function of Weather

The stop-bar detection performance was analyzed as a function of clear, rain, fog, and snow weather conditions during both daytime and nighttime. Weather condition data was collected for wind speeds of 15 km/hr or less, limiting the effects of wind during measurement. A total of 1746 daytime and 574 nighttime ground-truth calls were identified for these conditions by manual video review Figure 11 and Figure 12 show the accuracy levels and error margins for each of the three sensors under different weather conditions (clear, rain, snow, and fog).

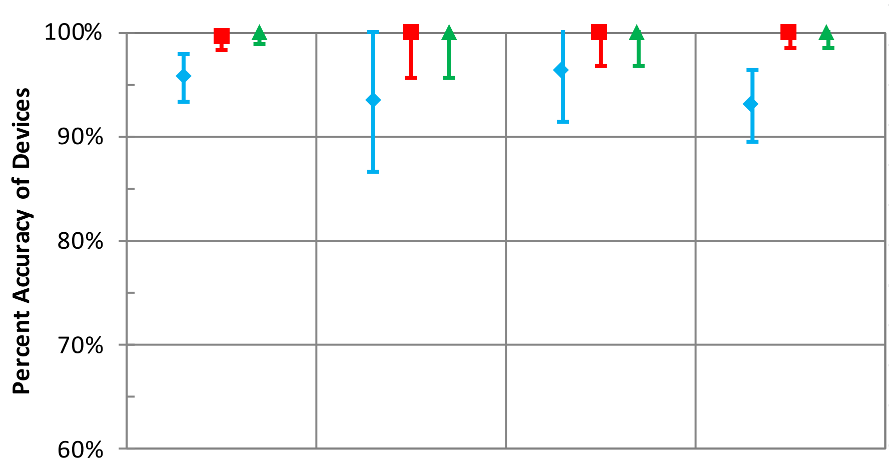


Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	1190	326	46	99
	Sensitivity	94.37 ± 1.09%	97.02 ± 1.71%	95.83 ± 6.98%	98.02 ± 3.43%
Iteris	# of vehicles detected	1250	335	48	101
	Sensitivity	99.13 ± 0.48%	99.7 ± 0.94%	100 ± 5.34%	100 ± 2.61%
Matrix	# of vehicles detected	1252	334	48	101
	Sensitivity	99.29 ± 0.44%	99.4 ± 1.05%	100 ± 5.34%	100 ± 2.61%
Ground Truth		1261	336	48	101

Figure 11: Daytime Weather Conditions (1, 3, 5, 7) for Zone 27

The accuracy of the three sensors during daytime ranged from 100.0 percent (for Iteris and Matrix during snow and fog) to 94.4 percent (for Autoscope during clear conditions). Nighttime weather conditions performed similarly with the maximum accuracy achieved by Iteris and Matrix during all conditions with near 100 percent accuracy. A minimum accuracy of 92.9 percent was seen with Autoscope during fog conditions.

In summary, all three sensors performed with high accuracy. Autoscope performed the poorest but still had accuracy levels over 92 percent. Due to the small sample size for zone 27 the results were likely skewed.



Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	240	56	76	171
	Sensitivity	95.62 ± 2.36%	93.33 ± 6.66%	96.2 ± 4.76%	92.93 ± 3.39%
Iteris	# of vehicles detected	250	60	79	184
	Sensitivity	99.6 ± 1.25%	100 ± 4.32%	100 ± 3.31%	100 ± 1.45%
Matrix	# of vehicles detected	251	60	79	184
	Sensitivity	100 ± 1.07%	100 ± 4.32%	100 ± 3.31%	100 ± 1.45%
Ground Truth		251	60	79	184

Figure 12: Nighttime Weather Conditions (2, 4, 6, 8) for Zone 27

C.2.2 Sensitivity as a Function of Illumination

Illumination condition data was collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, to limit the effects of wind and weather during measurement. A total of 1715 ground-truth calls were identified for these conditions by manual video review in zone 27. Figure 13 shows the accuracy levels and error margins for each of the three sensors under the different illumination conditions.

The accuracy of the three sensors ranged from 74.5 percent (for Autoscope during dawn) to 100.0 percent for Matrix during dusk and nighttime conditions. Under ideal conditions (i.e. cloudy noon), Iteris and Matrix performed well with 98.4 and 98.1 percent accuracy levels, respectively. However, Autoscope resulted in a lower accuracy of 84.5 percent, which could be due to other uncontrolled factors.

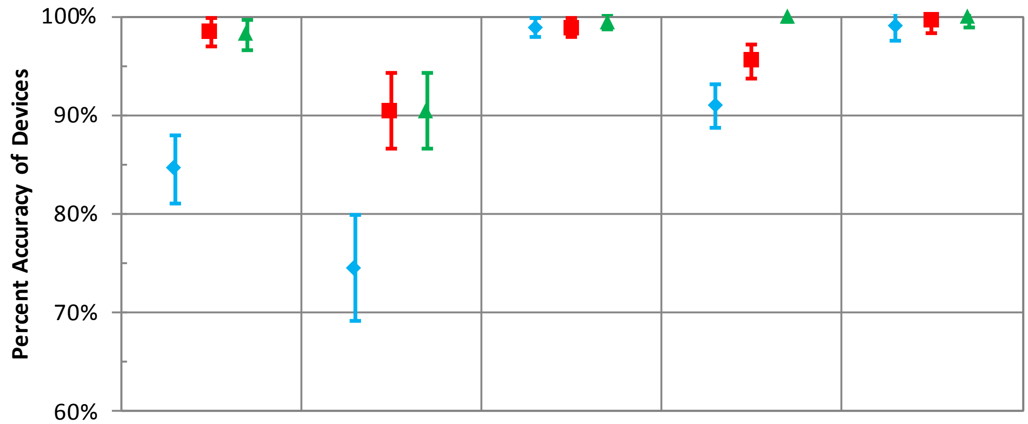
All three sensors performed well under sunny afternoon, dusk, and night conditions with accuracy levels of over 90 percent. Dawn lighting conditions had the greatest effect on detection performance for all three sensors, with the highest effect on Autoscope resulting in the lowest accuracy level of 74.5 percent and Iteris and Matrix at 90.4 percent accuracy.

Overall, Matrix was the least effected by the different lighting conditions, maintaining an accuracy level of greater than 90 percent. Iteris performed similarly to Matrix under the different illumination conditions, except during the dusk condition resulting in approximately 5 percent lower accuracy level than Matrix, at 95.4 percent.

C.2.3 Sensitivity as a Function of Wind

The stop-bar detection performance was analyzed as a function of low (less than 15 km/hr), moderate (between 15 and 30 km/hr), and strong (greater than 30 km/hr) wind conditions for sunny daytime, cloudy noon, and nighttime lighting conditions. This allowed for the evaluation of combination effects on sensor performance. The low wind condition was established as the baseline condition for all three lighting conditions.

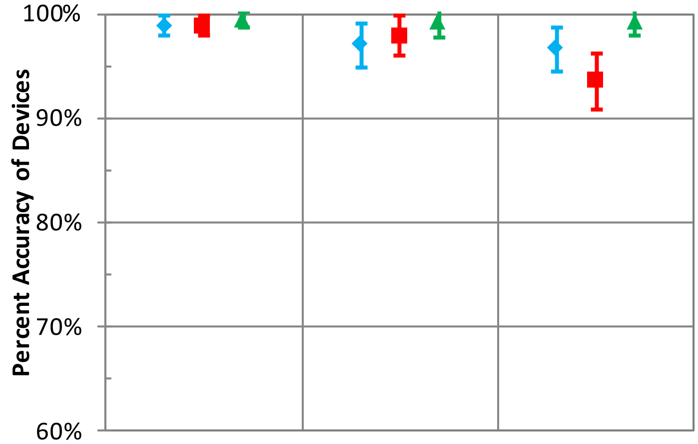
Wind condition data was collected for no adverse weather conditions, to limit the effects of weather during measurement. A total of 994 sunny daytime, 830 cloudy noon, and 602 nighttime ground-truth calls were identified for these conditions by manual video review. Figure , Figure 15, and Figure   show the accuracy levels and error margins for each of the three sensors under the different wind speed conditions, for sunny daytime, cloudy noon, and nighttime conditions, respectively.



Device		Noon	Dawn	Afternoon	Dusk	Night
Autoscope	# of vehicles detected	268	140	492	419	240
	Sensitivity	84.54 ± 3.42%	74.47 ± 5.35%	98.8 ± 0.96%	90.89 ± 2.27%	99 ± 1.48%
Iteris	# of vehicles detected	312	170	492	440	250
	Sensitivity	98.42 ± 1.42%	90.43 ± 3.76%	98.8 ± 0.96%	95.44 ± 1.69%	99.6 ± 1.25%
Matrix	# of vehicles detected	311	170	495	461	251
	Sensitivity	98.11 ± 1.51%	90.43 ± 3.76%	99.4 ± 0.78%	100 ± 0.58%	100 ± 1.07%
Ground Truth		317	188	498	461	251

Figure 13: Illumination Conditions (9, 10, 11, 12, 13) for Zone 27

Under the sunny daytime lighting condition, the accuracy of the three sensors showed little fluctuation ranging from 93.5 percent (for Iteris during strong wind) to 99.4 percent (for Matrix during low wind), shown in Figure 14. Under the ideal condition of low wind, all three sensors performed with high accuracy levels between 98.8 and 99.4 percent. All three sensors preformed slightly poorer under moderate wind conditions with accuracy levels reduced by 1.8 to 0.1 percent relative to their baseline conditions. Strong wind conditions did not have an effect on Matrix; however, Iteris and Autoscope were affected with a decrease in accuracy of 4.2 and 2.2 percent, respectively, from low wind speed.



Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	492	226	254
	Sensitivity	98.8 ± 0.96%	97 ± 2.15%	96.58 ± 2.09%
Iteris	# of vehicles detected	492	228	246
	Sensitivity	98.8 ± 0.96%	97.85 ± 1.92%	93.54 ± 2.67%
Matrix	# of vehicles detected	495	231	261
	Sensitivity	99.4 ± 0.78%	99.14 ± 1.51%	99.24 ± 1.34%
Ground Truth		498	233	263

Figure 14: Sunny, Daytime Wind Conditions (11, 15, 18) for Zone 27

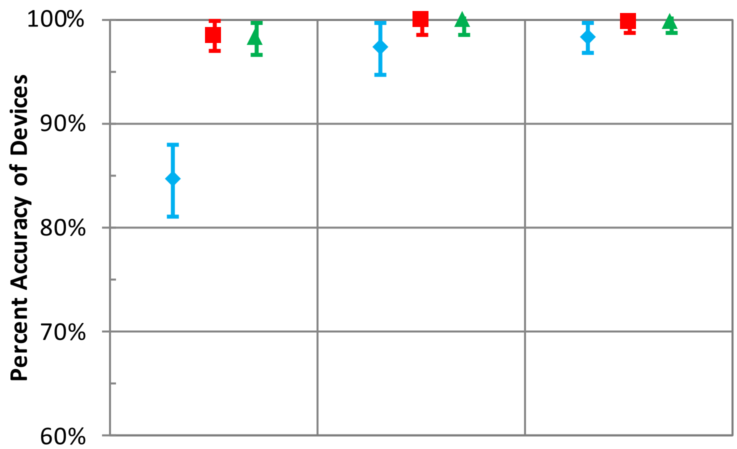
The effect of strong wind on Iteris and Autoscope can be explained by their high mounting heights.

Under the cloudy noon lighting condition, the accuracy of the three sensors ranged from 84.5 percent (for Autoscope during low wind) to 100.0 percent (for Iteris and Matrix during moderate wind), shown in Figure 14. Under the ideal condition of low wind, the three sensors range in performance levels with Iteris at the highest accuracy level of 98.4 percent for Iteris and Autoscope at the lowest accuracy level of 84.5 percent. Autoscope's lower accuracy level under ideal conditions could be due to other factors, such as the lower call levels. All three sensors performed similarly under moderate wind conditions, with all devices performing better than low wind speed. Strong wind conditions did not have a significant effect on sensor performance under cloudy noon conditions, with all sensors having accuracy levels greater than 98 percent. Improved accuracy with increasing wind speeds was not the expected result. Low count levels, making the study statistically insignificant by zone, are likely the main contributor to the measured results.

Under the nighttime lighting condition, the accuracy of the three sensors ranged from 81.4 percent (for Autoscope during moderate wind) to 100.0 percent (for Matrix during low wind), shown in Figure 15.

Under the ideal condition of low wind, all three sensors performed with high accuracy levels of 99 percent or greater. Moderate and strong winds reduced the sensor's performance by approximately 1 to 17 percent.

In summary, moderate winds had the highest effect on all three sensor's performances, followed by strong wind conditions during nighttime conditions. Performance accuracies were higher in most cases than in total performance review (review of all four zones in combination) this may be attributable to the low ground truth calls available. The detection devices performed better in zone 27 than in zone 26, for Autoscope and Iteris this may be attributable to zone 27 nearer the centre of the intersection. This does explanation is not applicable to Matrix.



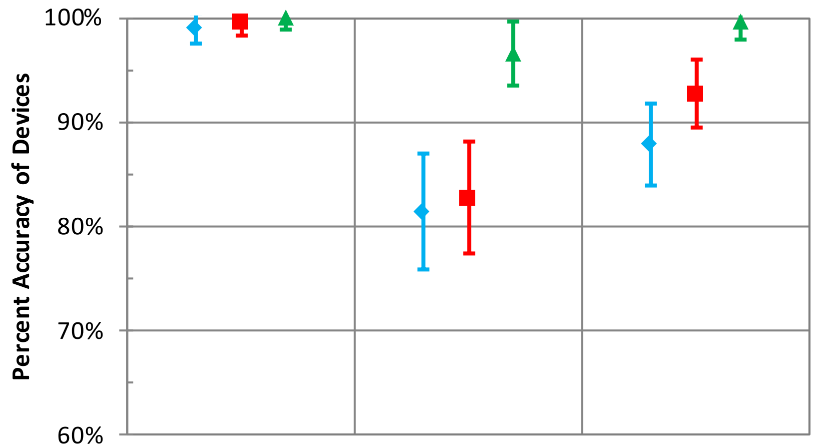
Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	268	173	329
	Sensitivity	84.54 ± 3.42%	97.19 ± 2.5%	98.21 ± 1.43%
Iteris	# of vehicles detected	312	178	334
	Sensitivity	98.42 ± 1.42%	100 ± 1.5%	99.7 ± 0.94%
Matrix	# of vehicles detected	311	178	334
	Sensitivity	98.11 ± 1.51%	100 ± 1.5%	99.7 ± 0.94%
Ground Truth		317	178	335

Figure 15: Noon Cloudy, Daytime Wind Conditions (9, 17, 20) for Zone 27

C.2.4 Sensitivity as a Function of Traffic

The stop-bar detection performance was analyzed as a function of am peak, pm peak, and free flow day and night traffic conditions. The free flow daytime condition was established as the baseline condition.

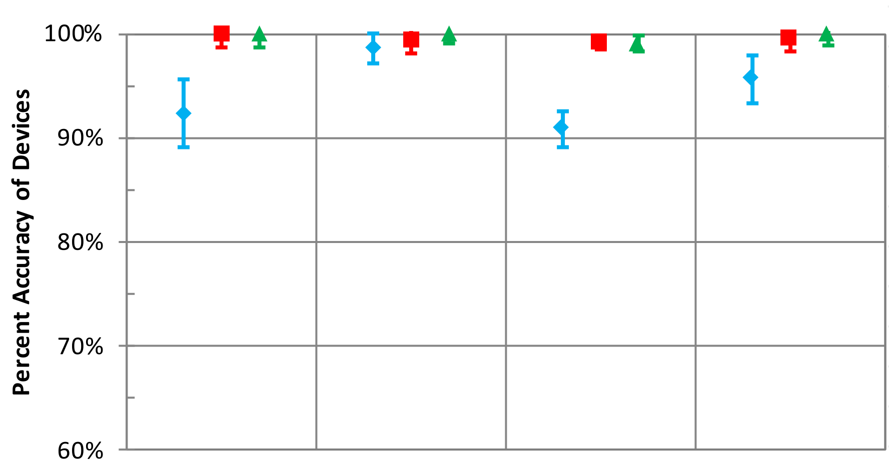
Traffic condition data was collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, to limit the effects of wind and weather during measurement. A total of 602 ground-truth calls were identified for these conditions by manual video review. Figure 16 shows the accuracy levels and error margins for each of the three sensors under the different traffic conditions.



Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	240	118	181
	Sensitivity	99 ± 1.48%	81.38 ± 5.53%	87.86 ± 3.92%
Iteris	# of vehicles detected	250	120	191
	Sensitivity	99.6 ± 1.25%	82.76 ± 5.39%	92.72 ± 3.21%
Matrix	# of vehicles detected	251	140	205
	Sensitivity	100 ± 1.07%	96.55 ± 3.06%	99.51 ± 1.52%
Ground Truth		251	145	206

Figure 16: Nighttime Wind Conditions (13, 16, 19) for Zone 27

The accuracy of the three sensors ranged from 90.8 percent (for Autoscope during daytime free flow traffic) to 100 percent (for Iteris during a.m. peak and Matrix during a.m. peak, p.m. peak and free flow night). Iteris and Matrix sensors were the least effected by different traffic conditions with accuracy minimum accuracy levels of 99.1 and 99.0 percent, respectively. Autoscope was the most affected by the am peak and free flow day traffic with accuracy levels at 92.3 and 90.8 percent, respectively.



Device		a.m. peak	p.m. peak	Free flow day	Free flow night
Autoscope	# of vehicles detected	193	286	663	240
	Sensitivity	92.34 ± 3.25%	98.62 ± 1.45%	90.82 ± 1.79%	95.62 ± 2.36%
Iteris	# of vehicles detected	209	288	724	250
	Sensitivity	100 ± 1.28%	99.31 ± 1.22%	99.18 ± 0.66%	99.6 ± 1.25%
Matrix	# of vehicles detected	209	290	723	251
	Sensitivity	100 ± 1.28%	100 ± 0.92%	99.04 ± 0.7%	100 ± 1.07%
Ground Truth		209	290	730	251

Figure 17: Traffic Conditions (21, 22, 23, 24) for Zone 27

C.3 ZONE 28

Zone 28 was one of the two through lanes in the test intersection, it was the lane located third south from the centre median. Zone 28, as well as zone 29, had higher traffic volumes than the turning lanes, zones 26 and 27.

C.3.1 Sensitivity as a Function of Weather

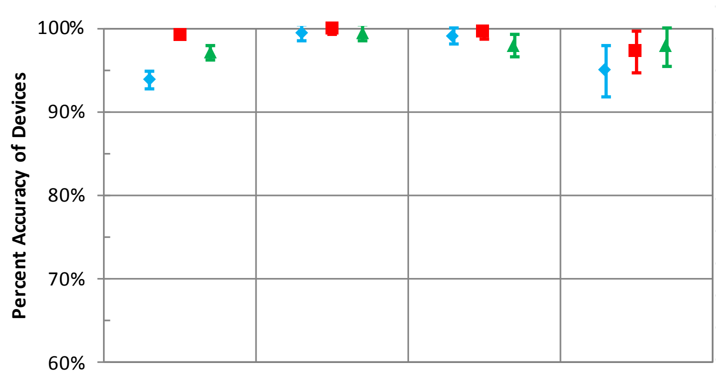
The stop-bar detection performance was analyzed as a function of clear, rain, fog, and snow weather conditions during both daytime and nighttime. Weather condition data was collected for wind speeds of 15 km/hr or less, limiting the effects of wind during measurement. A total of 2258 daytime and 1067 nighttime ground-truth calls were identified for these conditions by manual video review. Figure 18 and Figure 19 show the accuracy levels and error margins for each of the three sensors under different weather conditions (clear, rain, snow, and fog).

