CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 13-014
UILU-ENG-2013-2009
ISSN: 0197-9191

FIELD EVALUATION OF SMART SENSOR VEHICLE DETECTORS AT INTERSECTIONS—VOLUME 2: PERFORMANCE UNDER ADVERSE WEATHER CONDITIONS

Prepared By
Juan C. Medina
Rahim F. Benekohal
Hani Ramezani
University of Illinois at Urbana-Champaign

Research Report FHWA-ICT-13-014

A report of the findings of
ICT-R27-95
Field Evaluation of Smart Sensor Vehicle Detectors at Intersections and Railroad Crossings

Illinois Center for Transportation

April 2013

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-ICT-13-014		

4. Title and Subtitle	5. Report Date
Field Evaluation of Smart Sensor Vehicle Detectors at Intersections—Volume 2: Performance Under Adverse Weather Conditions	April 2013
	6. Performing Organization Code
	8. Performing Organization Report N o. ICT-13-014 UILU-ENG-2013-2009
7. Author(s) Juan C. Medina, Rahim F. Benekohal, Hani Ramezani	
9. Performing Organization Name and Address Department of Civil and environmental Engineering University of Illinois at Urbana-Champaign 205 N. Mathews Ave Urbana, IL 61801	10. Work Unit (TRAIS)
	11. Contract or Grant No. R27-95
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address Illinois Department of Transportation Bureau of Materials and Physical Research 126 E. Ash Street Springfield, IL 62704	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Two microwave-based systems for vehicle detection (by Wavetronix and MS SEDCO) were evaluated at stop bar and advance zones of a signalized intersection under three adverse weather conditions: (1) wind, (2) snow-covered roadway, and (3) rain. Weather effects were very different for the two systems both in terms of the type of condition that could affect performance and in the magnitude of those effects. For Wavetronix, wind had significant effects on the advance zone by increasing false calls to over 50%, but it did not affect the stop bar zones. On the other hand, false calls in snow significantly increased to more than 40% in the stop bar zones and to about 30% in the advance zone. Snow also increased missed and stuck-on calls but in lower proportion than the false calls. Rain also affected the detection at stop bar zones, but all error types were below 8%, and it did not affect the advance zone. For Intersector, weather effects were less pronounced both at the stop bar and advance zones. Snow increased false calls to a range of about 4% to 8% compared to 1.65% to about 4% in normal weather. In addition, rain increased stuck-on calls to a range of 2.7% to 6.35% at the stop bar zones and increased missed calls at advance zones to 3.44%. Wind had no significant effects at stop bar or advance zones. In particular for the rain data, the intensity of the precipitation seemed to be related to the degree of performance degradation. In datasets with higher precipitation per unit of time, higher false calls were observed at Wavetronix stop bar zones, and a higher frequency of missed calls was observed at the Intersector advance zone. Findings from this evaluation can provide valuable information to users and manufacturers of these products regarding expected performance under adverse weather conditions at locations with similar mountings and settings, as well as insight about potential solutions to preventing negative effects in such scenarios.

17. Key Words	18. Distribution Statement
Microwave radar vehicle detection, Wavetronix, Matrix, Intersector, MS SEDCO, stop bar and advance detection error, performance adverse weather, snow, wind, rain	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	38	

ACKNOWLEDGMENT AND DISCLAIMER

This publication is based on the results of ICT-R27-95, Field Evaluation of Smart Sensor Vehicle Detectors at Intersections and Railroad Crossings. ICT-R27-95 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation; and the U.S. Department of Transportation, Federal Highway Administration.

Members of the Technical Review Panel are the following:

Yogesh Gautam, IDOT (Chair)

Stanley Milewski, ICC (Co-chair)

Scott Kullerstrand, IDOT

David Burkybile, IDOT

William Shaw, IDOT

Kevin Price, IDOT

Michael Brownlee, IDOT

Dean Mentjes, FHWA

EXECUTIVE SUMMARY

This report presents an evaluation of the Wavetronix and MS SEDCO microwave-based systems for vehicle detection at stop bar and advance zones of a signalized intersection under adverse weather conditions. For this evaluation, one Matrix and one Advance unit were installed by the authorized Wavetronix distributor in Illinois, and one Intersector unit was installed by MS SEDCO representatives. The systems were fine-tuned prior to the adverse weather evaluation. A first report on this study (Medina et al. 2012) contains a description of the initial setup and the setup after fine-tuning. The adverse weather conditions include (1) wind, (2) snow-covered roadway, and (3) rain. Detailed analysis was performed at the level of each individual zone.

Weather effects were very different for the two systems both in terms of the type of condition that could affect performance and in the magnitude of those effects. In addition, the units from the two systems were not installed side by side; therefore, factors such as the device location varied from one system to the other.

For Wavetronix, wind had a significant effect on the performance of the Advance unit by increasing the frequency of false calls to over 50%, but it did not affect the performance of the Matrix at the stop bar zones. On the other hand, false calls in snow significantly increased to more than 40% in the stop bar zones (Matrix) and to about 30% in the advance zone (Advance). Snow also increased the frequency of missed and stuck-on calls but in lower proportion than the false calls. Rain likewise affected detection at stop bar zones, but all error types remained below 8%. Rain did not affect performance in the advance zone.

For Intersector, weather effects were less pronounced at the stop bar and advance zones. Snow had some effect by increasing false calls to a range of about 4% to 8%, compared to 1.65% to about 4% in normal weather. In addition, rain increased stuck-on calls, which almost doubled in frequency to a range of 2.7% to 6.35% at the stop bar zones. Rain also increased missed calls at advance zones, reaching 3.44% of vehicles missed. No significant effects of windy conditions were found.

In particular for the rain data, the intensity of the precipitation seems to be related to the degree of performance degradation. In datasets with higher precipitation per unit of time, higher false calls were observed at Wavetronix stop bar zones, and a higher frequency of missed calls was observed at the Intersector advance zone.

Results from this evaluation showed that two products using similar technology behaved very differently under the same adverse weather conditions, with significant effects of some of these conditions occurring even though the systems were installed and fine-tuned (during good weather) directly by the manufacturer or the authorized distributor of the product.

Data showed that wind greatly affected Wavetronix performance, but those devices were placed near traffic signals on horizontal mast arms; therefore, they experienced significantly more oscillation movement with high wind speeds than Intersector (located on the vertical pole holding the mast arm). However, other issues such as the increase of false calls when the roadway was covered with snow (and without significant wind) were not obvious in terms of the location of the devices.

Findings from this evaluation can provide valuable information to users and manufacturers of these products regarding expected performance under adverse weather conditions at locations with similar mountings and settings, as well as insight about potential solutions to preventing negative effects in such scenarios.

CONTENTS

CHAPTER 1 INTRODUCTION

This report presents the results of an evaluation of two microwave systems for vehicle detection at signalized intersections under adverse weather conditions. The adverse weather conditions include (1) snow-covered roadway, (2) windy conditions, and (3) rain.

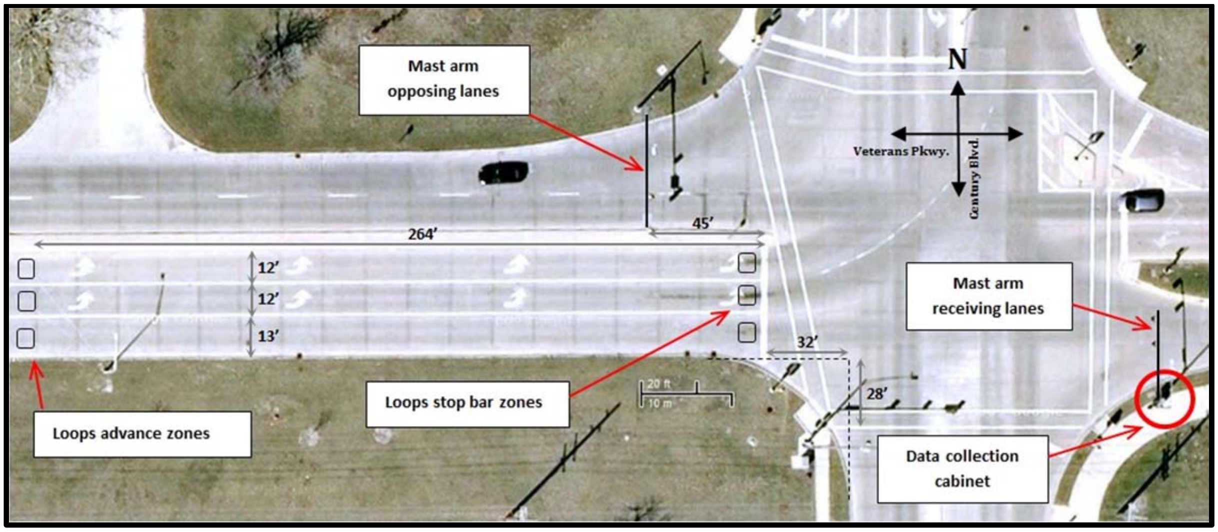
The two systems tested were (1) SmartSensor by Wavetronix LLC and (2) Intersector by MS SEDCO. Stop bar and advance detection zones were evaluated separately for each system. This is the second stage of the evaluation; in the first stage, the performance of the systems was analyzed under normal weather conditions, and includes results before and after the manufacturers and/or product distributors were given two opportunities to adjust the configuration and settings of the initial setup, if they wanted. A report on the findings of the first stage has been already published (Medina, Benekohal, and Ramezani 2012).

This report compares the systems' performance in adverse weather conditions to their performance in normal weather conditions. The configuration of the systems was the same between the first and second stages of this study; thus, a direct comparison of the results is possible.

In addition to data for adverse weather conditions, a new set of data was collected and analyzed for normal weather conditions (no rain, snow, or significant wind). These data were used to check whether any unexpected changes in a system's performance due to misalignment or malfunctioning of the devices had occurred during adverse weather conditions. Data for adverse weather and normal conditions were collected during winter 2011 and spring 2012.

For each condition, selected datasets included data from multiple days in order to have a more representative sample of system performance. The evaluation was conducted using a procedure identical to that used in the first report of this study (Medina et al. 2012), which can be found on the website of the Illinois Center for Transportation (ICT) at http://ict.illinois.edu/. A brief explanation of the methodology to determine the detection errors and a description of the system configuration are included in this report, but details can be found in the first report of this study.

The test site was at the intersection of Century Boulevard and Veterans Parkway in Rantoul, IL. The eastbound (EB) approach of this intersection was instrumented for the evaluation. The EB approach has two left-turn lanes and a shared right through-lane. Six inductive loops (6 ft x 6 ft) were installed near the stop bar and the advance locations (one per lane). The longitudinal distance between the two sets of loop detectors was about 264 ft. In addition, a camera from the Autoscope video detection system was used to record video images of the eastbound approach. Sample images of the subject approach are shown in Figure 1.



(a) Instrumented approach at Century Boulevard and Veterans Parkway
(source: Google Maps)

(b) Eastbound approach

(c) Advance loops

Figure 1. Layout and sample images from the intersection of
Veterans Parkway and Century Boulevard.

The two systems were configured by trained personnel of the product manufacturer or distributor. For Intersector, representatives from MS SEDCO and its distributor in Illinois (Brown Traffic, Inc.) were present at the site. For Wavetronix, representatives from Traffic Control Corporation (TCC), the distributor of the system in Illinois at the time, who were in communication via telephone with technical staff at Wavetronix. The representatives were exclusively in charge of the device installation and were told do the best setup for the test site.

They completed system setup by assigning separate detection zones for individual lanes at stop bar and advance zones, if possible. These instructions could be followed for the two systems at the stop bar zones, but a different arrangement of the zones had to be adopted at the advance locations. For Wavetronix, it was not possible to provide individual detection for each lane with the equipment provided; thus, a single zone covering all three lanes was configured. For Intersector, on the other hand, individual detection for each zone was possible, but only one output remained with the single device installed at the intersection. Therefore, it was decided to place the detection zone (at the advance location) covering the center lane only.