The accuracy of the three sensors during daytime ranged from 100.0 percent (for Iteris during rain) to 93.8 percent (for Autoscope during clear). Nighttime weather conditions performed similarly with the maximum accuracy achieved by Iteris during rain with 100.0 percent, and minimum accuracy of 93.4 percent with Autoscope during clear.

All three sensors, Autoscope, Iteris, and Matrix, performed at high accuracy levels under clear weather conditions during both day and nighttime conditions, with 93.8, 99.2, and 97.1 percent accuracy levels during daytime and 93.4, 99.1, and 99.1 percent accuracy levels at nighttime, respectively. Clear conditions are used as the baseline condition.
Rain did not affect the performance of the sensors during daytime; however, the accuracy level of Matrix during nighttime was reduced by 3.3 percent relative to the clear conditions. Iteris was not adversely affected by rain during both daytime and nighttime conditions.

Snow conditions reduced the accuracy levels of Iteris and Matrix during nighttime conditions by 4.0 and 3.7 percent respectively.

Fog during daytime impacted Iteris with a decrease in accuracy level of 2.1 percent. Iteris performed slightly poorer in fog conditions compared to snow. Fog during nighttime impacted Matrix with a decrease of 1.2 percent.



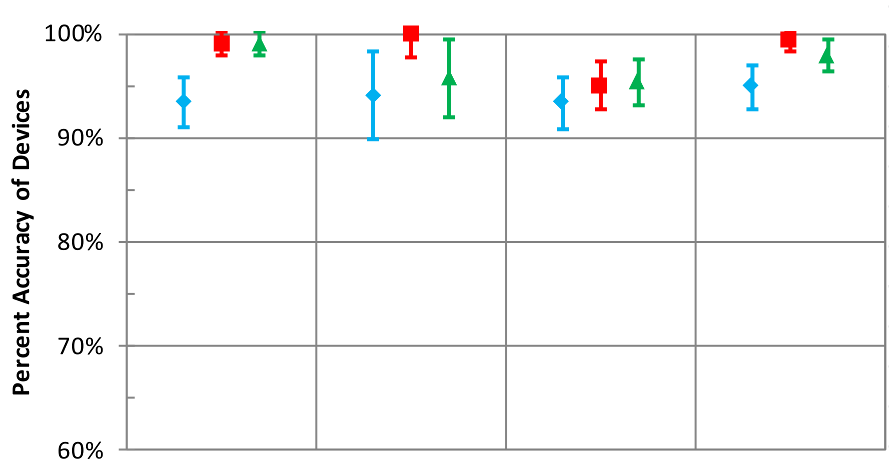
Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	1241	340	412	168
	Sensitivity	93.8 ± 1.11%	99.42 ± 1.03%	99.04 ± 1.01%	94.92 ± 3.07%
Iteris	# of vehicles detected	1313	342	414	172
	Sensitivity	99.24 ± 0.44%	100 ± 0.79%	99.52 ± 0.85%	97.18 ± 2.52%
Matrix	# of vehicles detected	1284	340	407	173
	Sensitivity	97.05 ± 0.79%	99.42 ± 1.03%	97.84 ± 1.33%	97.74 ± 2.35%
Ground Truth		1323	342	416	177

Figure 18: Daytime Weather Conditions (1, 3, 5, 7) for Zone 28

C.3.2 Sensitivity as a Function of Illumination

The stop-bar detection performance was analyzed as a function of varying illumination conditions to assess the effects of glare and shadows on sensor performance. The analyzed lighting conditions were cloudy noon (baseline), dawn, sunny afternoon, dusk, and night. Cloudy noon was identified in literature as being the ideal lighting conditions for video sensors, and was therefore the baseline condition.

Illumination condition data was collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, to limit the effects of wind and weather during measurement. A total of 1770 ground-truth calls were identified for these conditions by manual video review. Figure 20 shows the accuracy levels and error margins for each of the three sensors under the different illumination conditions.

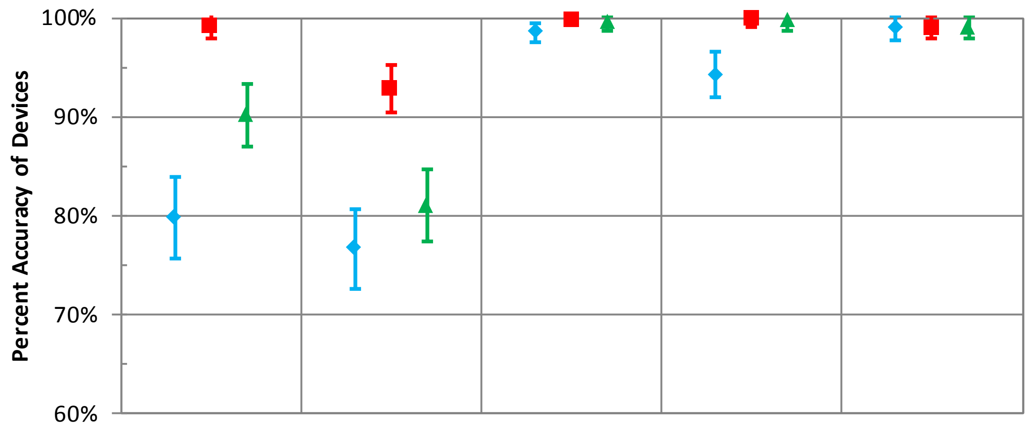


Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	296	110	282	314
	Sensitivity	93.38 ± 2.43%	94.02 ± 4.19%	93.38 ± 2.5%	94.86 ± 2.14%
Iteris	# of vehicles detected	314	117	287	329
	Sensitivity	99.05 ± 1.23%	100 ± 2.26%	95.03 ± 2.22%	99.4 ± 1.07%
Matrix	# of vehicles detected	314	112	288	324
	Sensitivity	99.05 ± 1.23%	95.73 ± 3.76%	95.36 ± 2.16%	97.89 ± 1.52%
Ground Truth		317	117	302	331

Figure 19: Nighttime Weather Conditions (2, 4, 6, 8) for Zone 28

The accuracy of the three sensors ranged from 76.6 percent (for Autoscope during dawn) to 100.0 percent (for Iteris during dusk). Under ideal conditions (i.e. cloudy noon), Iteris and Matrix performed well with 99.2 and 90.1 percent accuracy levels, respectively. However, Autoscope resulted in a lower accuracy of 79.8 percent, which could be due to other uncontrolled factors.

All three sensors performed well under sunny afternoon, dusk, and night conditions with accuracy levels of over 98 percent. Dawn lighting conditions had the most effect on detection performance for all three sensors, with the highest effect on Autoscope resulting in the lowest accuracy level of 76.6 percent.



Device		Noon	Dawn	Afternoon	Dusk	Night
Autoscope	# of vehicles detected	209	246	549	295	296
	Sensitivity	79.77 ± 4.17%	76.64 ± 3.94%	98.56 ± 0.96%	94.25 ± 2.31%	99 ± 1.24%
Iteris	# of vehicles detected	260	298	556	313	314
	Sensitivity	99.24 ± 1.34%	92.83 ± 2.49%	99.82 ± 0.57%	100 ± 0.86%	99.05 ± 1.23%
Matrix	# of vehicles detected	236	260	554	312	314
	Sensitivity	90.08 ± 3.18%	81 ± 3.67%	99.46 ± 0.7%	99.68 ± 1%	99.05 ± 1.23%
Ground Truth		262	321	557	313	317

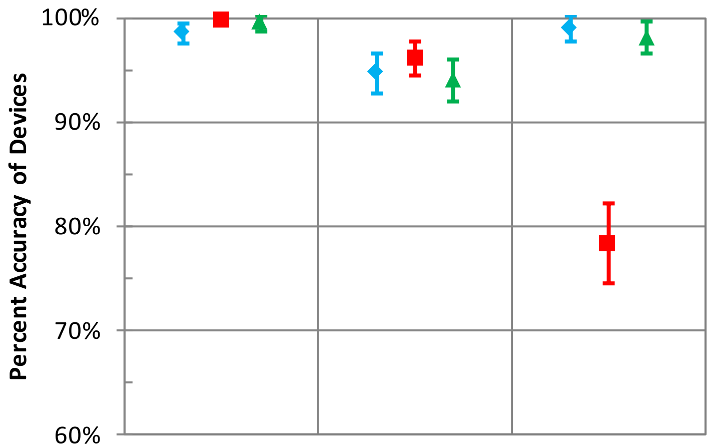
Figure 20: Illumination Conditions (9, 10, 11, 12, 13) for Zone 28

Overall, Iteris was the least effected by the different lighting conditions, maintaining an accuracy level of greater than 92 percent. Matrix generally performed similarly to Iteris under the different lighting conditions, except during the dawn condition resulting in approximately 10 percent lower accuracy level than Iteris, at 81.0 percent.

C.3.3 Sensitivity as a Function of Wind

The stop-bar detection performance was analyzed as a function of low (less than 15 km/hr), moderate (between 15 and 30 km/hr), and strong (greater than 30 km/hr) wind conditions for sunny daytime, cloudy noon, and nighttime lighting conditions. This allowed for the evaluation of a combination of effects on sensor performance. The low wind condition was established as the baseline condition for all three lighting conditions.

Wind condition data was collected for no adverse weather conditions, to limit the effects of weather during measurement. A total of 1284 sunny daytime, 1002 cloudy noon, and 930 nighttime ground-truth calls were identified for these conditions by manual video review. Figure 21, Figure 22, and Figure 23 show the accuracy levels and error margins for each of the three sensors under the different wind speed conditions, for sunny daytime, cloudy noon, and nighttime conditions, respectively.



Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	549	391	311
	Sensitivity	98.56 ± 0.96%	94.67 ± 1.92%	99.04 ± 1.24%
Iteris	# of vehicles detected	556	397	246
	Sensitivity	99.82 ± 0.57%	96.13 ± 1.68%	78.34 ± 3.89%
Matrix	# of vehicles detected	554	388	308
	Sensitivity	99.46 ± 0.7%	93.95 ± 2.02%	98.09 ± 1.52%
Ground Truth		557	413	314

Figure 21: Sunny, Daytime Wind Conditions (11, 15, 18) for Zone 28

Under the sunny daytime lighting condition, the accuracy of the three sensors ranged from 78.3 percent (for Iteris during strong wind) to 99.8 percent (for Iteris during low wind), shown in Figure 21. Under the ideal condition of low wind, all three sensors performed very well, with accuracy levels between 99.4 and 99.8 percent. All three sensors preformed slightly poorer under moderate wind conditions with accuracy levels reduced by 3.7 to 5.5 percent relative to their baseline conditions. Strong wind conditions didn't have an effect on Autoscope and Matrix, however, Iteris was significantly affected with a decrease of 21.5 percent. This was because Iteris was mounted at the highest height (40 feet) on a mast arm pole which was highly susceptible to movement by wind force.

Under the cloudy noon lighting condition, the accuracy of the three sensors ranged from 79.8 percent (for Autoscope during low wind) to 100.0 percent (for Iteris during strong wind), shown in Figure 22. Under the ideal condition of low wind, the three sensors range in performance levels with Iteris at the highest accuracy level of 99.2 percent and Autoscope at the lowest accuracy level of 79.8 percent. Autoscope's lower accuracy level under ideal conditions could be due to other uncontrollable factors. All three sensors perform well under moderate wind conditions, with only Iteris having slightly lower accuracy levels. At moderate wind levels Autoscope improved from 7. 9.8 percent to 96.6 percent. Matrix also improved during moderate wind levels from 90.1 percent to 95.7 percent.

Strong wind conditions did not affect sensor performance under cloudy noon conditions, with all sensors having accuracy levels greater than 99 percent.

Under the nighttime lighting condition, the accuracy of the three sensors ranged from 83.2 percent (for Autosope during moderate wind) to 99.1 percent (for all three sensors during low wind), shown in Figure 23.

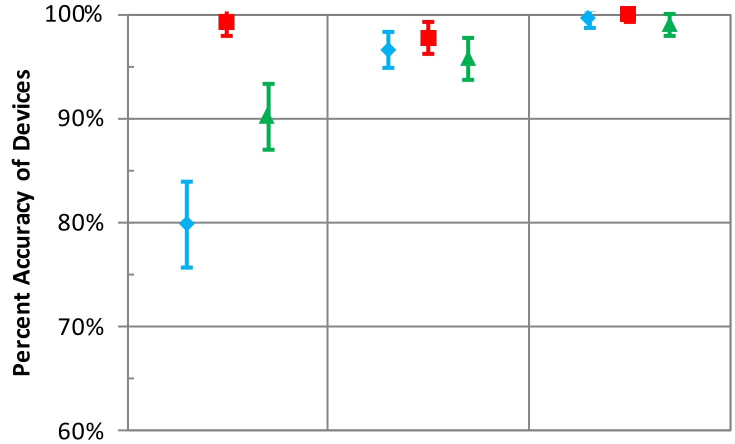
Under the ideal condition of low wind, all three sensors performed with high accuracy levels of greater than 99 percent. Moderate and strong winds reduced the sensor's performance by approximately 5 to 15 percent.

In summary, Iteris was the most effected by strong winds in sunny afternoon conditions due to its high mounted height, resulting in a 78.3 percent accuracy level. The highest reduction in accuracy levels was due to moderate winds during nighttime conditions, with a reduction of 5 to 15 percent accuracy. However under daytime conditions (i.e. cloudy noon and sunny daytime) wind did not significantly affect the sensor performances, with all three sensors resulting in greater than 90 percent accuracies.

C.3.4 Sensitivity as a Function of Traffic

The stop-bar detection performance was analyzed as a function of am peak, pm peak, and free flow day and night traffic conditions. The free flow daytime condition was established as the baseline condition.

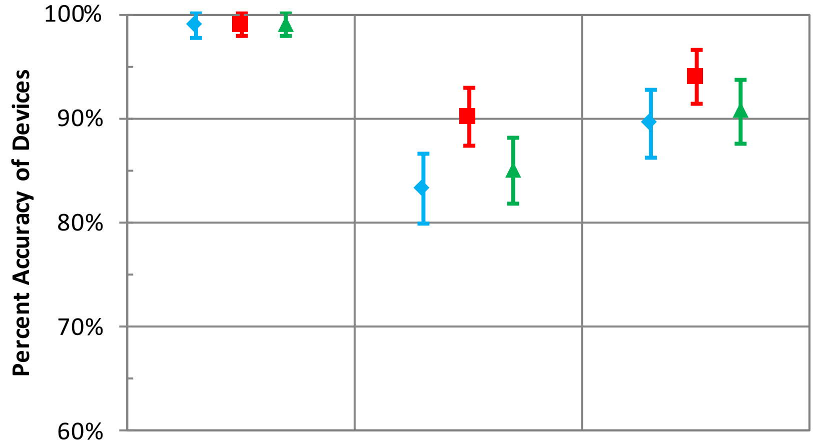
Traffic condition data was collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, to limit the effects of wind and weather during measurement. A total of 1680 ground-truth calls were identified for these conditions by manual video review. Figure 24 shows the accuracy levels and error margins for each of the three sensors under the different traffic conditions



Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	209	337	389
	Sensitivity	79.77 ± 4.17%	96.56 ± 1.77%	99.49 ± 0.9%
Iteris	# of vehicles detected	260	341	391
	Sensitivity	99.24 ± 1.34%	97.71 ± 1.52%	100 ± 0.69%
Matrix	# of vehicles detected	236	334	387
	Sensitivity	90.08 ± 3.18%	95.7 ± 1.93%	98.98 ± 1.08%
Ground Truth		262	349	391

Figure 22: Noon Cloudy, Daytime Wind Conditions (9, 17, 20) for Zone 28

The accuracy of the three sensors ranged from 86.9 percent (for Autoscope during am peak) to 100.0 percent (for Iteris and Matrix during pm peak). Iteris and Matrix sensors were the least effected by different traffic conditions with accuracy minimum accuracy levels of 97.8 and 91.7 percent, respectively. Autoscope was the most affected by the am peak and free flow day traffic with less than 90 percent accuracy levels. Its performance under pm peak was similar to that of Iteris and Matrix.



Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	296	288	239
	Sensitivity	99 ± 1.24%	83.24 ± 3.37%	89.51 ± 3.21%
Iteris	# of vehicles detected	314	312	251
	Sensitivity	99.05 ± 1.23%	90.17 ± 2.73%	94.01 ± 2.57%
Matrix	# of vehicles detected	314	294	242
	Sensitivity	99.05 ± 1.23%	84.97 ± 3.23%	90.64 ± 3.07%
Ground Truth		317	346	267

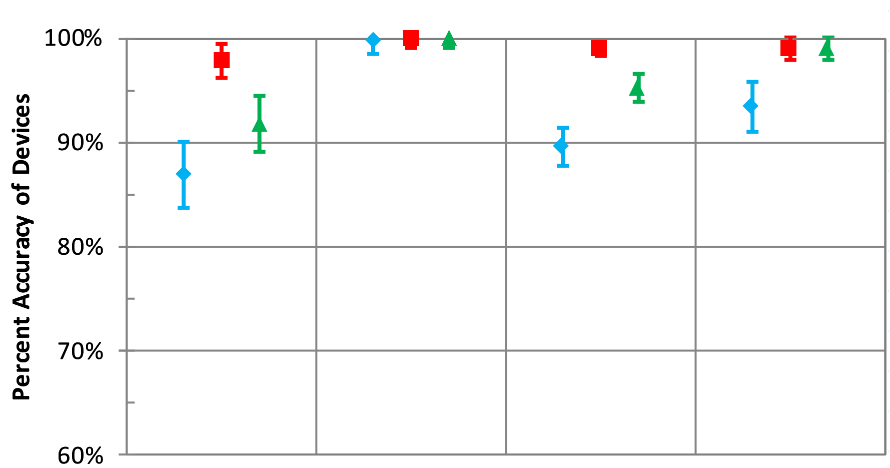
Figure 23: Nighttime Wind Conditions (13, 16, 19) for Zone 28

C.4 ZONE 29

Zone 29 was the south most through lane of the test intersection. The location of the lane potentially affected the accuracy of the sensors as it was not near the centre of the test lanes and was furthest away from the Matrix microwave sensor.

C.4.1 Sensitivity as a Function of Weather

The stop-bar detection performance was analyzed as a function of clear, rain, fog, and snow weather conditions during both daytime and nighttime. Weather condition data was only collected for wind speeds of 15 km/hr or less, limiting the effects of wind during measurement. A total of 2285 daytime and 1199 nighttime ground-truth calls were identified for these conditions by manual video review. Figure 25 and Figure 26 show the accuracy levels and error margins for each of the three sensors under different weather conditions (clear, rain, snow, and fog).



Device		a.m. peak	p.m. peak	Free flow day	Free flow night
Autoscope	# of vehicles detected	272	285	684	296
	Sensitivity	86.9 ± 3.23%	99.65 ± 1.1%	89.53 ± 1.85%	93.38 ± 2.43%
Iteris	# of vehicles detected	306	286	756	314
	Sensitivity	97.76 ± 1.61%	100 ± 0.94%	98.95 ± 0.7%	99.05 ± 1.23%
Matrix	# of vehicles detected	287	286	727	314
	Sensitivity	91.69 ± 2.69%	100 ± 0.94%	95.16 ± 1.32%	99.05 ± 1.23%
Ground Truth		313	286	764	317

Figure 24: Traffic Conditions (21, 22, 23, 24) for Zone 28

The accuracy of the three sensors during daytime ranged from 94.2 percent (for Autoscope during clear conditions) to 99.7 percent (for Iteris during rain). Nighttime weather conditions performed similarly with the maximum accuracy achieved by Iteris and Matrix during rain with 100 percent accuracy, and minimum accuracy of 92.9 percent with Autoscope during snow.

All three sensors, Autoscope, Iteris, and Matrix, performed at high accuracy levels under clear weather conditions during both day and nighttime conditions, with 94.2, 99.1, and 97.3 percent accuracy levels during daytime and 94.5, 98.9, and 98.6 percent accuracy levels at nighttime, respectively. Clear conditions were established as the baseline condition.

Daytime rain conditions showed an improvement in accuracy for all three sensors. During daytime rain conditions Autoscope performed better than the base condition with an improvement of 2.2 percent. Iteris improved marginally in rain conditions and Matrix improved by 1.5 percent. During nighttime rain conditions Autoscope increased by 1.3 percent, Iteris improved by 1.1 percent and Matrix improved by 1.4.

Snow conditions increased the accuracy levels of all three sensors during daytime by 2.3, 0.4 and 1.3 percent respectively, for Autoscope, Iteris and Matrix. During nighttime snow conditions, Autoscope decreased in accuracy by 1.6 percent, Iteris decreased by 3.1 percent and Matrix decreased by 3.1 percent.

Fog during daytime increased the accuracy of Autoscope by 1.2 percent and decreased the accuracy of Iteris by 2.5 percent and Matrix by 0.7 percent. For fog during nighttime conditions the accuracy of Autoscope improved by 1.4 percent. Fog during nighttime conditions also increased the accuracy of Iteris (by 0.5 percent. Matrix performed worse during nighttime fog conditions than base conditions with a decrease of 0.5 percent.

C.4.2 Sensitivity as a Function of Illumination

The stop-bar detection performance was analyzed as a function of varying illumination conditions to assess the effects of glare and shadows on sensor performance. The analyzed lighting conditions are cloudy noon (baseline), dawn, sunny afternoon, dusk, and night. Cloudy noon is identified in literature as being the ideal lighting conditions for video sensors, and is therefore the baseline condition.

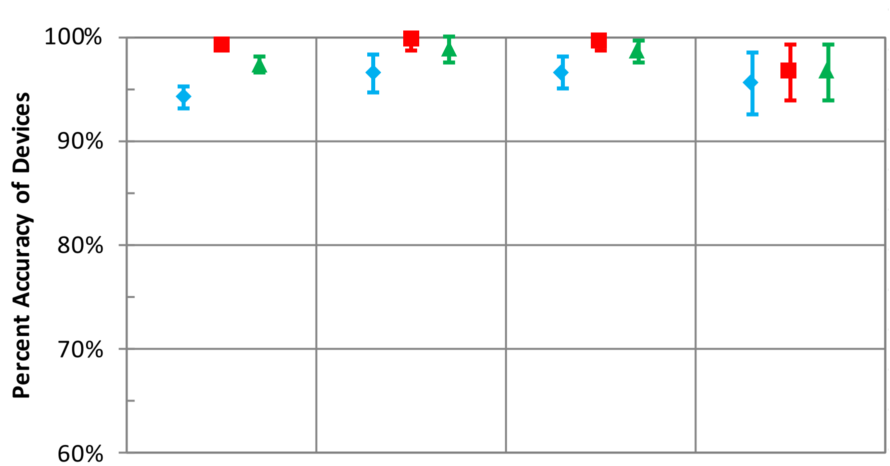
Illumination condition data was collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, to limit the effects of wind and weather during measurement. A total of 1837 ground-truth calls were identified for these conditions by manual video review. Figure 27 shows the accuracy levels and error margins for each of the three sensors under the different illumination conditions.

The accuracy of the three sensors ranged from 72.4 percent (for Autoscope during dawn conditions) to 100 percent (for Iteris during dusk). Under ideal conditions (i.e. cloudy noon), Iteris and Matrix performed well with 98.6 and 95.9 percent accuracy levels, respectively. However, Autoscope resulted in a lower accuracy of 87.8 percent, which could be due to other uncontrolled factors.

All three sensors performed well under sunny afternoon, dusk, and night conditions with accuracy levels of over 94 percent. Iteris was the least effected by the different lighting conditions, maintaining an accuracy level of greater than 94 percent.

C.4.3 Sensitivity as a Function of Wind

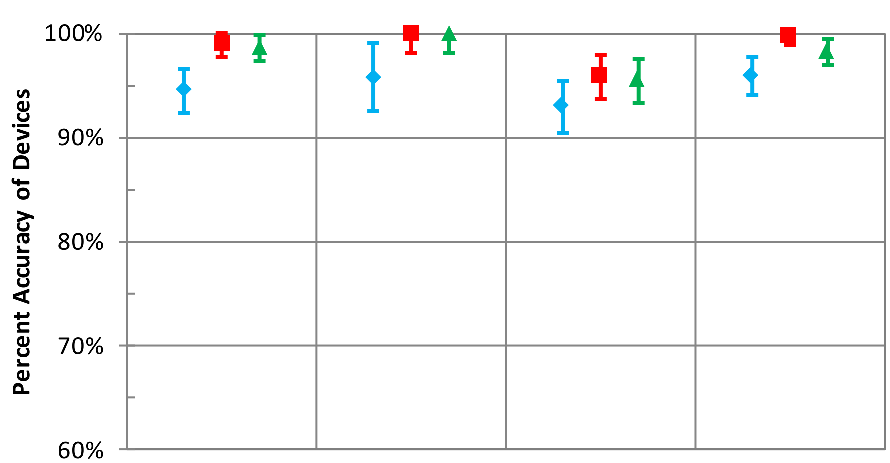
The stop-bar detection performance was analyzed as a function of low (less than 15 km/hr), moderate (between 15 and 30 km/hr), and strong (greater than 30 km/hr) wind conditions for sunny daytime, cloudy noon, and nighttime lighting conditions. This allowed for the evaluation of a combination effects on sensor performance. The low wind condition was identified as the baseline condition for all three lighting conditions.



Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	1259	325	421	168
	Sensitivity	94.24 ± 1.07%	96.44 ± 1.83%	96.56 ± 1.55%	95.45 ± 2.96%
Iteris	# of vehicles detected	1324	336	434	170
	Sensitivity	99.1 ± 0.47%	99.7 ± 0.93%	99.54 ± 0.81%	96.59 ± 2.68%
Matrix	# of vehicles detected	1300	333	430	170
	Sensitivity	97.31 ± 0.75%	98.81 ± 1.25%	98.62 ± 1.1%	96.59 ± 2.68%
Ground Truth		1336	337	436	176

Figure 25: Daytime Weather Conditions (1, 3, 5, 7) for Zone 29

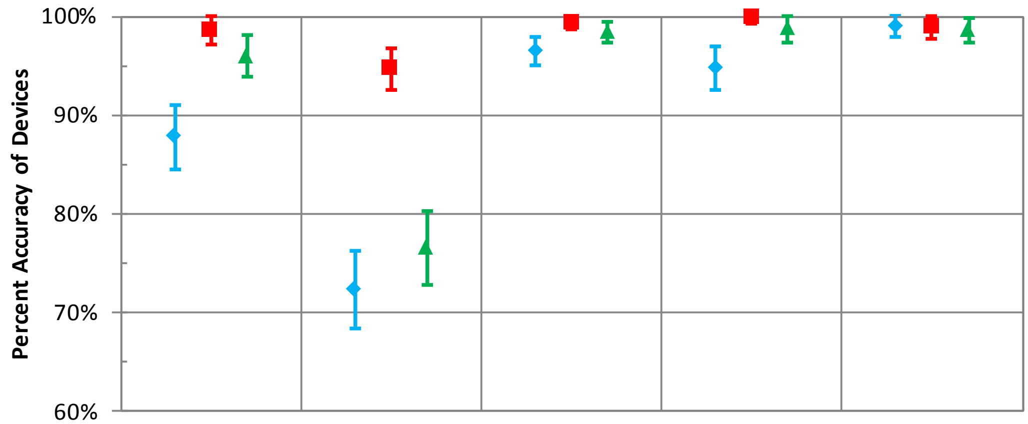
Wind condition data was collected for no adverse weather conditions, to limit the effects of weather during measurement. A total of 1192 sunny daytime, 1040 cloudy noon, and 1024 nighttime ground-truth calls were identified for these conditions by manual video review. Figure 28, Figure 29, and Figure 30 show the accuracy levels and error margins for each of the three sensors under the different wind speed conditions, for sunny daytime, cloudy noon, and nighttime conditions, respectively.



Device		Clear	Rain	Snow	Fog
Autoscope	# of vehicles detected	342	136	289	368
	Sensitivity	94.48 ± 2.1%	95.77 ± 3.31%	92.93 ± 2.52%	95.83 ± 1.81%
Iteris	# of vehicles detected	358	142	298	383
	Sensitivity	98.9 ± 1.16%	100 ± 1.87%	95.82 ± 2.04%	99.74 ± 0.82%
Matrix	# of vehicles detected	357	142	297	377
	Sensitivity	98.62 ± 1.25%	100 ± 1.87%	95.5 ± 2.1%	98.18 ± 1.32%
Ground Truth		362	142	311	384

Figure 26: Nighttime Weather Conditions (2, 4, 6, 8) for Zone 29

Under the sunny daytime lighting condition, the accuracy of the three sensors ranged from 69.2 percent (for Iteris during strong wind) to 99.4 percent (for Iteris during low wind), shown in Figure 28. Under the ideal condition of low wind, all three sensors performed well, with accuracy levels between 96.4 and 99.4 percent. All three sensors preformed slightly poorer under moderate wind conditions with accuracy levels reduced by 2.1 to 2.4 percent relative to their baseline conditions. Strong wind conditions had a small effect on Autoscope (0.9 percent) and Matrix (1.3 percent, however, Iteris was significantly affected with a decrease of 30.2 percent. Iteris is mounted at the highest height (40 feet) on a mast arm pole which was highly susceptible to movement by wind force.