As shown in Figures 2 and 3, the installation by MS SEDCO consisted of a single detection unit facing the eastbound approach of Veterans Parkway. The unit was installed on the vertical combination pole on the southeast corner of the intersection that supports the signal mast arm and the arm for the luminaire. On the other hand, the installation for Wavetronix consisted of two units. One unit was a Matrix device, to detect traffic at the stop bar zones, installed on the mast arm of the receiving lanes of the westbound approach, just across the median from the subject approach. The second unit was an Advance device, installed on the mast arm of the eastbound receiving lanes, next to the signal heads also aiming at the eastbound approach.

The data collection process was achieved through the use of onsite equipment installed in a signal control cabinet located at the subject intersection. This cabinet housed the detector racks, inductive loops' CC cards, proprietary equipment from Wavetronix and MS SEDCO, an I/O device for data logging, and a desktop computer for data and video recording. A separate traffic control cabinet housed the controller and detection equipment to operate the signals at the intersection.

Figure 2. Sample pictures of the Intersector unit facing eastbound traffic.

(a) Wavetronix Matrix on westbound mast arm
overlooking the stop bar zones of eastbound lanes.

(b) Wavetronix Advance facing eastbound traffic
and directed toward advance zones.

Figure 3. Sample pictures of the Matrix and the Advance units.

This installation allowed for the acquisition of two types of data: (1) activation/ deactivation times of loops and radar-based detectors (timestamps) and (2) video images. The timestamps provide accurate data that allow automation of the initial stages of the analysis using computer algorithms and the use of large datasets. Timestamps were collected using an input/output (I/O) device to monitor vehicle presence as identified by each inductive loop and outputs for the radar-based detectors. Every 50 milliseconds, the I/O device verified the state of the six loop detectors and the individual detection outputs from Wavetronix (three at stop bar and two at advance zones) and Intersector (three at stop bar and one at advance zones).

As mentioned above, video images were taken from an overhead camera aimed at the subject approach. These images were fed as an input to a quad processor, along with a real-time graph generated by I/O device with the status (vehicle/no vehicle) of loops and the other detectors. This graph provided an additional tool to visually confirm whether a call took place in any of the detectors. The recorded video images were also used to provide visual verification of the potential errors automatically identified with the computer algorithms. In addition, the video images served as the ground truth to identify errors by the loops and helped ascertain the lighting, weather, and traffic conditions at the study location.

Chapter 2 of report describes the methodology, followed by a description of the data in Chapter 3. Chapter 4 presents the results of the analysis, Chapter 5 includes a summary of all analyzed conditions using tables, and Chapter 6 presents the main findings and conclusions.

CHAPTER 2 METHODOLOGY

The evaluation of the microwave radar-based detectors was conducted using a similar methodology the authors have tested in previous studies for video-based detection and wireless magnetometers (Medina et al. 2008, 2009a, 2009b, 2009c, 2012).

Four performance measures (PMs) were used to quantify the detection errors and to evaluate the systems: false calls, missed calls, dropped calls, and stuck-on calls. These PMs were estimated for each detector separately by automatically identifying potential errors using computer algorithms, and then by manually verifying every potential error before it was labeled as an actual detection error. The automated error detection enabled the use of large datasets by speeding up the time required to complete the analysis.

The computer code reads the timestamps from loops and radar-based detectors, establishing whether there were discrepancies between them. A time window was used when comparing the activation/deactivation times of loops and other detectors, allowing for a small time difference in the detection of the two different technologies. However, a discrepancy greater than the time windows does not necessarily indicate the existence of an error; it just points out a potential error that later was visually verified. The concepts used to define the PMs, as well as the logic used in the computer code, are briefly discussed below. For a more comprehensive description of the methodology and the algorithms, please see previous studies conducted using this test bed (Medina et al. 2008, 2009a, 2009b, 2009c, 2012).

2.1. MISSED CALLS

Missed calls occur when a sensor fails to detect a vehicle. In the field, these errors could have adverse safety effects due to potential red light runners in cases where the corresponding phase is not called by the controller. In terms of timestamps, every loop call for which there is no corresponding call from the radar-based detector was considered a potential missed call. The algorithm identified loop calls and searched for a call from the detectors in a 2-second window before the start of loop call and 2 seconds after the end of the loop call. Potential missed calls were visually verified to make sure that they were indeed missed calls. The percentage of missed calls was calculated as the number of missed calls over the total number of loop calls.

2.2. FALSE CALLS

False calls were divided into two subgroups:

1. False calls that were placed when there was no vehicle over the detection zone, but the sensor indicated there was one. Some of these were generated by vehicles in the adjacent lanes (small and heavy vehicles traveling in the same approach) or even without the presence of vehicles in the vicinity of the zone (or due to vehicles in other approaches).
2. Flickering false calls, or multiple calls generated by a single vehicle occupying the detection area. In the field, false calls could have a negative effect on the operational efficiency of a signalized intersection.

In the algorithm, for every call by a detector, if there was no call from the corresponding loop detector within a reasonable time window, it was considered a potential false call. The algorithm identified the detector calls and then searched for a loop call placed between 1 second before the beginning of the detector call and 1 second after the detector call was dropped. Potential false calls were visually verified to make sure that they were indeed false calls. The percentage of false calls was estimated as the ratio of the number of false calls over the total number of calls placed by detector in that zone.

2.3. DROPPED CALLS

Dropped calls occur when detector activations are terminated while the vehicles are still present in the detection zone. A minimum drop time of 5 seconds was needed for the error to be flagged as a potential dropped call. Following the same procedure for other types of error, video images were used to visually confirm dropped calls. Operationally, if a zone prematurely drops a call placed to the controller, it might not allow the controller to serve the vehicle properly, generating potential safety issues such as red light running. This percentage was calculated as the ratio of dropped calls over the total number of loop calls (similar to missed calls).

2.4. STUCK-ON CALLS

A stuck-on call is defined as an activation that continues to indicate the presence of a vehicle when in reality the vehicle has already departed. A minimum stuck-on time of 10 seconds was needed for the error to be flagged as a potential stuck-on call. Stuck-on calls may affect the operational efficiency of a signalized intersection by extending green time unnecessarily. The percentage of stuck-on calls was estimated as the ratio of the number of stuck-on calls over the total calls from the zone (similar to false calls).

CHAPTER 3 DETECTION ZONE SETUP AND SELECTED DATA

As mentioned in Chapter 1, the configuration of the detection zones for the evaluation of adverse weather effects was identical to that in the first stage of this study (after the systems were fine-tuned). In this report, results are also presented using similar labels for each of the stop bar zones, as shown in Figure 4. A brief description of the configuration of the stop bar zones after fine-tuning is described in this section. For more detailed information, please refer to the first report of this study (Medina et al. 2012), available on the website of the Illinois Center for Transportation (http://ict.illinois.edu).

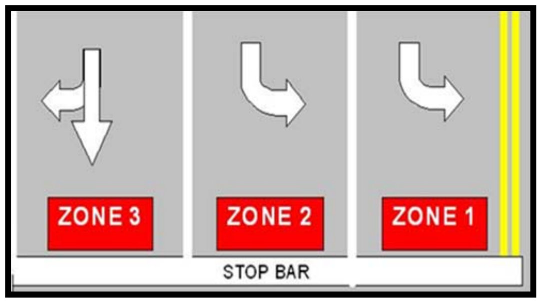


Figure 4. Stop bar zone labels.

The configuration of the detection zones for Intersector are shown in Figures 5 and 6 for the stop bar and advance zones, respectively. Note that the three stop bar zones have the same length (35 ft) but not the same width. The width of Zones 1 and 2 was 12 ft, whereas the width of Zone 3 (on the shared right through-lane) was 15 ft to prevent missed or dropped calls of right-turning vehicles. Also, 0.5 seconds of extension time in the three zones was provided to help reduce the number of flickering false calls. The advance zone (Figure 6) is 40-ft long and also has an extension time of 0.5 seconds. It is important to note that the advance zone was located exclusively in the center lane (therefore, its width was 12 ft), and there were no detection zones in the through or left-most lanes at the advance location.

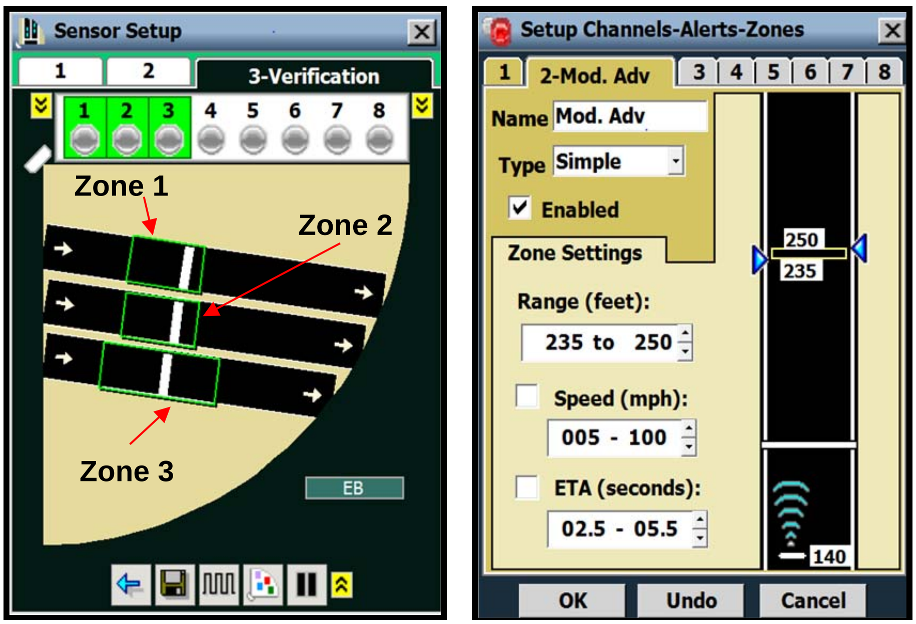
Zone	Y (feet)	X (feet)	Y Front (feet)	Y Behind (feet)	Width of Zone (feet)	Delay Time	Extension Time
1	143.0	53.0	15.0	20.0	12.0	0.0	0.5
2	143.0	42.0	15.0	20.0	12.0	0.0	0.5
3	143.0	27.0	15.0	20.0	18.0	0.0	0.5

Figure 5. Intersector settings for stop bar zones in modified setup.

Zone	Y (feet)	X (feet)	Y Front (feet)	Y Behind (feet)	Width of Zone (feet)	Delay Time	Extension Time
4	370.0	40.0	20.0	20.0	12.0	0.0	0.5

Figure 6. Intersector settings for advance zone in modified setup.

The configuration of the Wavetronix devices is shown in Figure 7. Figure 7(a) shows the stop bar zones, for which Zones 1 and 2 had the same size and extended past the stop bar to prevent dropped calls. Zone 3, on the other hand, was extended a longer distance both before and past the stop bar, with the same objective as the Intersector zone: preventing dropped calls of right-turning vehicles. The advance zone had a different user interface, as shown in Figure 7(b). This zone was 15-ft long and covered the three approaching lanes; therefore, its width was not specified.



(a) Stop bar zones (b) Advance zones

Figure 7. Wavetronix zone configuration.

Regarding the selected data, a total of 15 hours from different days was selected for each of the conditions (normal weather, snow, wind, and rain) covering both peak and off-peak hours. For the 60 hours of data collection, the systems processed more than 7,500 vehicles, all of which were included in the evaluation. If these data are added to the data collected after the system fine-tuning (described in the previous report), the total number of vehicles included in this study under the same system configuration is about 13,000.

The same datasets were used to evaluate both systems (Wavetronix and Intersector). Therefore, their performance can be directly compared at the stop bar detection zones, where each system had one zone per lane. At the advance zone, however, the detection zones were not configured to cover a similar area; thus, a direct comparison of them would not be meaningful.

CHAPTER 4 ANALYSIS OF RESULTS

The performance of the two microwave-based detection systems was analyzed under normal (Medina et al. 2012) and adverse weather conditions. The adverse weather scenarios included wind, snow (fully/partially snow-covered roadway), and rain.

Datasets for the snow conditions were selected based on visual confirmation of a snow-covered roadway using the video images and on records from the weather station at the Rantoul airport, about 1 mile away from the test site.

Windy conditions were selected based on the records from the weather station and could also be confirmed from the videos given the movement of the camera (located near the luminaire of the receiving lanes facing the subject approach). All selected windy conditions showed periods with gusts in excess of 25 mph and sustained winds of more than 17 mph.

Rain conditions were also ascertained based on data from the weather station and confirmed through the video images. Precipitation intensity, measured every 20 minutes, was at least 0.03 in. (light rain), with periods of up to 0.44 in. (very heavy rain).

The detection errors are reported individually for each zone, and details are provided on the type of errors and the different situations that caused them. Results for each of the two systems are presented separately in the following subsections. In addition, total aggregates for two systems are available in Chapter 5.

4.1. CONFIRMING PERFORMANCE IN NORMAL WEATHER CONDITIONS

Winter weather or some other factors (tilting, displacement, or equipment failures) might have affected the system setup, causing performance deterioration. To see whether that was true, data were collected in normal weather conditions during the months for which adverse weather data were collected. The results of those normal weather conditions were compared to older data for normal weather conditions to assess whether this claim is valid. If the claim is false, then the frequency of errors should resemble those found in the previous report of this study (Medina et al. 2012).

The datasets for normal weather conditions were selected from five days between December 27, 2011, and February 13, 2012. These dates are encompassed within the dates selected for the adverse weather analysis, showing that the systems did not suffer changes at the end of fall 2011 and through winter 2011/2012.

The results from summer and fall 2011 were presented in detail in the previous report of this study. Those results are presented below, with the results collected December 2011 through February 2012. Detection errors from summer and fall data are based on 17.5 hours of data (each). Similarly, the results for normal weather in winter 2011/2012 are based on 15 hours of data.

Tables 1 and 2 show the normal weather performance of Wavetronix and Intersector, respectively. From the tables, it can be observed that detection errors in winter 2011/2012 were very similar to those found in summer and fall 2011. This is true for all types of error, all zones, and for the two systems, with differences in detection errors always lower than 1% compared to errors found in summer or fall 2011 (except for a 2.15% difference in false calls in the Wavetronix advance zone). This indicates that there was consistency in detection during normal weather from summer 2011 through winter 2011/2012; therefore, no degradation of the performance occurred in such conditions over this time period.

Table 1. Wavetronix Performance in Normal Weather Conditions

Zone		Period	Number of Activations		Verified Errors						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Wavetronix	Loop	Vehicles not present in adjacent lanes	Vehicles in adjacent lanes	Flickering	Traveling between lanes	Clearly traveling over zone		
Stop Bar Zones	Zone 1	Summer 2011	701	837	0	0	2	1	1	0	0
					0.29%			0.24%		0.00%	0.00%
		Fall 2011	542	647	0	3	2	0	0	0	0
					0.92%			0.00%		0.00%	0.00%
		Winter 2011-2012	418	444	0	0	0	0	2	0	0
					0.00%			0.45%		0.00%	0.00%
	Zone 2	Summer	1004	1126	0	1	0	1	2	0	1
					0.10%			0.27%		0.00%	0.09%
		Fall	861	967	0	6	5	0	6	0	0
					1.28%			0.62%		0.00%	0.00%
		Winter 2011-2012	585	650	0	2	1	1	3	0	0
					0.51%			0.62%		0.00%	0.00%
	Zone 3	Summer	797	969	0	3	4	1	56	1	3
					0.88%			5.88%		0.13%	0.31%
		Fall	743	899	0	12	6	1	55	8	0
					2.42%			6.23%		1.08%	0.00%
		Winter 2011-2012	507	563	0	3	4	1	37	2	0
					1.38%			6.75%		0.39%	0.00%
Advance Zone		Summer	2928	2816	81	-	57	-	36	0	0
					4.71%			1.28%		0.00%	0.00%
		Fall	2672	2623	247	-	79	-	22	0	0
					12.20%			0.84%		0.00%	0.00%
		Winter 2011-2012	1923	1746	238	0	38	-	7	0	0
					14.35%			0.40%		0.00%	0.00%

Table 2. Intersector Performance in Normal Weather Conditions

Zone		Period	Number of Activations		Verified Errors						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Intersector	Loop	Vehicles not present in adjacent lanes	Vehicles in adjacent lanes	Flickering	Traveling between lanes	Clearly traveling over zone		
Stop Bar Zones	Zone 1	Summer 2011	706	837	0	8	9	0	2	20	1
					2.41%			0.24%		2.83%	0.12%
		Fall 2011	565	647	0	9	14	0	2	16	1
					4.07%			0.31%		2.83%	0.15%
		Winter 2011-2012	425	444	2	5	0	0	0	15	0
					1.65%			0.00%		3.53%	0.00%
	Zone 2	Summer	1012	1126	0	23	15	0	0	9	2
					3.75%			0.00%		0.89%	0.18%
		Fall	887	967	0	17	21	0	2	13	2
					4.28%			0.21%		1.47%	0.21%
		Winter 2011-2012	598	650	2	13	4	0	0	8	0
					3.18%			0.00%		1.34%	0.00%
	Zone 3	Summer	903	969	0	17	12	0	0	11	0
					3.21%			0.00%		1.22%	0.00%
		Fall	838	899	0	19	14	0	1	5	0
					3.94%			0.11%		0.60%	0.00%
		Winter 2011-2012	553	563	1	16	1	0	0	10	0
					3.25%			0.00%		1.81%	0.00%
Advance Zone		Summer	1227	1361	0	2	8	99	9	1	0
					0.81%			0.66%		0.08%	0.00%
		Fall	1049	1143	0	3	3	70	11	0	0
					0.57%			0.96%		0.00%	0.00%
		Winter 2011-2012	755	793	4	0	0	46	6	0	0
					0.53%			0.76%		0.00%	0.00%

4.2. PERFORMANCE IN ADVERSE WEATHER CONDITIONS

As mentioned above, three adverse weather conditions were analyzed: snow, wind, and rain. Sample datasets for these conditions were selected, and the performances for Wavetronix and Intersector were determined based on the frequency of detection errors. A detailed description of this analysis is presented first for Wavetronix and then for Intersector.

4.2.1. Wavetronix

4.2.1.1. Wind

The performance of Wavetronix in windy conditions is described in this section. All zones were analyzed individually, starting with the stop bar zones and followed by the advance zone. Datasets were selected based on actual records from a nearby weather station at the Rantoul airport and the video images. The maximum and minimum wind speeds registered in the selected datasets are shown in Table 3.

Table 3. Maximum and Minimum Wind in Selected Windy Datasets

Data Set #	Date	Time	Minimum Average wind speed (mph)	Maximum Average wind speed (mph)	Minimum wind gust (mph)	Maximum wind gust (mph)
1	Jan 1	6:00PM - 10:00PM	17.3	35.7	32.2	43.7
2	Feb 26	12:00PM - 3:00PM	27.6	32.2	34.5	38
3	Mar 7	7:00AM - 10:00AM	21.9	31.1	26.5	42.6
4	Mar 6	11:00AM - 4:00PM	20.7	34.5	29.9	48.3

4.2.1.1.1. Stop Bar Zones

For Zone 1, the frequency of errors in windy conditions was comparable to those found in normal weather (Table 4). None of the types of error increased due to the presence of wind gusts or sustained wind speeds. No missed, stuck-on, or dropped calls were found in the selected datasets, and only one flickering false call was observed in a sample of more than 600 vehicles that traveled over Zone 1.

Table 4. Detection Errors for Wavetronix Zone 1 in Windy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Wavetronix	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Jan 1	6:00PM - 10:00PM	78	91	0	0	0	0	0	0	0
2	Feb 26	12:00PM - 3:00PM	107	123	0	0	1	1	0	0	0
3	Mar 7	7:00AM - 10:00AM	100	113	0	0	0	0	0	0	0
4	Mar 6	11:00AM - 4:00PM	252	302	0	0	0	0	0	0	0
	Sum		537	629	0	0	1	1	0	0	0
					0.19%				0.00%	0.00%	0.00%

Similarly, Zone 2 was virtually unaffected by wind for all four error types, as can be seen in Table 5. False calls were slightly higher than in normal weather but remained very low at 1.35%, and missed calls were similar, at 0.48%. The four vehicles missed in Zone 2 were passenger cars or pick-up trucks that traveled over the zone without stopping for the green light. No stuck-on and dropped calls were found.

Table 5. Detection Errors for Wavetronix Zone 2 in Windy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Wavetronix	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Jan 1	6:00PM - 10:00PM	118	123	1	0	1	0	0	0	0
2	Feb 26	12:00PM - 3:00PM	138	159	0	0	0	0	1	0	0
3	Mar 7	7:00AM - 10:00AM	144	157	0	2	2	0	0	0	0
4	Mar 6	11:00AM - 4:00PM	340	401	0	3	1	0	3	0	0
	Sum		740	840	1	5	4	0	4	0	0
					1.35%				0.48%	0.00%	0.00%

A similar trend was found for Zone 3, with the number of errors for windy conditions similar to those detected during normal weather (Table 6). In fact, missed calls in this zone were lower in the selected windy datasets (2.82%) compared to 5.88% in the normal weather datasets.

Table 6. Detection Errors for Wavetronix Zone 3 in Windy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Wavetronix	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Jan 1	6:00PM - 10:00PM	129	143	0	0	1	0	3	0	0
2	Feb 26	12:00PM - 3:00PM	131	153	0	0	1	0	6	1	2
3	Mar 7	7:00AM - 10:00AM	132	158	0	2	3	0	4	0	1
4	Mar 6	11:00AM - 4:00PM	267	325	0	3	1	0	9	1	1
	Sum		659	779	0	5	6	0	22	2	4
					1.67%				2.82%	0.30%	0.51%

4.2.1.1.2. Advance Zone

Wind effects at the advance zone were significant. The total number of activations was more than 2.5 times those from the loop. This is a strong contrast with normal weather datasets, where this ratio was close to 1. It follows that the frequency of false calls significantly increased, accounting for the higher ratio of calls generated by the Advance sensor. Before these false calls are discussed in detail, it is noted that wind did not have significant effects on the other types of errors. Missed calls remained low at 0.3%, and there were no stuck-on or dropped calls, similar to normal weather conditions, as shown in Table 7.

Table 7. Missed, Stuck-On, and Dropped Calls for Wavetronix Advance Zone in Windy Conditions

Data Set #	Date	Time	**Number of Activations**		**Verified Errors for Wavetronix**			
			Wavetronix	Loop	**Missed Calls**		**Stuck-on Calls**	**Dropped Calls**
					Traveling Between Lanes	Clearly Traveling Over Zone		
1	Jan 1	6:00PM - 10:00PM	1298	370	0	2	0	0
2	Feb 26	12:00PM - 3:00PM	1311	457	0	1	0	0
3	Mar 7	7:00AM - 10:00AM	1186	445	0	2	0	0
4	Mar 6	11:00AM - 4:00PM	2714	1086	0	2	0	0
	Sum		6509	2358	0	7	0	0
						0.30%	0.00%	0.00%

Regarding false calls, the number of potential errors from the computer algorithm was in the thousands. The top rows of Table 8 show that even under very long time windows, the total number of potential false calls was very high. Recall that the time window is the time that the algorithm searches for a loop call around a given sensor call; if a corresponding loop call is not found, then it is considered a potential false call. Similarly, the bottom rows of Table 8 show the number of potential false calls that occurred when there was no vehicle within the whole time window, thus eliminating potential flickering false calls. The total number of potential false calls even with a very long window of 5 seconds (that is, 5 seconds before the beginning of the call and 5 seconds after the end of the call) was still in the thousands.