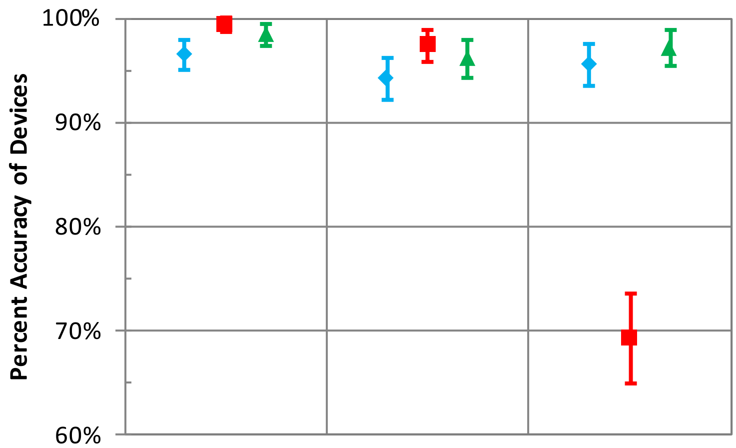


Device		Noon	Dawn	Afternoon	Dusk	Night
Autoscope	# of vehicles detected	259	259	484	303	342
	Sensitivity	87.8 ± 3.24%	72.35 ± 3.93%	96.41 ± 1.46%	94.69 ± 2.21%	99 ± 1.13%
Iteris	# of vehicles detected	291	339	499	320	358
	Sensitivity	98.64 ± 1.43%	94.69 ± 2.08%	99.4 ± 0.78%	100 ± 0.84%	98.9 ± 1.16%
Matrix	# of vehicles detected	283	274	494	316	357
	Sensitivity	95.93 ± 2.08%	76.54 ± 3.73%	98.41 ± 1.06%	98.75 ± 1.32%	98.62 ± 1.25%
Ground Truth		295	358	502	320	362

Figure 27: Illumination Conditions (9, 10, 11, 12, 13) for Zone 29

Under the cloudy noon lighting condition, the accuracy of the three sensors ranged from 69.2 percent (for Iteris during strong wind) to 99.4 percent (for Iteris during low wind), shown in Figure 29. Under the ideal condition of low wind, the three sensors range in performance levels with Iteris at the highest accuracy level of 99.4 percent and Autoscope at the lowest accuracy level of 96.4 percent. All three devices decreased in accuracy for moderate wind conditions when compared to low conditions. The decreases were: 2.2, 2.1, and 2.4 percent for Autoscope, Iteris and Matrix, respectively.

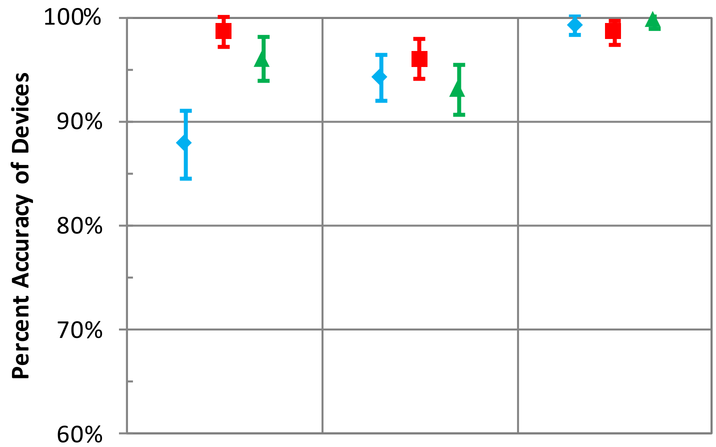
During strong wind conditions the accuracy levels of Autoscope and Matrix decreased slightly (less than 1.3 percent) from baseline conditions. Iteris experienced a significant drop in accuracy during strong wind conditions with a decrease of 30.2 percent.



Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	484	356	298
	Sensitivity	96.41 ± 1.46%	94.18 ± 2.09%	95.51 ± 2.1%
Iteris	# of vehicles detected	499	368	216
	Sensitivity	99.4 ± 0.78%	97.35 ± 1.53%	69.23 ± 4.35%
Matrix	# of vehicles detected	494	363	303
	Sensitivity	98.41 ± 1.06%	96.03 ± 1.79%	97.12 ± 1.77%
Ground Truth		502	378	312

Figure 28: Sunny, Daytime Wind Conditions (11, 15, 18) for Zone 29

Under the nighttime wind conditions, the accuracy of the three sensors ranged from 86.4 percent (for Matrix during moderate wind) to 99.0 percent (for Autoscope during low wind), shown in Figure 30.



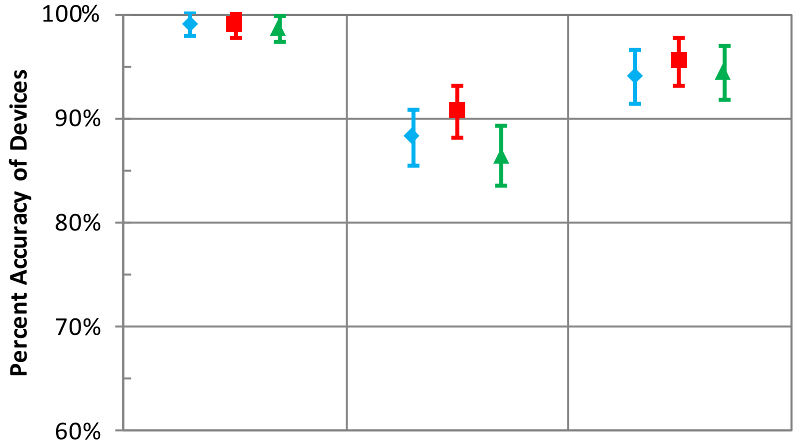
Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	259	326	396
	Sensitivity	87.8 ± 3.24%	94.22 ± 2.19%	99.25 ± 0.98%
Iteris	# of vehicles detected	291	332	393
	Sensitivity	98.64 ± 1.43%	95.95 ± 1.9%	98.5 ± 1.2%
Matrix	# of vehicles detected	283	322	398
	Sensitivity	95.93 ± 2.08%	93.06 ± 2.36%	99.75 ± 0.79%
Ground Truth		295	346	399

Figure 29: Noon Cloudy, Daytime Wind Conditions (9, 17, 20) for Zone 29

Under the ideal condition of low wind, all three sensors performed well with accuracies over 98.0 percent. Moderate winds reduced the sensors' accuracy by 8.2 to 12.2 percent. While strong wind also decreased sensor performance, decreases were less at 3.4 to 5.0 percent from baseline.

C.4.4 Sensitivity as a Function of Traffic

The stop-bar detection performance was analyzed as a function of am peak, pm peak, and free flow day and night traffic conditions. The free flow daytime condition was established as the baseline condition.



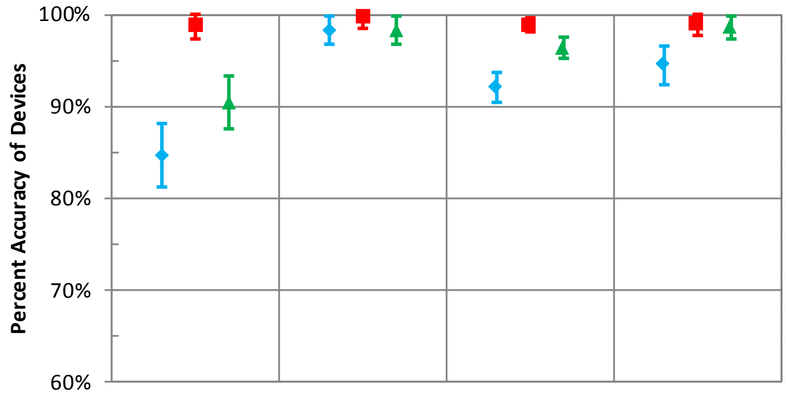
Device		Low (<15 km/hr)	Moderate (15-30 km/hr)	Strong (> 30 km/hr)
Autoscope	# of vehicles detected	342	350	249
	Sensitivity	99 ± 1.13%	88.16 ± 2.73%	93.96 ± 2.59%
Iteris	# of vehicles detected	358	360	253
	Sensitivity	98.9 ± 1.16%	90.68 ± 2.48%	95.47 ± 2.31%
Matrix	# of vehicles detected	357	343	250
	Sensitivity	98.62 ± 1.25%	86.4 ± 2.89%	94.34 ± 2.52%
Ground Truth		362	397	265

Figure 30: Nighttime Wind Conditions (13, 16, 19) for Zone 29

Traffic condition data was collected for low wind (wind speeds of 15 km/hr or less) and no adverse weather conditions, to limit the effects of wind and weather during measurement. A total of 1752 ground-truth calls were identified for these conditions by manual video review. Figure 31 shows the accuracy levels and error margins for each of the three sensors under different traffic conditions.

The accuracy of the three sensors ranged from 84.7 percent (for Autoscope during am peak) to 99.7 percent (for Iteris during pm peak). Iteris and Matrix sensors were the least effected by different traffic conditions with minimum accuracy levels of 98.7 and 90.4

percent, respectively. Autoscope was the most affected by the am peak with under 90 percent accuracy level.



Device		a.m. peak	p.m. peak	Free flow day	Free flow night
Autoscope	# of vehicles detected	265	285	724	342
	Sensitivity	84.66 ± 3.43%	98.28 ± 1.55%	91.99 ± 1.62%	94.48 ± 2.1%
Iteris	# of vehicles detected	309	289	778	358
	Sensitivity	98.72 ± 1.34%	99.66 ± 1.08%	98.86 ± 0.71%	98.9 ± 1.16%
Matrix	# of vehicles detected	283	285	758	357
	Sensitivity	90.42 ± 2.85%	98.28 ± 1.55%	96.32 ± 1.15%	98.62 ± 1.25%
Ground Truth		313	290	787	362

Figure 31: Traffic Conditions (21, 22, 23, 24) for Zone 29

D. ADVANCE ZONE ANALYSIS

This section analyzed the advance detection performance of Autoscope video and Iteris video (both near and far configurations) for each of the through lane zones (i.e. zones 23 and 24). The analysis was conducted for the six best performing and six worst performing conditions from the stop-bar analysis. For the by-zone analysis, the number of ground-truth calls per device was significantly less than the 1080 calls required for statistical significance in the total device performance. Variation in ground-truth calls was caused by zone (lane) location in the intersection as well as traffic flow variation due to temporal and climate influences. Figure 32 shows the test intersection configuration with the zones labeled. Table 10 shows condition numbers and descriptions.

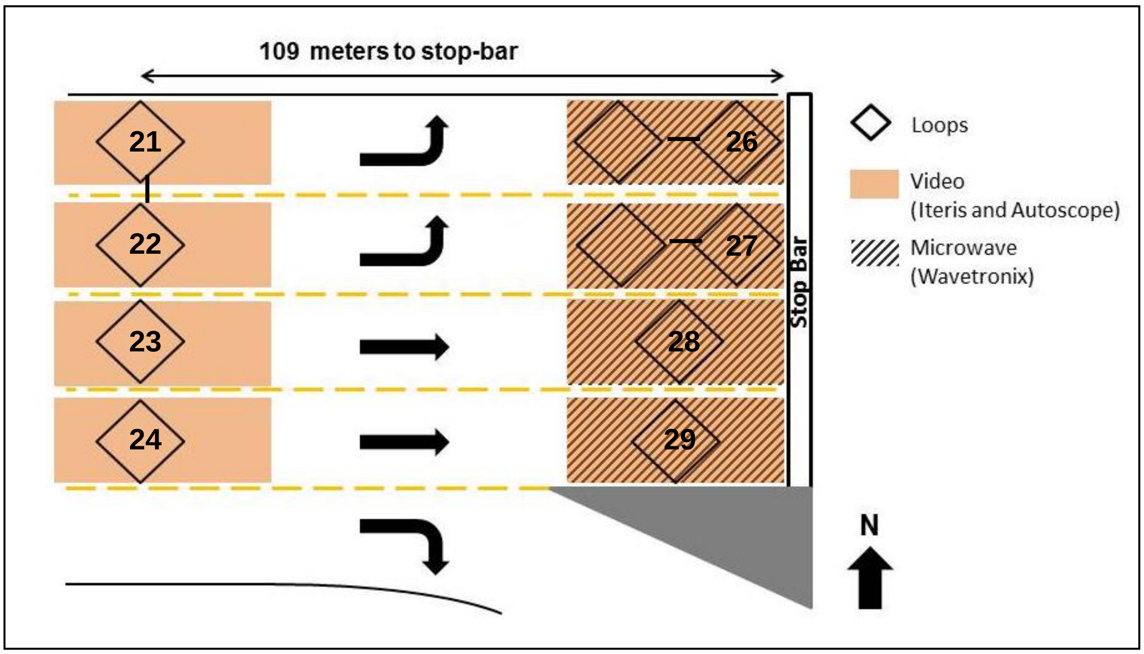


Figure 32: General detection zone layout at eastbound approach

Table 10: Condition Numbers with Descriptions

Condition #	Description
Condition Criteria	
Weather Conditions	
1	no wind, clear, day
2	no wind, clear, night
3	no wind, rain, day
4	no wind, rain, night
5	no wind, snow, day
6	no wind, snow, night
7	no wind, fog, day
8	no wind, fog, night
Illumination Conditions	
9	no wind, no adverse weather, noon, cloudy
10	dawn, no wind, no adverse weather
11	sunny afternoon, no wind
12	dusk, no wind, no adverse weather
13	night, no wind, no adverse weather
Wind Conditions	
15	wind light to moderate, no adverse weather, sunny afternoon
16	wind light to moderate, no adverse weather, night
17	wind light to moderate, no adverse weather, cloudy, noon
18	wind moderate to strong, no adverse weather, sunny afternoon
19	wind moderate to strong, no adverse weather, night'
20	wind moderate to strong, no adverse weather, cloudy, noon
Traffic Conditions	
21	no wind, no adverse weather, a.m. peak
22	no wind, no adverse weather, p.m. peak
23	no wind, no adverse weather,free flow, day
24	no wind, no adverse weather, free flow, night

Note: Condition 14 was redundant with condition 9. Condition 14 does not appear in the above table or elsewhere in the report.

D.1 ZONE 23

Zone 23 was the advanced zone located in the North most through lane.

D.1.1 Sensitivity for Conditions Performing Well in Stop-bar Analysis

The six best performing conditions from the stop-bar analysis were:

- Weather: daytime rain (condition 3)
- Illumination: sunny afternoon (condition 11)
- Illumination: dusk (condition 12)
- Illumination: night (condition 13)

- Wind: Moderate to strong wind during cloudy noon (condition 20)
- and Traffic: p.m. peak (condition 22)

A total of 4452 ground-truth calls were identified for these conditions using an Excel macro-program for comparison of loop function with video sensor function. Figure 33 shows the accuracy levels and error margins for each sensor under the six defined conditions.

The accuracy of the Autoscope sensor ranged from 20.3 percent during dusk illumination to 99 percent during nighttime illumination conditions. The 99 percent accuracy level was an exception as all other accuracy levels under the different conditions range between 20.3 and 39.3 percent. The accuracy of the Iteris sensor ranged from 81.9 percent during daytime rain conditions and sunny afternoon conditions to 97.1 percent during dusk.

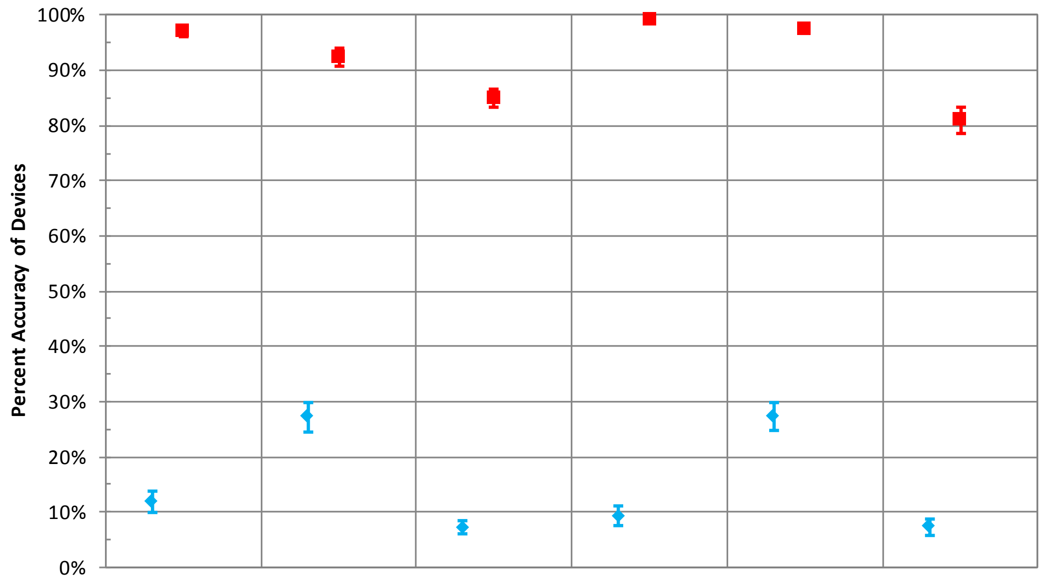
Autoscope performed with significantly lower advance detection accuracy levels relative to Iteris (between 40 and 70 percent lower accuracy levels) under all of the identified best performing conditions, except during nighttime illumination conditions. No reason has been identified for Autoscope's exceptionally high accuracy level under nighttime condition.

D.1.2 Sensitivity for Conditions Performing Poorly in Stop-bar Analysis

The six worst performing conditions from the stop-bar analysis were:

- Weather: snow during nighttime (condition 6)
- Illumination: cloudy noon (condition 9)
- Illumination: dawn (condition 10)
- Wind: light to moderate wind at nighttime (condition 16)
- Wind: moderate to strong wind during sunny afternoons (condition 18)

- Traffic: a.m. peak (condition 21)

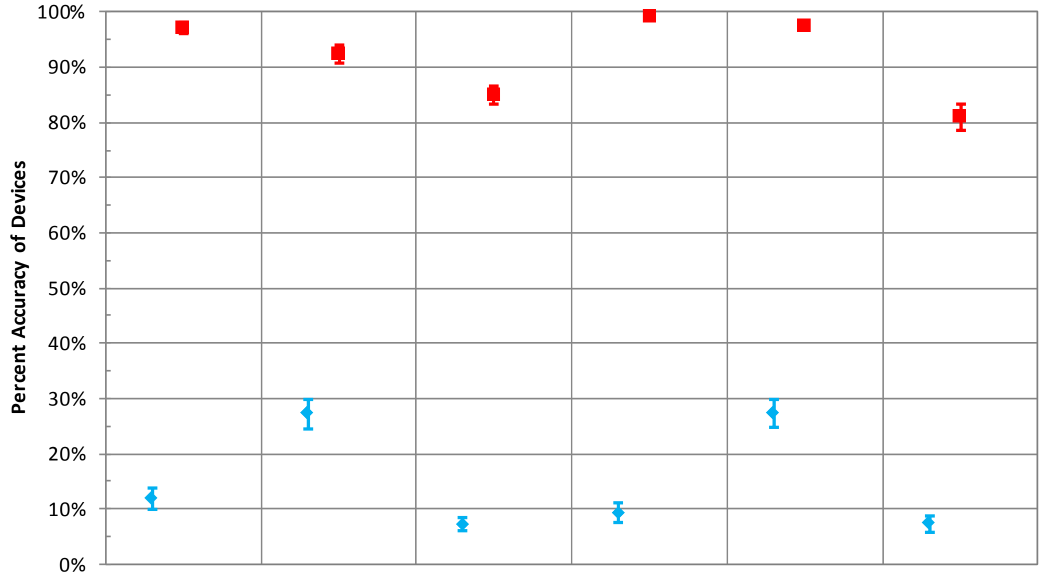


Device		Weather, snow, night	Illumination, noon, cloudy	Illumination, dawn	Wind, light to moderate, night	Wind, strong, sunny afternoon	Traffic, a.m. peak
Autoscope	# of vehicles detected	96	198	83	63	234	57
	Sensitivity	11.96 ± 1.91%	27.2 ± 2.73%	7.22 ± 1.27%	9.31 ± 1.87%	27.4 ± 2.52%	7.28 ± 1.56%
Iteris	# of vehicles detected	779	672	977	671	833	634
	Sensitivity	97.01 ± 1.04%	92.31 ± 1.66%	84.96 ± 1.75%	99.11 ± 0.71%	97.54 ± 0.92%	80.97 ± 2.33%
Ground Truth		803	728	1150	677	854	783

Figure 33: Sensitivity for Conditions Performing Well in Stop-bar Analysis, Zone 23

A total of 4995 ground-truth calls were identified for these conditions. Figure 34 shows the accuracy levels and error margins for each sensor under the six defined conditions.