Table 8. Potential False Calls at Wavetronix Advance Zone in Windy Conditions Using Different Time Windows

Potential False Calls	Time Window	Jan 1 6pm - 10pm	Feb 26 12pm - 3pm	Mar 7 7am - 10am	Mar 6 11am - 4pm	Total	
						Frequency	% Potential False Calls *
All potential false calls	1 Second	949	868	762	1711	4290.00	65.91%
	3 Seconds	913	841	753	1615	4122.00	63.33%
	5 Seconds	893	797	724	1486	3900.00	59.92%
Only potential false calls generated with no cars within the window (eliminates potential flickering calls)	1 Second	892	794	708	1495	3889.00	59.75%
	3 Seconds	805	665	620	1209	3299.00	50.68%
	5 Seconds	741	568	543	992	2844.00	43.69%

* % of potential error is estimated based on the total number of calls placed by the sensor (from Table 7)

Based on the high number of potential false calls, it was decided to visually verify a sample of 10% of those calls and determine the share of calls that corresponded to (1) flickering false calls, (2) false calls generated when there was no vehicle in the vicinity of the zone, and (3) remaining potential false calls that were not actual errors. Results are shown in Table 9, where a total of 97% of the sampled potential false calls were actual errors (94% when there were no vehicles near the zone and 3% flickering false calls).

Table 9. Visually Verified Errors from a Sample of Potential False Calls by Wavetronix Advance in Windy Conditions

Sampled Potential False Calls (10% of total)		DATASET				Total	
		Jan 1 6pm - 10pm	Feb 26 12pm - 3pm	Mar 7 7am - 10am	Mar 6 11am - 4pm	Frequency	%
Verified false calls	No vehicles in vicinity of zone	91	84	72	157	404	94.0%
	Flickering	1	2	1	9	13	3.0%
Calls that were NOT actual errors		3	1	4	5	13	3.0%
Total		**95**	**87**	**77**	**171**	**430**	**100.0%**

Assuming the error distribution from Table 9 and the data from Table 8, this analysis indicates that even in a very conservative scenario (such as using a time window of 5 seconds), about 58% of the calls placed by the Advance sensor in windy conditions were false calls (59.92% x 0.97=58.1%), and more than 40% were placed when there were no vehicles 5 seconds before and 5 seconds after the false calls (43.69 x 0.94 = 41.1%). These approximations demonstrate the very high frequency of errors occurring during windy conditions.

To summarize, the performance of Wavetronix was not affected by wind at the stop bar zones, but it was significantly impacted at the advance zone due to increased false calls (estimated as greater than 50% of the total calls). It is recalled that stop bar zones use the Wavetronix Matrix detector and the advance zone uses the Advance detector. Those detectors have different operating settings and were installed at different locations.

4.2.1.2. Snow

<u>4.2.1.2.1. Stop Bar Zones</u>

In Zone 1, the total number of activations was greater for Wavetronix compared to loops (Table 10). This contrasts with previous results obtained in normal weather conditions (Table 1), where the activations at the stop bar zones were fewer for Wavetronix. Under normal weather conditions, it was expected to have fewer calls from Wavetronix, given that the zone is longer; thus, vehicles traveling close to each other are likely to place one single (and longer) call instead of two separate calls (more likely with the loops).

False calls in Zone 1 were significantly higher (Table 10), mostly due to activations generated without any vehicle present at or near the zone. Compared to results from normal weather conditions, where false calls were lower than 1%, false calls in snow conditions increased to about 45%. From the video images, the two main observable differences compared to normal weather were the snow-covered roadway and occasional wind gusts. Even though results (detailed in the previous section) showed that wind itself was not an important factor in Wavetronix performance at stop bar zones, it is possible to see some effect as a result of wind combined with snow. Table 11 shows the wind speeds for the selected datasets in snow conditions.

Missed calls in Zone 1 also increased compared to results from normal weather conditions. In snow conditions, missed calls were 2.86%, compared to less than 0.5% in normal weather. The sample size from normal weather in Zone 1 (Table 1) was greater than 1900 vehicles, with a total of three vehicles missed, compared to a sample of fewer than 400 vehicles with snow and 11 vehicles clearly missed while traveling in the lane (Table 10). The type of missed vehicles ranged from small passenger cars to pick-up trucks. Some of the missed vehicles traveled the zone without stopping, and some others were not detected even though they waited at the red light and then departed when the light turned green.

Stuck-on calls in Zone 1 also increased, for a total of five observed cases, compared to zero cases in normal weather. These stuck-on calls lasted between 17 seconds and 20 minutes. During the longest stuck-on call, several vehicles traveled over the zone without terminating the activation.

Table 10. Detection Errors for Wavetronix Zone 1 in Snow Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Wavetronix	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Dec 27	5:30AM - 7:30AM	130	25	105	3	1	0	1	4	0
2	Jan 13	6:00AM - 12:00PM	200	150	46	17	5	0	7	0	0
3	Jan 19	2:00PM - 3:00PM	42	49	0	0	0	0	0	0	0
4	Jan 20	6:30PM - 11:30PM	221	153	78	1	5	0	2	0	1
5	Feb 13	10:30PM - 11:30PM	21	8	15	1	0	0	1	1	0
	Sum		614	385	244	22	11	0	11	5	1
					45.11%				2.86%	0.81%	0.26%

Table 11. Maximum and Minimum Wind Speeds in Snow Conditions

Data Set #	Date	Time	Minimum wind speed (mph)	Maximum wind speed - including gusts (mph)
1	Dec 27	5:30AM - 7:30AM	4.6	6.9
2	Jan 13	6:00AM - 12:00PM	13.8	26.5
3	Jan 19	2:00PM - 3:00PM	9.2	11.5
4	Jan 20	6:30PM - 11:30PM	10.4	26.5
5	Feb 13	10:30PM - 11:30PM	12.7	13.8

The results from Zone 2 were similar to those in Zone 1 (Table 12). A greater number of calls was found with Wavetronix compared to the corresponding loop, with a significant increase in the frequency of false calls and, in lower proportion, in missed calls.

False calls in Zone 2 were 42.42% and mostly generated when there were no vehicles near the detection area. The snow datasets showed that more than 305 false calls were generated without the presence of nearby vehicles, as opposed to zero occurrences of such cases in the normal weather.

Missed calls in Zone 2 increased by more than 6%, for a total of 42 cases in a sample of 662 vehicles (Table 12), compared to 11 vehicles missed in a sample of more than 2700 vehicles in normal weather (Table 1). Similar to Zone 1, missed vehicles were passenger cars and pick-up trucks, and some of the missed vehicles stopped at the red light or arrived during the green light and did not stop. Missed calls in Zone 2 occurred almost exclusively in two of the datasets: January 13 and January 20, which happened to be the two windiest days (Table 11).

Stuck-on calls in Zone 2 increased in small proportion during snow conditions. These errors changed from zero occurrences in normal weather to seven in the selected snow datasets. The duration of the stuck-on calls varied between 29 seconds and about 5 minutes. In some of these cases, stuck-on calls were dropped after a second vehicle departed the zone, but in other cases, multiple vehicles went over the zone without terminating the activation.

Table 12. Detection Errors for Wavetronix Zone 2 in Snow Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Wavetronix	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Dec 27	5:30AM - 7:30AM	105	29	72	12	2	0	0	2	0
2	Jan 13	6:00AM - 12:00PM	392	334	85	21	1	0	17	1	0
3	Jan 19	2:00PM - 3:00PM	71	91	0	0	1	0	0	0	0
4	Jan 20	6:30PM - 11:30PM	266	178	113	29	0	0	24	4	0
5	Feb 13	10:30PM - 11:30PM	50	11	35	3	1	1	1	0	0
	Sum		884	643	305	65	5	1	42	7	0
					42.42%				6.53%	0.79%	0.00%

In Zone 3, detection errors followed a similar trend to those in Zones 1 and 2 (Table 13). False calls increased significantly (to 56.32%), compared to less than 3% in normal weather. Missed calls also increased in snow conditions, with a total of 63 vehicles missed in a sample of 564 cars, or 11.45%, compared to less than 7% in normal weather.

The frequency of stuck-on calls in Zone 3 was slightly higher in snow (1.42%) than in normal weather conditions, and the great majority occurred on the two days with stronger wind speeds. The duration of the stuck-on calls ranged from 14 seconds to 3 minutes.

Table 13. Detection Errors for Wavetronix Zone 3 in Snow Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Wavetronix	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Dec 27	5:30AM - 7:30AM	121	36	102	9	2	0	2	2	0
2	Jan 13	6:00AM - 12:00PM	295	207	90	37	1	1	14	3	0
3	Jan 19	2:00PM - 3:00PM	58	74	0	2	2	0	2	0	0
4	Jan 20	6:30PM - 11:30PM	231	207	61	7	3	0	37	7	0
5	Feb 13	10:30PM - 11:30PM	213	26	198	0	3	1	8	1	0
	Sum		918	550	451	55	11	2	63	13	0
					56.32%				11.45%	1.42%	0.00%

4.2.1.2.2. Advance Zone

At the advance zone, the most significant change in the snow condition was the increase in the frequency of false calls. A total of 29.59% of the calls were found to be false activations (Table 14), mostly due to calls generated without any vehicle in the vicinity of the zone, in any of the three approaching lanes.

Regarding missed calls, it was observed that one particular dataset (December 27 in Table 14) contains almost all of these errors. On December 27, 2011, during a 2-hour period, the advance zone missed 36 of the 105 vehicles approaching the intersection. This dataset had low incidence of winds (see Table 11), and the video images showed no obvious distinctive characteristic compared to the others. From the video images it could be observed that the missed vehicles were passenger cars, and there were cases of missed vehicles in all three approaching lanes; thus, these errors were not exclusive to a single lane or location across the roadway.

Table 14. Detection Errors for Wavetronix Advance Zone in Snow Conditions

Data Set #	Date	Time	**Number of Activations**		**Verified Errors for Wavetronix**					
					False Calls		**Missed Calls**			
			Wavetronix	Loop	No vehicles in vicinity of zone	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone	**Stuck-on Calls**	**Dropped Calls**
1	Dec 27	5:30AM - 7:30AM	54	105	1	3	0	36	0	0
2	Jan 13	6:00AM - 12:00PM	1058	737	298	59	0	3	0	0
3	Jan 19	2:00PM - 3:00PM	273	224	58	9	0	1	0	0
4	Jan 20	6:30PM - 11:30PM	681	580	153	39	0	1	0	0
5	Feb 13	10:30PM - 11:30PM	46	44	4	1	0	0	0	0
	Sum		2112	1690	514	111	0	41	0	0
					29.59%			2.43%	0.00%	0.00%

To summarize the effects of snow on Wavetronix performance, the occurrence of false calls greatly increased to over 40% at the stop bar zones and to about 30% at the advance zone. Missed and stuck-on calls also increased, although in lower proportion than false calls. Data showed that snow had important effects on the frequency of errors for both the Matrix and the Advance detectors.

4.2.1.3. Rain

<u>4.2.1.3.1. Stop Bar Zones</u>

In Zone 1, false calls were the most frequent type of error with 7.37% (Table 15), showing a significant increase compared to normal weather conditions (lower than 1%). Not all datasets displayed a similar frequency of false calls, and they were concentrated mainly in 4 of the 12 time periods analyzed. Therefore, the system's performance degraded in some rainy conditions but not in all cases. More specifically, only during periods of heavy precipitation (about 0.15 in. or higher over a period of 20 minutes) did the Matrix detector place calls without vehicles present at or near the zone. This can be observed in Table 15 for datasets 4, 5, 11, and 12, which contrasts with data from normal weather conditions, where false calls were always generated by vehicles at or near the zone. The precipitation intensity and wind speeds can be found in Table 18, which will be explained in more detail later in this section.

In contrast to false calls, other types of error did not increase significantly with rain compared to normal weather conditions and remained lower than 1%.

Table 15. Detection Errors for Wavetronix Zone 1 in Rainy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
			Wavetronix	Loop	False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
					No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Feb 4	4:00AM - 6:00AM	12	12	0	0	0	0	0	0	0
2	Jan 26	9:30AM - 11:30AM	61	74	0	0	0	1	0	0	0
3	Mar 8	6:00AM - 8:00AM	55	63	0	0	0	0	0	0	0
4	April 28	5:00 AM - 6:00AM	9	7	3	0	0	0	0	0	0
5	April 29	4:45PM - 5:45PM	54	60	5	1	0	1	0	0	0
6	April 30	5:00AM - 6:30AM	10	12	0	0	0	0	1	0	0
7	April 30	1:00PM - 2:00PM	51	57	0	0	0	0	0	0	0
8	May 1	10:30AM - 11:30AM	34	39	0	0	0	0	0	0	0
9	May 31	4:00PM - 5:30PM	107	140	0	0	0	0	0	0	0
10	June 4	7:30AM - 8:30AM	25	30	0	1	0	0	0	0	0
11	June 16	12:00PM - 12:30PM	30	29	4	4	0	0	0	1	0
12	June 16	10:55PM - 11:25PM	27	11	14	3	0	0	0	0	0
	Sum		475	534	26	9	0	2	1	1	0
					7.37%				0.19%	0.21%	0.00%

Zone 2 showed trends similar to those described for Zone 1 (Table 16). Missed, stuck-on, and dropped calls remained low and comparable to those in normal weather, and false calls increased in rainy conditions (to 6%) as opposed to less than 1.3% in normal weather. Most of the false calls (30 out of 45) occurred without vehicles at or near Zone 2.

Table 16. Detection Errors for Wavetronix Zone 2 in Rainy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
			Wavetronix	Loop	False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
					No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Feb 4	4:00AM - 6:00AM	12	12	0	0	0	0	0	0	0
2	Jan 26	9:30AM - 11:30AM	96	108	0	1	0	1	0	0	0
3	Mar 8	6:00AM - 8:00AM	98	108	0	2	0	0	1	0	0
4	April 28	5:00 AM - 6:00AM	14	8	5	1	0	0	0	0	0
5	April 29	4:45PM - 5:45PM	76	81	3	2	1	0	1	0	0
6	April 30	5:00AM - 6:30AM	23	23	0	0	0	0	0	0	0
7	April 30	1:00PM - 2:00PM	71	86	0	0	0	0	2	0	0
8	May 1	10:30AM - 11:30AM	48	51	0	0	1	0	0	0	1
9	May 31	4:00PM - 5:30PM	196	237	0	1	0	0	0	0	0
10	June 4	7:30AM - 8:30AM	55	60	0	1	0	0	0	0	0
11	June 16	12:00PM - 12:30PM	45	36	17	3	0	0	0	2	0
12	June 16	10:55PM - 11:25PM	24	22	5	2	0	0	0	0	0
	Sum		758	832	30	13	2	1	4	2	1
					5.94%				0.48%	0.26%	0.12%

In Zone 3, similar to Zones 1 and 2, false calls increased to 6.81% compared to 2.5% in normal weather, and most of false calls occurred without vehicles present at or near the zone. Missed calls did not seem to be affected and, at 5.15%, had a frequency similar to those in normal weather. Stuck-on and dropped calls remained very low and were not affected by rainy conditions.

Table 17. Detection Errors for Wavetronix Zone 3 in Rainy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
					False Calls			**Missed Calls**		**Stuck-on Calls**	**Dropped Calls**
			Wavetronix	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Feb 4	4:00AM - 6:00AM	15	16	0	0	0	0	1	0	0
2	Jan 26	9:30AM - 11:30AM	78	87	0	1	1	0	0	0	0
3	Mar 8	6:00AM - 8:00AM	67	81	0	3	0	0	5	0	0
4	April 28	5:00 AM - 6:00AM	13	5	6	0	1	0	0	0	0
5	April 29	4:45PM - 5:45PM	49	60	1	0	0	0	2	2	0
6	April 30	5:00AM - 6:30AM	24	25	0	0	0	0	0	0	0
7	April 30	1:00PM - 2:00PM	61	67	0	2	0	0	5	0	0
8	May 1	10:30AM - 11:30AM	46	50	0	2	0	0	1	0	0
9	May 31	4:00PM - 5:30PM	112	156	0	1	1	0	13	1	0
10	June 4	7:30AM - 8:30AM	36	45	0	0	0	0	5	1	0
11	June 16	12:00PM - 12:30PM	34	31	6	5	0	0	1	1	0
12	June 16	10:55PM - 11:25PM	23	18	7	1	0	0	0	0	0
	Sum		558	641	20	15	3	0	33	5	0
					6.81%				5.15%	0.90%	0.00%

A more detailed description of the frequency of false calls, together with precipitation intensity and wind gusts during the rainy conditions, is shown in Table 18. The frequency of false calls is shown for the three stop bar zones combined and divided by the number of vehicles approaching in any of the three lanes; thus, it is a measure of the number of false calls per vehicle. A graphical representation of these three variables (precipitation, wind, and false calls) in a 3D plot is provided in Figure 8, which shows that false calls were more frequent during heavier precipitation (greater than ~0.15 in. in 20 minutes).

Table 18. Precipitation, Wind, and Resulting False Calls per Vehicle at Stop Bar Zones in Rainy Conditions

Data Set #	Date	Time	Max 20 min Precipitation (in)	Max Wind Speed Including Gusts (mph)	Wind Gusts?	False Calls/Vehicle at stop bar zones
1	Feb 4 2012	4:00AM - 6:00AM	0.03	25.3	Yes	0.000
2	Jan 26 2012	9:30AM - 11:30AM	0.15	8.1	No	0.011
3	Mar 8 2012	6:00AM - 8:00AM	0.02	32.2	Yes	0.020
4	April 28 2012	5:00AM - 6:00AM	0.18	20.7	Yes	0.800
5	April 29 2012	4:45PM - 5:45PM	0.15	11.5	No	0.065
6	April 30 2012	5:00AM - 6:30AM	0.18	13.8	No	0.000
7	April 30 2012	1:00PM - 2:00PM	0.09	17.3	Yes	0.010
8	May 1 2012	10:30AM - 11:30AM	0.11	18.4	No	0.021
9	May 31 2012	4:00PM - 5:30PM	0.13	27.6	Yes	0.006
10	June 4 2012	7:30AM - 8:30AM	0.06	10.4	No	0.015
11	June 16 2012	12:00PM - 12:30PM	0.44	32.2	Yes	0.406
12	June 16 2012	10:55PM - 11:25PM	0.19	21.9	Yes	0.627

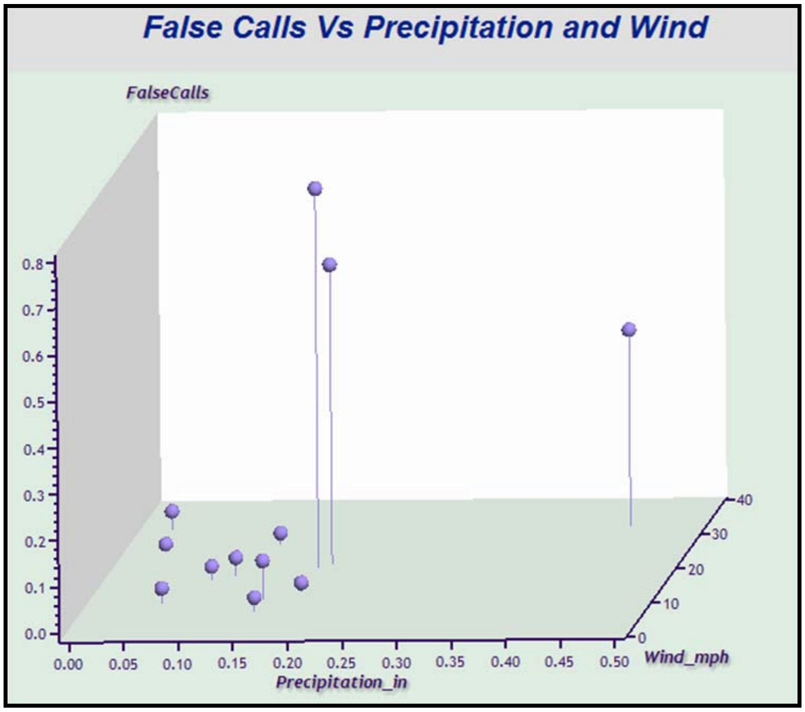


Figure 8. 3D plot of precipitation, wind, and false calls per vehicle at Wavetronix stop bar zones in rainy conditions.

4.2.1.3.2. Advance Zone

In the advance zone, false calls reached 16.53%, indicating a small increase compared to the results in normal weather conditions. Also, these changes were smaller than those observed at the stop bar zones. Other types of error did not show changes in the rainy conditions, with missed calls below 1% and zero dropped or stuck-on calls.

Table 19. Detection Errors for Wavetronix Advance Zone in Rainy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix					
					False Calls		Missed Calls		Stuck-on Calls	Dropped Calls
			Wavetronix	Loop	No vehicles in vicinity of zone	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Feb 4	4:00AM - 6:00AM	120	44	80	0	0	0	0	0
2	Jan 26	9:30AM - 11:30AM	298	289	26	6	0	2	0	0
3	Mar 8	6:00AM - 8:00AM	322	266	67	5	0	4	0	0
4	April 28	5:00 AM - 6:00AM	65	22	44	1	0	0	0	0
5	April 29	4:45PM - 5:45PM	10	7	2	0	0	0	0	0
6	April 30	5:00AM - 6:30AM	68	62	10	0	0	4	0	0
7	April 30	1:00PM - 2:00PM	218	222	13	2	0	1	0	0
8	May 1	10:30AM - 11:30AM	145	148	6	2	0	4	0	0
9	May 31	4:00PM - 5:30PM	553	586	35	6	0	1	0	0
10	June 4	7:30AM - 8:30AM	158	146	14	3	0	1	0	0
11	June 16	12:00PM - 12:30PM	124	101	25	2	0	0	0	0
12	June 16	10:55PM - 11:25PM	54	55	4	0	0	1	0	0
	Sum		2135	1948	326	27	0	18	0	0
					16.53%			0.92%	0.00%	0.00%

In summary, the performance of Wavetronix in rainy conditions showed an increased frequency in the number of false calls at stop bar zones, ranging between 5.94% and 7.37% (about a 5% increase compared to normal weather). However, other types of error at the stop bar zone, and the overall performance at the advance zone, were not affected by the rainy conditions.

4.2.2. Intersector

4.2.2.1. Wind

<u>4.2.2.1.1. Stop Bar Zones</u>

In Zone 1, false calls accounted for 1.46% of the total number of calls, and there were no missed vehicles (Table 20). Stuck-on calls were 3.47% of the calls placed by Intersector, and they lasted between 37 seconds and 3 minutes, with all of them terminated after a second vehicle traveled over the zone. This indicates that in this zone, no significant change occurred in the frequency of errors due to wind.

Table 20. Detection Errors for Intersector Zone 1 in Windy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Intersector						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Intersector	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Jan 1	6:00PM - 10:00PM	87	91	1	1	0	0	0	0	0
2	Feb 26	12:00PM - 3:00PM	107	123	0	2	0	0	0	4	0
3	Mar 7	7:00AM - 10:00AM	97	113	0	0	0	0	0	8	0
4	Mar 6	11:00AM - 4:00PM	257	302	0	2	2	0	0	7	1
	Sum		548	629	1	5	2	0	0	19	1
					1.46%				0.00%	3.47%	0.16%

The performance of Zone 2 in windy conditions was also similar to that in normal weather (Table 21). There were no missed calls, and the frequency of false calls was 2.8%. Stuck-on calls were also found in similar proportion (2.13%), and they lasted between 24 seconds and about 5 minutes. Dropped calls remained lower than 0.5%.

Table 21. Detection Errors for Intersector Zone 2 in Windy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Intersector						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Intersector	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Jan 1	6:00PM - 10:00PM	115	123	1	3	1	0	0	7	0
2	Feb 26	12:00PM - 3:00PM	145	159	4	2	0	0	0	3	1
3	Mar 7	7:00AM - 10:00AM	152	157	0	4	0	0	0	1	0
4	Mar 6	11:00AM - 4:00PM	339	401	0	2	4	0	0	5	1
	Sum		751	840	5	11	5	0	0	16	2
					2.80%				0.00%	2.13%	0.24%

In Zone 3, false calls were 2.57% of the total number of calls, and stuck-on calls were 1.86% (Table 22). This is very similar to previous results from normal weather data (Table 2), and no significant effects were observed due to wind. Stuck-on calls lasted between 11 seconds and more than 3 minutes, and some of the stuck-on calls were not terminated until multiple cars traveled over the lane.