The accuracy of the Autoscope sensor ranged from 27.4 percent during cloudy noon conditions of illumination to 7.2 percent during dawn illumination conditions. The accuracy of the Iteris sensor ranged from 81.0 percent during a.m. peak traffic conditions to 99.1 percent during moderate nighttime wind conditions.



Device		Weather, snow, night	Illumination, noon, cloudy	Illumination, dawn	Wind, light to moderate, night	Wind, strong, sunny afternoon	Traffic, a.m. peak
Autoscope	# of vehicles detected	96	198	83	63	234	57
	Sensitivity	11.96 ± 1.91%	27.2 ± 2.73%	7.22 ± 1.27%	9.31 ± 1.87%	27.4 ± 2.52%	7.28 ± 1.56%
Iteris	# of vehicles detected	779	672	977	671	833	634
	Sensitivity	97.01 ± 1.04%	92.31 ± 1.66%	84.96 ± 1.75%	99.11 ± 0.71%	97.54 ± 0.92%	80.97 ± 2.33%
Ground Truth		803	728	1150	677	854	783

Figure 34: Sensitivity for Conditions Performing Poorly in Stop-bar Analysis, Zone 23

D.2 ZONE 24

Zone 24 was the through lane closest to the curb (i.e. south most lane in the intersection).

D.2.1 Sensitivity for Conditions Performing Well in Stop-bar Analysis

The six best performing conditions from the stop-bar analysis were:

- Weather: daytime rain (condition 3)
- Illumination: sunny afternoon (condition 11)

- Illumination: dusk (condition 12)
- Illumination: night (condition 13)
- Wind: Moderate to strong wind during cloudy noon (condition 20)
- and Traffic: p.m. peak (condition 22)

A total of 3686 ground-truth calls were identified for these conditions using an Excel macro-program for comparison of loop function with video sensor function. Figure 35 shows the accuracy levels and error margins for each sensor under the six defined conditions.

The accuracy of the Autoscope sensor ranged from 99 percent during nighttime illumination to 15.9 percent during dusk illumination conditions. The 99 percent accuracy level was an exception as all other accuracy levels under the different conditions ranged between 37.8 and 15.9 percent. The accuracy of the Iteris sensor ranged from 84.9 percent during moderate wind during cloudy afternoon conditions to 49.3 percent during nighttime illumination.

Autoscope performed with significantly lower advance detection accuracy levels relative to Iteris (between 40 and 70 percent lower accuracy levels) under all of the identified best performing conditions, except during nighttime illumination conditions. No reason has been identified for Autoscope's exceptionally high accuracy level under nighttime condition.

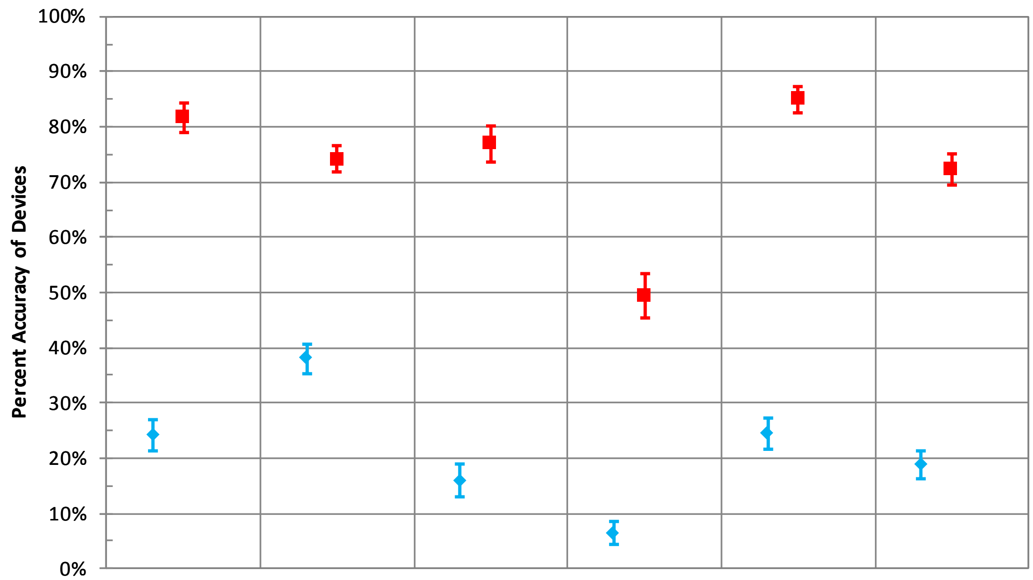
D.2.2 Sensitivity for Conditions Performing Poorly in Stop-bar Analysis

The six worst performing conditions from the stop-bar analysis were:

- Weather: snow during nighttime (condition 6)
- Illumination: cloudy noon (condition 9)

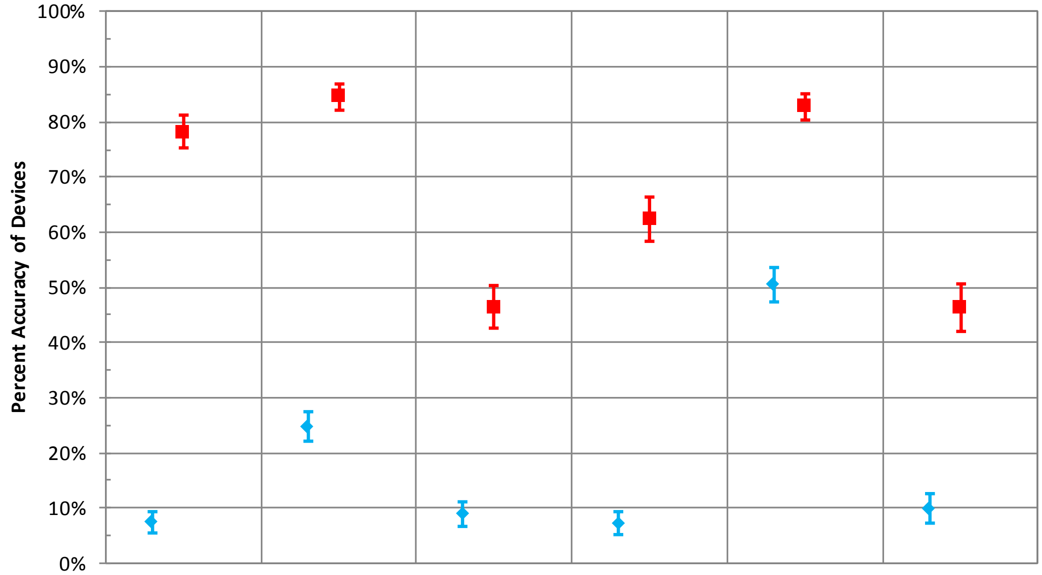
- Illumination: dawn (condition 10)Wind: light to moderate wind at nighttime (condition 16)
- Wind: moderate to strong wind during sunny afternoons (condition 18)
- Traffic: a.m. peak (condition 21)
- Wind: light to moderate wind at nighttime (condition 16)

A total of 3192 ground-truth calls were identified for these conditions. Figure 36 shows the accuracy levels and error margins for each sensor under the six defined conditions.



Device		Weather, rain, day	Illumination, sunny afternoon	Illumination, dusk	Illumination, night	Wind, moderate to strong, noon, cloudy	Traffic, p.m. peak
Autoscope	# of vehicles detected	148	356	72	27	146	125
	Sensitivity	24.18 ± 2.87%	37.99 ± 2.62%	15.93 ± 2.88%	6.4 ± 2.05%	24.46 ± 2.92%	18.77 ± 2.51%
Iteris	# of vehicles detected	500	695	348	208	507	481
	Sensitivity	81.7 ± 2.6%	74.17 ± 2.36%	76.99 ± 3.29%	49.29 ± 4.03%	84.92 ± 2.44%	72.22 ± 2.87%
Ground Truth		612	937	452	422	597	666

Figure 35: Sensitivity for Conditions Performing Well in Stop-bar Analysis, Zone 24



Device		Weather, snow, night	Illumination, noon, cloudy	Illumination, dawn	Wind, light to moderate, night	Wind, moderate to strong, sunny afternoon	Traffic, a.m. peak
Autoscope	# of vehicles detected	40	170	41	31	355	37
	Sensitivity	7.5 ± 1.93%	24.75 ± 2.73%	8.78 ± 2.22%	7.24 ± 2.14%	50.35 ± 3.11%	9.92 ± 2.63%
Iteris	# of vehicles detected	417	581	217	267	584	173
	Sensitivity	78.24 ± 2.97%	84.57 ± 2.29%	46.47 ± 3.82%	62.38 ± 3.88%	82.84 ± 2.36%	46.38 ± 4.28%
Ground Truth		533	687	467	428	705	373

Figure 36: Sensitivity for Conditions Performing Poorly in Stop-bar Analysis, Zone 24

The accuracy of the Autoscope sensor ranged from 50.4 percent during moderate to strong winds at sunny afternoon conditions to 7.27 percent during moderate nighttime wind conditions. The accuracy of the Iteris sensor ranged from 84.6 percent during cloudy noon illumination conditions to 46.4 percent during a.m. peak traffic. Similar to the best condition analysis, the Autoscope sensor performed with lower advance detection accuracy levels relative to Iteris.