Table 22. Detection Errors for Intersector Zone 3 in Windy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Intersector						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Intersector	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Jan 1	6:00PM - 10:00PM	135	143	4	1	0	0	0	4	0
2	Feb 26	12:00PM - 3:00PM	138	153	0	0	0	0	0	2	0
3	Mar 7	7:00AM - 10:00AM	143	158	0	5	1	0	0	3	0
4	Mar 6	11:00AM - 4:00PM	284	325	0	7	0	0	0	4	0
	Sum		700	779	4	13	1	0	0	13	0
					2.57%				0.00%	1.86%	0.00%

4.2.2.1.2. Advance Zone

Errors at the advance zone were low and similar to those found in the normal weather data (Table 23). There were 0.44% of false calls, 0.61% missed calls, no dropped calls, and no stuck-on calls. This indicates that there were no significant effects due to wind on the performance of Zone 3.

Table 23. Detection Errors for Intersector Advance Zone in Windy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Intersector						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Intersector	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Jan 1	6:00PM - 10:00PM	130	139	3	0	0	8	0	0	0
2	Feb 26	12:00PM - 3:00PM	186	194	1	0	0	8	1	0	0
3	Mar 7	7:00AM - 10:00AM	174	184	0	0	0	6	0	0	0
4	Mar 6	11:00AM - 4:00PM	419	470	0	0	0	23	5	0	0
	Sum		909	987	4	0	0	45	6	0	0
					0.44%				0.61%	0.00%	0.00%

In general, the performance of Intersector in windy conditions at stop bar and advance zones followed a trend similar to that in normal weather. Thus, the data show that at this installation, wind did not have a significant effect on the frequency of errors.

4.2.2.2. Snow

4.2.2.2.1. Stop Bar Zones

The frequency of errors observed in Zone 1 in snow conditions was very similar to that in the normal weather (Table 24). False calls were lower than 4% and remained in the same range as the datasets from Table 2. Missed calls were slightly higher and accounted for about 1%

of the vehicles sampled, with four occurrences. Vehicles missed included not only passenger cars but, on one occasion, a snow-plowing truck.

Stuck-on calls also occurred in a proportion similar to those in normal weather. A total of 13 cases were found, each lasting between 24 seconds and about 3.5 minutes. Stuck-on calls were not always dropped after a second vehicle traveled over the zone, but sometimes the detector remained in the “on” position after several vehicles departed the zone.

Table 24. Detection Errors for Intersector Zone 1 in Snow Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
					False Calls			**Missed Calls**		**Stuck-on Calls**	**Dropped Calls**
			Intersector	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Dec 27	5:30AM - 7:30AM	24	25	1	0	0	0	0	1	1
2	Jan 13	6:00AM - 12:00PM	136	150	2	2	2	0	1	6	0
3	Jan 19	2:00PM - 3:00PM	36	49	0	0	0	0	1	4	0
4	Jan 20	6:30PM - 11:30PM	149	153	2	1	4	0	2	2	0
5	Feb 13	10:30PM - 11:30PM	7	8	0	0	0	0	0	0	0
	Sum		352	385	5	3	6	0	4	13	1
					3.98%				1.04%	3.69%	0.26%

A similar situation was found in Zone 2, with the frequencies of missed, stuck-on, and dropped calls in snow conditions (Table 25) similar to those in normal conditions. However, false calls increased to 8.06% compared to less than 4.5% in normal weather. This increase was due to calls generated by vehicles in the adjacent lane, mostly because vehicles that approached the stop bar were following existing tire marks in the snow, which were not centered in the traveled lanes. In addition, the number of calls generated without any vehicles near the zones increased slightly in snow conditions. These calls were placed when the system initiated calls in all zones simultaneously without any obvious reason, similar to a “reset” in the system.

Table 25. Detection Errors for Intersector Zone 2 in Snow Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
					False Calls			**Missed Calls**		**Stuck-on Calls**	**Dropped Calls**
			Intersector	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Dec 27	5:30AM - 7:30AM	30	29	1	2	0	0	0	1	0
2	Jan 13	6:00AM - 12:00PM	325	334	2	10	9	0	1	3	3
3	Jan 19	2:00PM - 3:00PM	76	91	0	3	0	0	0	0	0
4	Jan 20	6:30PM - 11:30PM	201	178	2	21	1	0	0	0	0
5	Feb 13	10:30PM - 11:30PM	13	11	0	0	1	0	0	0	0
	Sum		645	643	5	36	11	0	1	4	3
					8.06%				0.16%	0.62%	0.47%

Zone 3 showed similar trends to those observed in Zones 1 and 2 (Table 26). The frequency of false calls was slightly higher than in normal weather, with the majority of them due to vehicles in the adjacent lane. Stuck-on calls lasted between 20 seconds and over 4 minutes, and a total of 13 cases were found. The frequency of dropped calls increased but remained very low, with only three occurrences.

Table 26. Detection Errors for Intersector Zone 3 in Snow Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
			Intersector	Loop	False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
					No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Dec 27	5:30AM - 7:30AM	39	36	1	4	0	0	0	2	0
2	Jan 13	6:00AM - 12:00PM	215	207	2	11	3	0	0	3	2
3	Jan 19	2:00PM - 3:00PM	61	74	0	2	1	0	0	1	1
4	Jan 20	6:30PM - 11:30PM	198	207	0	6	0	0	0	7	0
5	Feb 13	10:30PM - 11:30PM	28	26	0	1	1	0	0	0	0
	Sum		541	550	3	24	5	0	0	13	3
					5.91%				0.00%	2.40%	0.55%

If all dropped calls for the three stop bar zones are combined, a total of seven cases were found in the snow conditions (Tables 24, 25, and 26), in about 1600 vehicles (adding the loop calls of the three stop bar zones). This number is slightly higher than the number of dropped calls in normal weather (from Table 2), where a total of six cases were found for the three stop bar zones combined for more than 7000 sampled vehicles.

4.2.2.2.2. Advance Zone

At the advance zone, the effects of snow conditions were also very limited (Table 27). A slight increase was observed in the number of vehicles missed that were clearly traveling over the detection zone (1.43%). False calls remained similar (at 0.88%) and were mostly generated by the system reset mentioned above for Zone 2, which placed simultaneous short calls in all zones regardless of the presence of vehicles. No dropped or stuck-on calls were found in the advance zone.

Table 27. Detection Errors for Intersector Advance Zone in Snow Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Wavetronix						
			Intersector	Loop	False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
					No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Dec 27	5:30AM - 7:30AM	31	48	1	0	0	13	4	0	0
2	Jan 13	6:00AM - 12:00PM	422	430	1	1	0	13	2	0	0
3	Jan 19	2:00PM - 3:00PM	96	103	0	0	0	3	1	0	0
4	Jan 20	6:30PM - 11:30PM	231	247	3	0	1	16	5	0	0
5	Feb 13	10:30PM - 11:30PM	11	13	0	0	0	0	0	0	0
	Sum		791	841	5	1	1	45	12	0	0
					0.88%				1.43%	0.00%	0.00%

In general, the effects of snow conditions on the performance of Intersector were limited to a slight increase in the frequency of false calls in Zones 2 and 3 and in the missed calls at the advance zone.

4.2.2.3. Rain

4.2.2.3.1. Stop Bar Zones

Results for the rainy conditions for Zone 1 are shown in Table 28. Rain did not seem to have a significant effect on the performance of Intersector in Zone 1, except for an increase in the frequency of stuck-on calls. In normal weather, up to 3.53% of the calls were stuck-on, compared to 6.35% in the rainy datasets. Stuck-on calls lasted between 26 seconds and more than 4 minutes, and they were not always dropped after a second car traveled over the zone; sometimes the call was terminated after three or four vehicles departed the zone.

On the other hand, false calls accounted for 1.65% of the calls in Zone 1, mostly due to vehicles in adjacent lanes. A total of four vehicles were missed (all of them passenger cars), with two of them stopping at the stop bar zone without being detected. One dropped call was found.

Table 28. Detection Errors for Intersector Zone 1 in Rainy Conditions

Data Set #	Date	Time	**Number of Activations**		**Verified Errors for Intersector**						
					False Calls			**Missed Calls**		**Stuck-on Calls**	**Dropped Calls**
			Intersector	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Feb 4	4:00AM - 6:00AM	12	12	0	0	0	0	0	0	0
2	Jan 26	9:30AM - 11:30AM	63	74	0	0	0	0	0	1	0
3	Mar 8	6:00AM - 8:00AM	57	63	1	2	0	0	0	1	1
4	April 28	5:00 AM - 6:00AM	6	7	0	0	0	0	0	1	0
5	April 29	4:45PM - 5:45PM	50	60	0	1	0	0	0	3	0
6	April 30	5:00AM - 6:30AM	11	12	0	0	0	0	0	1	0
7	April 30	1:00PM - 2:00PM	36	57	0	0	0	0	0	9	0
8	May 1	10:30AM - 11:30AM	34	39	0	0	0	0	0	2	0
9	May 31	4:00PM - 5:30PM	104	140	0	2	0	0	1	6	0
10	June 4	7:30AM - 8:30AM	24	30	0	0	0	0	0	1	0
11	June 16	12:00PM - 12:30PM	17	29	0	0	0	0	3	2	0
12	June 16	10:55PM - 11:25PM	11	11	1	0	0	0	0	0	0
	Sum		425	534	2	5	0	0	4	27	1
					1.65%				0.75%	6.35%	0.19%

Zone 2 demonstrated a trend similar to that described for Zone 1, as shown in Table 29. Thus, false, missed, and dropped calls did not increase, but the frequency of stuck-on calls doubled (even though this increase was less than about 2%). The duration of the stuck-on calls was also very wide, with calls as short as 14 seconds and as long as about 5 minutes.

Table 29. Detection Errors for Intersector Zone 2 in Rainy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Intersector						
			Intersector	Loop	False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
					No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Feb 4	4:00AM - 6:00AM	12	12	0	0	0	0	0	0	0
2	Jan 26	9:30AM - 11:30AM	101	108	0	2	2	0	0	1	0
3	Mar 8	6:00AM - 8:00AM	88	108	1	2	0	0	0	4	0
4	April 28	5:00 AM - 6:00AM	9	8	0	0	0	0	0	0	0
5	April 29	4:45PM - 5:45PM	70	81	0	0	0	0	0	3	0
6	April 30	5:00AM - 6:30AM	22	23	0	0	0	0	0	3	0
7	April 30	1:00PM - 2:00PM	63	86	0	2	0	0	0	4	0
8	May 1	10:30AM - 11:30AM	47	51	0	0	0	0	0	1	0
9	May 31	4:00PM - 5:30PM	196	237	0	3	1	0	0	1	1
10	June 4	7:30AM - 8:30AM	56	60	0	2	0	0	0	0	0
11	June 16	12:00PM - 12:30PM	25	36	0	1	0	0	2	1	1
12	June 16	10:55PM - 11:25PM	19	22	0	2	1	0	1	1	0
	Sum		708	832	1	14	4	0	3	19	2
					2.68%				0.36%	2.68%	0.24%

In Zone 3, stuck-on calls were the only type of error that showed an increase in frequency compared to normal weather conditions. Stuck-on calls represented 3.47% of the total number of calls in the rain data (Table 30), which indicates that they almost doubled from normal weather (which were 1.81% at most). The stuck-on calls lasted between 12 seconds and more than 9 minutes, but in this zone all of them were terminated after a second vehicle traveled over the detection area. None of the other types of error showed a significant change compared to normal weather data.

Table 30. Detection Errors for Intersector Zone 3 in Rainy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Intersector						
			Intersector	Loop	False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
					No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Feb 4	4:00AM - 6:00AM	17	16	0	1	0	0	0	1	0
2	Jan 26	9:30AM - 11:30AM	82	87	1	2	0	0	0	1	0
3	Mar 8	6:00AM - 8:00AM	67	81	0	0	0	0	0	6	0
4	April 28	5:00 AM - 6:00AM	6	5	0	0	0	0	0	0	0
5	April 29	4:45PM - 5:45PM	51	60	0	1	0	0	0	3	0
6	April 30	5:00AM - 6:30AM	27	25	0	1	0	0	0	0	0
7	April 30	1:00PM - 2:00PM	62	67	0	0	0	0	0	1	0
8	May 1	10:30AM - 11:30AM	47	50	0	0	0	0	0	2	0
9	May 31	4:00PM - 5:30PM	132	156	0	4	0	0	0	2	0
10	June 4	7:30AM - 8:30AM	43	45	0	2	0	0	0	0	1
11	June 16	12:00PM - 12:30PM	27	31	0	0	0	0	1	1	0
12	June 16	10:55PM - 11:25PM	15	18	0	0	0	0	1	3	0
	Sum		576	641	1	11	0	0	2	20	1
					2.08%				0.31%	3.47%	0.16%

4.2.2.3.2. Advance Zone

In the advance zone, missed calls increased to 3.44% (Table 31), about double the missed calls observed in normal weather. Recall that these frequencies include only vehicles missed that were traveling *clearly* inside the center lane, without considering vehicles between lanes or changing lanes near the zone. In total, 36 vehicles were missed at the advance zone (out of about 1045 vehicles).

Further exploration was undertaken to determine potential effects of precipitation on the frequency of missed calls. In Figure 9, records for the maximum precipitation intensity in 20 minutes and maximum wind speed from the nearby weather station are shown with the detection errors for each dataset. The purpose of Figure 9 is to illustrate whether missed calls were more frequent in cases where precipitation and/or wind were greater.

From Figure 9, it can be observed that datasets with higher precipitation coincided with those having a higher number of missed vehicles; accordingly, there could be a relation between these two variables. However, the sample size should be increased before conclusive statements can be made. Results described in the previous section on windy conditions showed no significant effects of wind alone, but based on the data depicted in Figure 9, it could be worthwhile to explore a possible relation between high wind and precipitation in the occurrence of missed vehicles.

False calls at the advance zone were low and similar to those in normal weather conditions, at 0.56%. Likewise, no stuck-on or dropped calls were found.

Table 31. Detection Errors for Intersector Advance Zone in Rainy Conditions

Data Set #	Date	Time	Number of Activations		Verified Errors for Intersector						
					False Calls			Missed Calls		Stuck-on Calls	Dropped Calls
			Intersector	Loop	No vehicles in vicinity of zone	Vehicles on adjacent lane	Flickering	Traveling Between Lanes	Clearly Traveling Over Zone		
1	Feb 4	4:00AM - 6:00AM	16	18	0	0	0	2	0	0	0
2	Jan 26	9:30AM - 11:30AM	127	137	0	1	0	13	0	0	0
3	Mar 8	6:00AM - 8:00AM	114	133	2	0	0	4	7	0	0
4	April 28	5:00 AM - 6:00AM	9	11	0	0	0	2	0	0	0
5	April 29	4:45PM - 5:45PM	94	109	0	0	0	7	4	0	0
6	April 30	5:00AM - 6:30AM	22	26	0	0	0	2	2	0	0
7	April 30	1:00PM - 2:00PM	85	105	0	0	0	11	6	0	0
8	May 1	10:30AM - 11:30AM	57	62	0	0	0	2	1	0	0
9	May 31	4:00PM - 5:30PM	257	304	0	1	0	21	5	0	0
10	June 4	7:30AM - 8:30AM	64	72	0	0	0	4	1	0	0
11	June 16	12:00PM - 12:30PM	29	41	0	0	0	4	8	0	0
12	June 16	10:55PM - 11:25PM	23	27	0	1	0	2	2	0	0
	Sum		897	1045	2	3	0	74	36	0	0
					0.56%				3.44%	0.00%	0.00%

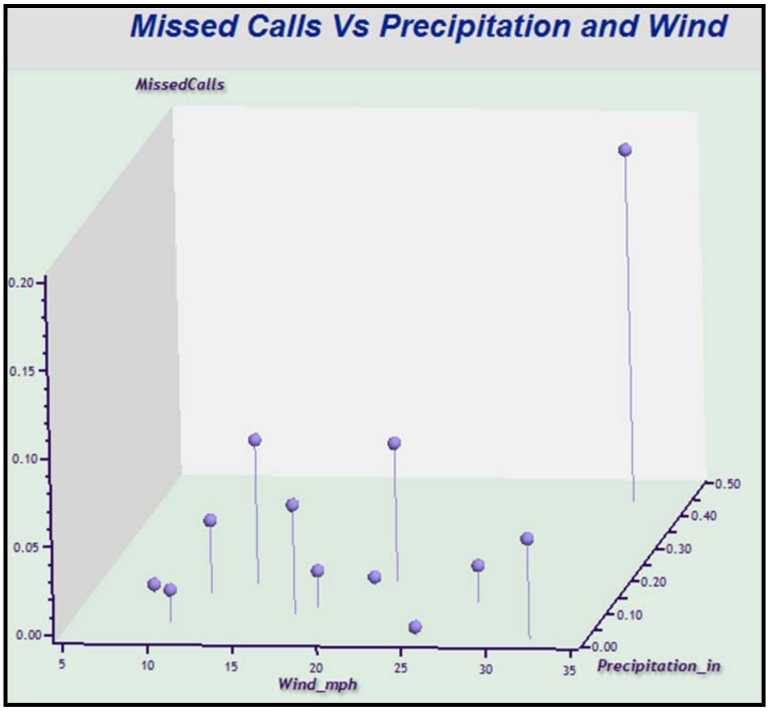


Figure 9. 3D plot of precipitation, wind and missed calls at Intersector advance zone in rainy conditions.

Overall, rainy conditions affected Intersector performance at the stop bar zones in terms of stuck-on calls, increasing to a range between 2.68% and 6.35%, whereas at the advance zone, missed calls increased to 3.44%.

4.3. FEEDBACK FROM COMPANIES

After the data analysis and completion of the report, the Technical Review Panel and companies were provided with copies of the draft document for their comments. Wavetronix and MS SEDCO received the sections corresponding to the results for their own system; thus, they could provide comments exclusively for the content relevant to their product.

MS SEDCO did not provide any comments to be added to the report, but Wavetronix provided feedback with respect to the installation and setup of their devices. The following are the relevant comments (in italics) submitted by Wavetronix to the research team after the draft report was provided to the company. These comments are included in the final report because they may provide useful information for future installations at similar sites.

4.3.1. Feedback from Wavetronix

<u>*Advance Detection*</u>

The SmartSensor Advance is designed as a dilemma-zone protector that tracks vehicles over long stretches of road looking for "gap-out" opportunities based on vehicle speed and ETA. Advance is not typically used for localized spot detection as a direct "loop replacement." Wavetronix maintains [that] *studying Advance using only a narrow loop duplication zone is not an effective test of its core functionality.*

Without filtering, Advance will typically detect any object that moves faster than 1 mph in the detection zone, which in adverse conditions can include tree limbs or other swaying road-side objects. In addition, device sway in heavy wind may cause brief detections of opposite-direction traffic or objects outside the normal detection boundaries. Because of this sensitivity—and especially when working with a single, narrow detection zone—it is important to use Advance's speed and ETA filters, neither of which were enabled for this study. (See Figure 10.)

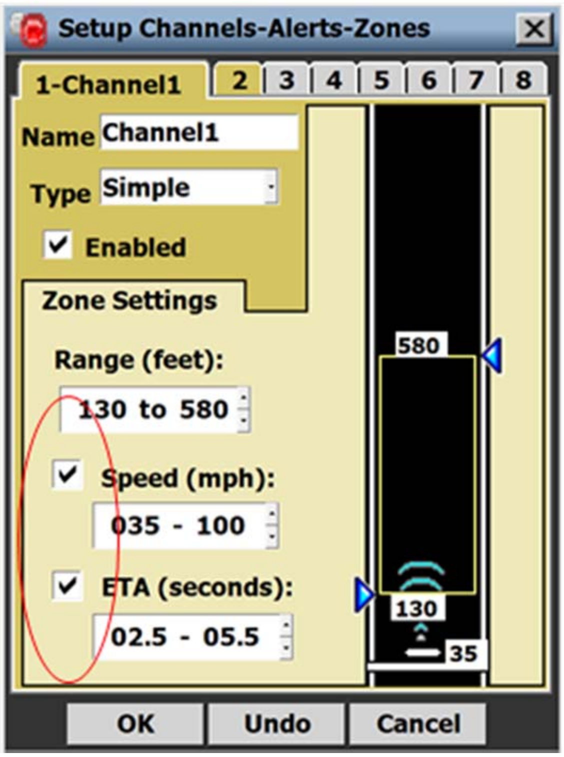
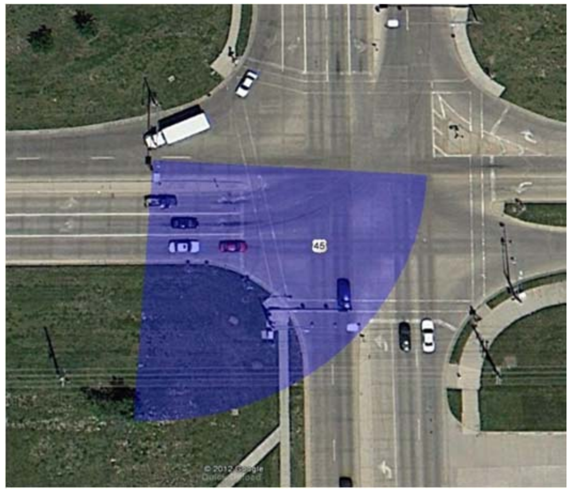


Figure 10. SmartSensor Advance's speed/ETA filters.

Proper use of these filters will help differentiate between anomalous detections and true vehicles that are tracked over time by their speed and/or ETA to the intersection. Advance also features an internal log function that can be manually enabled to record individual vehicle detections and events—a useful tool to check how Advance is translating each detection into composite vehicle records.

<u>SmartSensor Matrix</u>

As mentioned in Volume 1 [of this report]*, a Matrix installation location placed behind traffic will inherently be less effective than a more suitable location behind the stop bar facing forward.* (See Figure 11.) *Many of the detection problems noted—especially in Zone 3—during the normal weather segment due to its location will be exacerbated during adverse weather conditions.*



(a) Installed location and orientation

(b) Improved orientation for installed location

(c) Recommended installation location

Figure 11. Installed, improved, and recommended installation location of Matrix.

Due to the natural reflectiveness of water, weather conditions that include heavy rain or wet/slushy snow will create background radar patterns (albeit weak ones) that can *occasionally trigger false vehicle calls. Matrix has been deliberately designed to be very sensitive to radar signatures to minimize the chance of missing a vehicle, and the emphasis on sensitivity increases the risk of false detections. However, the desire to avoid missed calls in stop bar contexts usually makes the acceptance of some small percentage of false calls necessary for effective operation.*

As with Advance, the Matrix device has been equipped with user tools and filters to assist in weeding out invalid targets while keeping legitimate detections, and adverse weather makes the use of these thresholds and filters more important. Wavetronix recommends raising the sensitivity threshold 2-3 dB from default to reduce weaker, water-related radar signatures while still detecting legitimate vehicles.

Reducing the "wash-out" time period is another technique for adjusting Matrix in adverse weather. More frequent wash-outs will guard against missed calls due to pronounced snow conditions that may make vehicles hard to distinguish. An upcoming Matrix firmware release will also provide improved vehicle detection algorithms to reduce missed and false calls in snowy conditions.

In light of the comments provided by Wavetronix, it should be remembered that the authorized product distributor (TCC) was in charge of mounting, aiming, and setup of the Wavetronix devices with onsite feedback from Wavetronix representatives via telephone during the installation.

In addition, as mentioned in the Introduction of this report, the companies had two opportunities to make modifications to the system setup after the initial installation, if they wished. Therefore, before the final data collection, there were many opportunities to improve system performance, including both device relocation and parameter settings.

CHAPTER 5 SUMMARY OF RESULTS

This chapter presents general summary tables based on the results from normal and adverse weather conditions. These tables allow comparison of error frequencies for all conditions and thereby offer a general overview of the effects of adverse weather for each zone.

The dates and times for the selected datasets are the same for the two systems, allowing for direct comparison of results at the stop bar zones. However, at the advance zone, Intersector and Wavetronix covered a different number of lanes and are not directly comparable, even though the datasets are the same.

Table 32. Stop Bar/Wavetronix

Zone		Period		Number of Activations		Verified Errors						
						False Calls			Missed Calls			
				Wavetronix	Loop	Vehicles not present in adjacent lanes	Vehicles in adjacent lanes	Flickering	Traveling between lanes	Clearly traveling over zone	Stuck-on Calls	Dropped Calls
Stop Bar Zones	Zone 1	Good Weather	Summer 2011	701	837	0	0	2	1	1	0	0
						0.29%			0.12%		0.00%	0.00%
			Fall 2011	542	647	0	3	2	0	0	0	0
						0.92%			0.00%		0.00%	0.00%
			Winter 2011-2012	418	444	0	0	0	0	2	0	0
						0.00%			0.45%		0.00%	0.00%
		Adverse Weather	Snow	614	385	244	22	11	0	11	5	1
						45.11%			2.86%		0.81%	0.26%
			Wind	537	629	0	0	1	1	0	0	0
						0.19%			0.00%		0.00%	0.00%
			Rain	475	534	26	9	0	2	1	1	0
						7.37%			0.19%		0.21%	0.00%
	Zone 2	Good Weather	Summer	1004	1126	0	1	0	1	2	0	1
						0.10%			0.18%		0.00%	0.09%
			Fall	861	967	0	6	5	0	6	0	0
						1.28%			0.62%		0.00%	0.00%
			Winter 2011-2012	585	650	0	2	1	1	3	0	0
						0.51%			0.46%		0.00%	0.00%
		Adverse Weather	Snow	884	643	305	65	5	1	42	7	0
						42.42%			6.53%		0.79%	0.00%
			Wind	740	840	1	5	4	0	4	0	0
						1.35%			0.48%		0.00%	0.00%
			Rain	758	832	30	13	2	1	4	2	1
						5.94%			0.48%		0.26%	0.12%
	Zone 3	Good Weather	Summer	797	969	0	3	4	1	56	1	3
						0.88%			5.78%		0.13%	0.31%
			Fall	743	899	0	12	6	1	55	8	0
						2.42%			6.12%		1.08%	0.00%
			Winter 2011-2012	507	563	0	3	4	1	37	2	0
						1.38%			6.57%		0.39%	0.00%
		Adverse Weather	Snow	918	550	451	55	11	2	63	13	0
						56.32%			11.45%		1.42%	0.00%
			Wind	659	779	0	5	6	0	22	2	4
						1.67%			2.82%		0.30%	0.51%
			Rain	558	641	20	15	3	0	33	5	0
						6.81%			5.15%		0.90%	0.00%

Table 33. Advance Zone/Wavetronix

Zone	Period		Number of Activations		Verified Errors						
					False Calls			Missed Calls			
			Wavetronix	Loop	Vehicles not present in adjacent lanes	Vehicles in adjacent lanes	Flickering	Traveling between lanes	Clearly traveling over zone	Stuck-on Calls	Dropped Calls
Advance Zone	Good Weather	Summer	2928	2816	81	-	57	-	36	0	0
					4.71%			1.28%		0.00%	0.00%
		Fall	2672	2623	247	-	79	-	22	0	0
					12.20%			0.84%		0.00%	0.00%
		Winter 2011-2012	1923	1746	238	-	38	-	7		
					14.35%			0.40%		0.00%	0.00%
	Adverse Weather	Snow	2112	1690	514	-	111	0	41	0	0
					29.59%			2.43%		0.00%	0.00%
		Wind	6509	2358	>50%*			0	7	0	0
								0.30%		0.00%	0.00%
		Rain	2135	1998	326	0	27	0	18	0	0
					16.53%			0.90%		0.00%	0.00%

* Percentage estimated based 10% of total calls visually verified

Table 34. Stop Bar/Intersector

Zone		Period		Number of Activations		Verified Errors						
						False Calls			Missed Calls			
				Wavetronix	Loop	Vehicles not present in adjacent lanes	Vehicles in adjacent lanes	Flickering	Traveling between lanes	Clearly traveling over zone	Stuck-on Calls	Dropped Calls
Stop Bar Zones	Zone 1	Good Weather	Summer 2011	706	837	0	8	9	0	2	20	1
						2.41%			0.24%		2.83%	0.12%
			Fall 2011	565	647	0	9	14	0	2	16	1
						4.07%			0.31%		2.83%	0.15%
			Winter 2011-2012	425	444	2	5	0	0	0	15	0
						1.65%			0.00%		3.53%	0.00%
		Adverse Weather	Snow	352	385	5	3	6	0	4	13	1
						3.98%			1.04%		3.69%	0.26%
			Wind	548	629	1	5	2	0	0	19	1
						1.46%			0.00%		3.47%	0.16%
			Rain	425	534	2	5	0	0	4	27	1
						1.65%			0.75%		6.35%	0.19%
	Zone 2	Good Weather	Summer	1012	1126	0	23	15	0	0	9	2
						3.75%			0.00%		0.89%	0.18%
			Fall	887	967	0	17	21	0	2	13	2
						4.28%			0.21%		1.47%	0.21%
			Winter 2011-2012	598	650	2	13	4	0	0	8	0
						3.18%			0.00%		1.34%	0.00%
		Adverse Weather	Snow	645	643	5	36	11	0	1	4	3
						8.06%			0.16%		0.62%	0.47%
			Wind	751	840	5	11	5	0	0	16	2
						2.80%			0.00%		2.13%	0.24%
			Rain	708	832	1	14	4	0	3	19	2
						2.68%			0.36%		2.68%	0.24%
	Zone 3	Good Weather	Summer	903	969	0	17	12	0	0	11	0
						3.21%			0.00%		1.22%	0.00%
			Fall	838	899	0	19	14	0	1	5	0
						3.94%			0.11%		0.60%	0.00%
			Winter 2011-2012	553	563	1	16	1	0	0	10	0
						3.25%			0.00%		1.81%	0.00%
		Adverse Weather	Snow	541	550	3	24	5	0	0	13	3
						5.91%			0.00%		2.40%	0.55%
			Wind	700	779	4	13	1	0	0	13	0
						2.57%			0.00%		1.86%	0.00%
			Rain	576	641	1	11	0	0	2	20	1
						2.08%			0.31%		3.47%	0.16%

Table 35. Advance Zone/Intersector

Zone	Period		Number of Activations		Verified Errors						
					False Calls			Missed Calls			
			Wavetronix	Loop	Vehicles not present in adjacent lanes	Vehicles in adjacent lanes	Flickering	Traveling between lanes	Clearly traveling over zone	Stuck-on Calls	Dropped Calls
Advance Zone	Good Weather	Summer	1227	1361	0	2	8	99	9	1	0
					0.81%			0.66%		0.08%	0.00%
		Fall	1049	1143	0	3	3	70	11	0	0
					0.57%			0.96%		0.00%	0.00%
		Winter 2011-2012	755	793	4	0	0	46	6	0	0
					0.53%			0.76%		0.00%	0.00%
	Adverse Weather	Snow	791	841	5	1	1	45	12	0	0
					0.88%			1.43%		0.00%	0.00%
		Wind	909	987	4	0	0	45	6	0	0
					0.44%			0.61%		0.00%	0.00%
		Rain	897	1045	2	3	0	74	36	0	0
					0.56%			3.44%		0.00%	0.00%

CHAPTER 6 CONCLUSIONS

Two microwave-based systems for vehicle detection (by Wavetronix and MS SEDCO) were evaluated at stop bar and advance zones of a signalized intersection under adverse weather conditions. For this evaluation, one Matrix and one Advance unit were installed by the authorized Wavetronix distributor in Illinois, and one Intersector unit was installed directly by MS SEDCO representatives. The systems were fine-tuned prior to the adverse weather evaluation. A first report on this study (Medina et al. 2012) contains a description of the initial setup and the setup after fine-tuning. The adverse weather conditions include (1) wind, (2) snow-covered roadway, and (3) rain. Detailed analysis was performed for each individual zone.

Weather effects differed significantly for the two systems both in terms of the type of condition that could affect performance and in the magnitude of those effects. In addition, the units from the two systems were not installed side by side; therefore, factors such as device location varied from one system to the other.

For Wavetronix, wind had a significant effect on the performance of the Advance unit by increasing the frequency of false calls to over 50%, but wind did not affect the performance of the Matrix unit at stop bar zones. On the other hand, false calls in snow significantly increased to more than 40% in the stop bar zones (Matrix) and to about 30% in the advance zone (Advance). Snow also increased the frequency of missed and stuck-on calls but in lower proportion than the false calls. Rain also affected detection at stop bar zones but in lower proportion, with any given type of error below 8%, and it did not affect performance in the advance zone.

For Intersector, weather effects were less pronounced both at the stop bar and advance zones. Snow had some effects by increasing false calls to about 4% to 8%, compared to 1.65% to about 4% in normal weather. In addition, rain increased stuck-on calls; they almost doubled in frequency to a range of 2.7% to 6.35% at the stop bar zones. Rain also increased missed calls at advance zones, reaching 3.44% of vehicles missed. No significant effects of windy conditions were found.

For the rain data in particular, the intensity of the precipitation seemed to be related to the degree of performance degradation. In datasets with higher precipitation per unit of time, more false calls were observed at Wavetronix stop bar zones, and a higher frequency of missed calls was observed at the Intersector advance zone.

Results from this evaluation showed that two products using similar technology behaved very differently under the same adverse weather conditions, with significant effects seen during some of these conditions even though the systems were installed and fine-tuned (during good weather) directly by the manufacturer or an authorized distributor of the product.

Data showed that wind greatly affected Wavetronix performance, but those devices were placed near traffic signals on horizontal mast arms; therefore, they experienced significantly more oscillation movement with high wind speeds than Intersector (located on the vertical pole holding the mast arm). However, other issues such as the increase of false calls when the roadway was covered with snow (and without significant wind) were not obvious in terms of the location of the devices.

Findings from this evaluation can provide valuable information to users and manufacturers of these products regarding expected performance under adverse weather conditions at locations with similar mountings and settings, as well as insight about potential solutions to preventing negative effects in such scenarios.

REFERENCES

Medina, J.C., Benekohal, R.F., and Chitturi, M. Evaluation of Video Detection Systems: Volume 1—Effects of Configuration Changes in the Performance of Video Detection Systems. Illinois Center for Transportation. Report No. FHWA-ICT-08-024. 2008.

Medina, J.C., Benekohal, R.F., and Chitturi, M. Evaluation of Video Detection Systems: Volume 2—Effects of Illumination Conditions in the Performance of Video Detection Systems. Illinois Center for Transportation. Report No. FHWA-ICT-09-046. 2009a.

Medina, J.C., Benekohal, R.F., and Chitturi, M. Evaluation of Video Detection Systems: Volume 3—Effects of Windy Conditions in the Performance of Video Detection Systems. Illinois Center for Transportation. Report No. FHWA-ICT-09-047. 2009b.

Medina, J.C., Benekohal, R.F., and Chitturi, M. Evaluation of Video Detection Systems: Volume 4—Effects of Adverse Weather Conditions in the Performance of Video Detection Systems. Illinois Center for Transportation. Report No. FHWA-ICT-09-039. 2009c.

Medina, J.C., Benekohal, R.F., Ramezani, H. Field Evaluation of Smart Sensor Vehicle Detectors at Intersections: Volume 1—Normal Weather Conditions. Illinois Center for Transportation. Report No. FHWA-ICT-12-016. 2012.

Illinois Department of Transportation

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN