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FIELD EVALUATION OF SMART SENSOR VEHICLE DETECTORS AT RAILROAD GRADE CROSSINGS—VOLUME 4: PERFORMANCE IN ADVERSE WEATHER CONDITIONS

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16. Abstract

The performance of a microwave radar system for vehicle detection at a railroad grade crossing with quadrant gates was evaluated in adverse weather conditions: rain (light and torrential), snow (light and heavy), dense fog, and wind. The first part of this report compares the results of the modified system setup in adverse weather conditions with those from good weather conditions (as presented in Volume 3 of this study). Then, the results of a re-modified system setup were compared to the results for the modified system setup in good and adverse weather conditions. The re-modification was in response to increased detection errors in adverse weather conditions. With the modified setup, system performance was sensitive to the adverse weather conditions. In torrential rain, false calls increased to 24.82%–27.08% (e.g., May 28 and June 1) when there was some traffic on the crossing. However, when there was torrential rain but only one vehicle (e.g., May 31) or no traffic flow (e.g., June 10), the radar units generated 15 false calls on each of those 2 days. For all heavy snow datasets combined, missed calls by a single radar unit and by the two radar units working as a combined unit (i.e., systemwide) represented 13.51% and 11.66% of the loop calls, respectively. The most severe snow effects were found during freezing rain/ice. In dense fog, false calls increased to 11.58%, and all false calls were generated when the gates were moving or in the down position. Wind did not affect system performance, and the errors were similar to those in good weather conditions. With the re-modified setup, the frequency of errors in heavy rain and heavy snow conditions was reduced and system performance was similar to the good weather, light rain, and light snow conditions. In heavy rain, false calls in the re-modified setup were reduced to 2.6% compared with 30.5% in the modified setup. This reduction was the result of a significant decrease in the false calls generated without objects in the crossing. The re-modified setup eliminated the systemwide missed calls in heavy snow. The re-modified setup also reduced the false calls to less than 1% in good weather, light rain, and light snow conditions and practically had no missed, stuck-on, or dropped calls. Results indicate that re-modifications improved the performance of detection system.

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EXECUTIVE SUMMARY

The performance of a microwave radar system for vehicle detection at a railroad grade crossing with four-quadrant gates was evaluated in four adverse weather conditions: rain (light and torrential), snow (light and heavy), dense fog, and wind. The system consisted of two radar units aimed at the crossing from two opposing quadrants; each radar unit covered a detection area similar to that provided by standard inductive loops located between the tracks and between the gates and the outer tracks. The outputs from the two radar units could be used independently or together to provide redundancy in vehicle detection and to achieve potential improvement in system performance.

The first chapters of this report compares the results of the modified system setup in good weather, presented in Volume 3 of this study, with the results observed in adverse weather conditions. Then, in Chapter 6, the results of a re-modification of the system by the vendor are presented as a response to increased detection errors in adverse weather. System performance with the modified and the re-modified setups is summarized as follows:

Performance with the Modified Setup

Analysis of the adverse weather data shows that system performance was affected by certain weather events, and the effect of such events varied significantly. Snow-covered roadways with significant snow accumulation and freezing rain/ice (part of the heavy snow data) resulted in the most significant performance changes in terms of missed calls. For all heavy snow datasets combined, missed calls by single radar were estimated at 13.51%, while missed calls by the two radar outputs combined (i.e., systemwide missed calls) were 11.66%. In addition, one of the datasets showed stuck-on calls (2.6%) with durations ranging between 10 and 270 seconds. It should be noted that missed calls were not observed in all datasets with heavy snow but were generated primarily in periods of freezing rain/ice.

During rainy conditions, missed, stuck-on, and dropped calls did not increase. However, the system generated an increasing number of false calls, specifically when the rain was torrential. A precipitation of 0.10 inch or higher within 10 minutes, as reported by a nearby weather station, with heavy rain confirmed at the crossing using video images, was classified as torrential. During torrential rain, and when traffic was using the crossing (e.g., May 28 and June 1), the false calls increased to 24.82%–27.08%. However, when there was torrential rain but only one vehicle (e.g., May 31) or no traffic flow (e.g., June 10), the radar units generated 15 false calls on each of these 2 days. All false calls during torrential rain were generated when there were no objects in the crossing and the gates were in the upright position. These results contrast with results from good weather conditions, for which this type of false calls had a low frequency (0.15%), and some false calls occurred when the gates were moving or down.

For the evaluation of fog conditions, only dense fog datasets with visibility of 0.8 mile or lower were selected. It must be noted that weather stations report a visibility of 10 miles in clear conditions. In dense fog conditions, false calls increased to 11.58%, and all false calls occurred when gates were moving or in the down position. Thus, the false calls generated during fog were attributed to different causes than the false calls generated during rain. Other types of error did not increase in fog conditions.

The evaluation of windy conditions was based on datasets with sustained winds of more than 20 mph and less than 36 mph and gusts of more than 28 mph and less than 57 mph. The video images did not show any swaying or oscillation of the radar units or the mounting poles. The frequency of errors did not increase in wind datasets, indicating no performance concerns when the sensors were mounted on the poles holding the gates.

In summary, the performance of the microwave radar vehicle detection system was affected by different types of weather events. The frequency of errors was affected by the intensity and characteristics of

weather conditions. Performance degradation in short periods of heavy (torrential) rain was significant and greater in magnitude compared with light rain, and the effects of freezing rain/ice with snow accumulation on the road were more significant than those during light snowfall. Dense fog increased false calls caused by gates that were moving or in the down position. Finally, the overall system performance during periods of high wind was similar to that observed in good weather conditions.

Performance with the Re-Modified Setup

The re-modified system was the result of further configuration changes made to the modified setup by the vendor. The need for a re-modified system emerged after the results from adverse weather conditions in the modified setup, particularly the false and missed calls during heavy (or torrential) rain and snow.

Results of the performance evaluation showed that the re-modified setup reduced the frequency of errors in heavy rain and heavy snow conditions, while maintaining a similar performance in good weather, light rain, and light snow. In heavy rain, false calls were reduced to 2.6% with the re-modified setup compared to 30.5% in the previous setup. This reduction was the result of a significant decrease in the false calls generated without objects in the crossing.

In heavy snow the most critical error frequency in the modified setup was the systemwide missed calls (11.7%). The re-modified setup eliminated systemwide missed calls. False calls were also reduced from 3.9% to 0.3% by preventing activations without objects in the crossing and because of the gates being lowered or raised.

More favorable conditions (good weather, light rain, and light snow) had less than 1% false calls and practically no missed, stuck-on, or dropped calls.

Results from this evaluation show that the performance of detection system improved after re-modification.

The redundancy obtained by having two units sensing the same areas in the crossing reduced the frequency of systemwide missed calls, as expected. This redundancy is strongly recommended because missing a single vehicle at a grade crossing has the potential to result in inadequate gate operation, increasing risks of accidents.

Installations using this detection system are recommended to be tested at crossings with a greater number of tracks, as well as locations with multiple lanes in a given direction of traffic.

Further monitoring is also recommended to build confidence on system performance at other locations and different weather conditions.

CONTENTS

CHAPTER 1 INTRODUCTION

This report presents an analysis of the performance of a system with two microwave radar units for vehicle detection at a railroad grade crossing, specifically during adverse weather conditions. Datasets for this evaluation were carefully selected to evaluate the detection system under a variety of adverse weather scenarios that included rain (light and torrential), snow (light and heavy), dense fog, and wind.

This system was first evaluated in good weather, and the findings were presented in Volume 3 of this report series (report number FHWA-ICT-13-028, available on the ICT website: https://apps.ict.illinois.edu/projects/getfile.asp?id=3105).

Previous parts of this study also included two microwave radar vehicle detection systems were evaluated at stop bar and advance detection zones of a signalized intersection. One system was manufactured by Wavetronix, and the second system was manufactured by MS SEDCO. The findings of the evaluation at the signalized intersection were reported in Volumes 1 and 2 of this report series (report numbers FHWA-ICT-12-016 and FHWA-ICT-13-014, respectively, available on the ICT website: https://apps.ict.illinois.edu/projects/getfile.asp?id=3065 and https://apps.ict.illinois.edu/projects/getfile.asp?id=3084).

The vehicle detection system at the railroad crossing evaluated in this report was manufactured by Wavetronix LLC and installed and configured by ByStep LLC. The main components of the system were two identical microwave radar units aimed at the crossing from opposing quadrants. The radar units were modified versions of the Wavetronix Matrix radar, typically used for vehicle detection at stop bar zones of a signalized intersection. The units were installed at a height of about 19.5 feet, on extension poles attached to the poles that held the gates.

Additional radar features for the railroad application included bidirectional detection of vehicles, AREMA-compliant power supply, and operation based on combining outputs from multiple radar units.

An aerial view of the test site is shown in Figure 1, and the locations of the radar units and detection zones are shown in Figure 2.

Figure 1. Top view of selected grade crossing on Monroe Street, near Hinsdale Avenue.

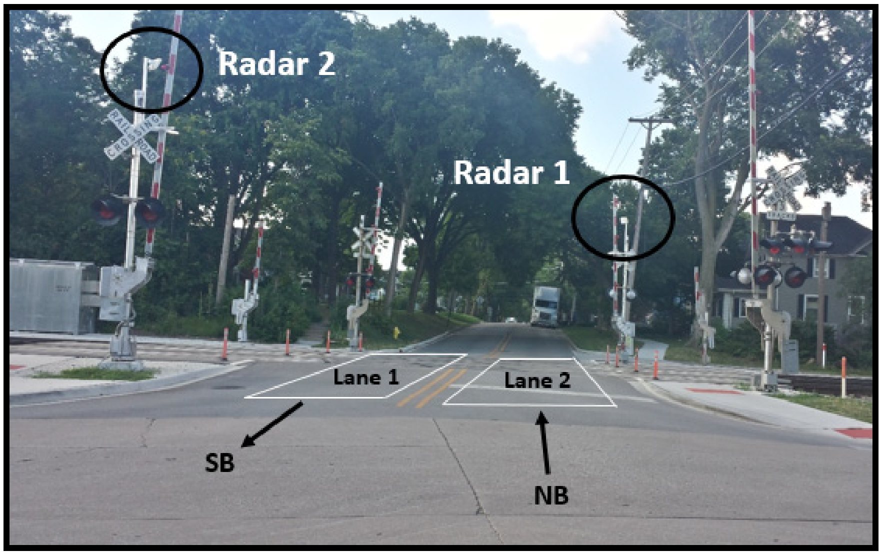


Figure 2. Location and numbering of radar units and detection zones.

CHAPTER 2 METHODOLOGY

The methodology for the performance evaluation in adverse weather followed the same two-step procedure as used in good weather. First, flags for potential errors were automatically identified by finding discrepancies between activation and deactivation times from loops and radar units using computer algorithms. Second, potential errors were manually verified using video images before being labeled as actual detection errors.

System performance was evaluated based on the frequency of four types of detection errors: false calls, missed calls, dropped calls, and stuck-on calls. These errors were estimated for each radar and lane separately, following the two-step procedure mentioned above.

In the first step, the computer code read the activation and deactivation times (or time stamps) from loops and radar units, thus detecting any significant discrepancies between them. Time windows were used when comparing time stamps of loops and radar units, allowing for small time differences because of the two different technologies and preventing them from being identified as potential errors.

The small discrepancies detected at the beginning or the end of activation times of loops and radar units did not indicate an error. Only significant discrepancies—greater than the allowed time windows—created a pointer to a potential error, which would be visually verified in the second stage of the analysis process.

The concepts defining the detection errors, as well as the logic used in the computer code, are briefly described below. The previous reports (FHWA-ICT-08-024, 2008; and FHWA-ICT-12-016, 2012) provide a more comprehensive explanation of the methodology and the algorithms used in this study. Key observations regarding the total number of calls by radar units and loops and the definitions of the detection error types are mentioned below.

2.1. DISCREPANCIES BETWEEN THE TOTAL NUMBER OF RADAR AND LOOP CALLS

It is noted that during a specific analysis period, the total number of individual calls generated by radar and loop detectors may not match exactly even without any detection errors. This was mainly because of the two following situations:

- Vehicles closely following each other—generating a continuous call in the loops but two separate calls in the radar zones—decreasing the relative number of loop calls, compared with the calls from the radar units.
- Vehicles occupying portions of both traveled lanes, particularly when turning to or from the intersecting street, and resulting in two calls (one in each lane). These situations, mostly observed for the radar zones, resulted in an increase in the relative number of radar calls, compared with the calls from the loops.

Depending on the frequency of the two cases, the total number of calls generated by the two systems may vary. Therefore, ***it is likely that the total number of calls placed by the radar units minus false calls plus missed calls will not be equal to the total number of calls placed by the loop detectors***.

2.2. MISSED CALLS

A missed call occurs when a sensor fails to detect a vehicle. In terms of the time stamps, every loop call for which there is no corresponding call from the radar is considered a potential missed call. The algorithm identified loop calls and searched for a call from the radar 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 determine if they were true missed calls. The percentage of missed calls was calculated as the number of missed calls over the total number of loop calls. In practice, missed calls can have adverse safety effects because exit gates can be lowered even when vehicles are occupying the crossing.

2.3 FALSE CALLS

False calls were classified into the following categories:

- No objects present: False calls placed when there was no vehicle or any other object over the detection zone or in the vicinity (including the adjacent lane) and when the gates were not moving.
- Gates moving: False calls placed when there was no vehicle over the detection zone or in the vicinity (including the adjacent lane) and when the gates were moving or in the down position.
- Bicycles and pedestrians: Activations placed by the radar units because of bicycles or pedestrians in the crossing. These calls were tallied only if no other vehicles were in or near the crossing, confirming that the activations were generated by a bicycle or a pedestrian.

In the algorithm, a call placed by the radar was considered a potential false call if there were no calls from the loop detectors within a reasonable time window. The algorithm identified the radar calls and then searched for a loop call placed between 1 second before the beginning of the radar call and 1 second after the call was terminated. Potential false calls were visually verified to determine if they were true false calls.

The percentage of false calls was estimated as the ratio of the number of false calls to the total number of calls placed by the radar in that zone. In practice, false calls can have adverse safety effects because the exit gates can remain in the up position or can be raised again if a detector call is placed when a train is present or approaching.

In this particular evaluation, activations generated by vehicles in the adjacent lanes were not considered false activations. For example, wide turning movements of a vehicle from the T- intersection adjacent to the crossing, which activated the two detection zones, were not considered a detection error after the video images were verified.

2.4 DROPPED CALLS

Dropped calls occur when radar 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 as for other types of error, video images were used to visually confirm dropped calls. Operationally, if a call placed by a vehicle is prematurely dropped, the exit gates may be lowered even though a vehicle is still occupying the crossing area. The percentage of dropped calls was calculated as the ratio of dropped calls to the total number of loop calls.

2.5 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 safety of the crossing because they may prevent the exit gates from being lowered, thus increasing chances of vehicles entering the conflicting areas when a train is present or approaching. The percentage of stuck-on calls was estimated as the ratio of the number of stuck-on calls to the total number of calls from the zone.

CHAPTER 3 PERFORMANCE IN GOOD WEATHER CONDITIONS

A summary of results from the good weather analysis is shown in Tables 1 and 2. These data serve as a benchmark for determining if the adverse weather has a significant effect on the performance of the system.

Tables 1 and 2 briefly summarize the findings included in Volume 3 of this evaluation. For all good weather datasets, 0.96% of the activations were false calls, 0.09% of vehicles were missed by only one of the radar units, none of the vehicles was missed when the two radar unit outputs were combined (systemwide), and there were zero stuck-on and zero dropped calls.

False calls were mostly generated when gates were moving up or down and almost exclusively resulted from calls in Radar 2 Lane 1 (see Table 2). Errors attributed to moving gates could be prevented by installing the radar units on poles separate from those holding the gates, thus preventing oscillation of the units and the detection areas when gates are moving, and by reducing the length of the detection zones so that the area of influence of the gates is excluded. None of the false calls was caused by motorcycles.

Table 1. Performance in Good Weather Conditions

Date	Activations		Trains	False Calls (including bicycles and pedestrians that radars detected but loops did not)					Missed Calls		Stuck-on Calls
	Radars 1 and 2 (All Zones)	Loops x 2 (All Zones)		Bicycles	Pedestrians	No Object	Gates Moving	TOTAL	Single Radar	System-wide	
Nov 17, 2012 (24 hr)	6,464	6,098	97	11	37	5	68	121	2	0	0
Nov 29, 2012 (24 hr)	7,733	7,106	133	0	8	6	13	27	2	0	0
Dec 14, 2012 (24 hr)	7,926	7,354	143	2	11	8	38	59	1	0	0
Dec 23, 2012 (24 hr)	5,392	5,454	63	2	15	36	41	94	6	0	0
Jan 8, 2013 (24 hr)	7,520	7,020	137	2	0	6	60	68	16	0	0
Jan 14, 2013 (24 hr)	6,738	6,304	124	0	8	0	25	33	7	0	0
TOTAL	**41,773**	**39,336**	**697**	**17**	**79**	**61**	**245**	**402**	**34**	**0**	**0**
				0.04%	**0.19%**	**0.15%**	**0.59%**	**0.96%**	**0.09%**	**0.00%**	**0.00%**

Table 2. Performance in Good Weather Condition by Radar and Lane

Weather and Time (a)	Sensor (b)	Activations		Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not)					Missed Calls **		Stuck-on Calls (m)
		Radar (c)	Loop † (d)		Bicycles (f)	Pedestrians (g)	No Object (h)	Gates Moving (i)	TOTAL (j)	Single Radar (k)	System-wide (l)	
Good Weather 5 days (120 hours)	Radar1Lane1	11,779	10,631	697	3	20	28	0	51	1	0	0
	Radar2Lane1	10,235	10,631		3	20	10	241	274	14	0	0
	Radar1Lane2	9,721	9,037		5	23	3	1	32	0	0	0
	Radar2Lane2	10,038	9,037		6	16	20	3	45	19	0	0
Total		**41,773**	**39,336**	**697**	**17**	**79**	**61**	**245**	**402**	**34**	**0**	**0**
					0.04%	**0.19%**	**0.15%**	**0.59%**	**0.96%**	**0.09%**	**0.00%**	**0.00%**

* The percentage of false calls is estimated as the number of false calls (total of column j) divided by the total number of calls placed by the radar units (total of column c).

** The percentage of missed calls is estimated as the ratio of the total of column k or l divided by the total of column d.

† Number of vehicles detected by loops is the total of column d divided by 2.

CHAPTER 4 DATASETS FOR ADVERSE WEATHER CONDITIONS

Datasets for the adverse weather analysis were selected based on the visual verification of such weather conditions using video recordings of the crossing, with the support of records from the weather station located at Midway Airport (about 10 miles from the site).

Specific times from multiple days were identified and selected to isolate the effects of each of the four conditions: rain, snow, fog, and wind. The rain conditions were further divided into normal rain and torrential rain. Similarly, the snow conditions were divided into light and heavy snow. Data archives collected and stored by the research team included time stamps and video recordings for almost every day of the evaluation period, allowing a comprehensive selection of situations.

The evaluation period started on November 14, 2012, after the modified (final) setup was available, and ended on June 21, 2013.

General characteristics of the selected datasets for the four adverse conditions are shown in Tables 3, 4, and 5. Specific periods of torrential rain are shaded in light gray, and these periods are supplemented by 1 or 2 hours of additional data before and after the torrential precipitation, as shown in Table 3. The supplemental data highlighted the brief effects of heavy rain, compared with the extended periods for lighter rain.

In addition to temperature and winds, Table 3 shows rain and snow precipitation data measured by the weather station as a rough estimation of the actual precipitation rates observed at the crossing. Table 4 shows visibility data in fog conditions, and Table 5 shows the range of the recorded wind and gust speeds in windy conditions.

Table 3. Selected Datasets for Rainy and Snow Conditions

Weather Condition	Date	Hours	Local Time		Precipitation (in)		Temperature (◦F)		Wind (mph)	Gusts (mph)	Observation
			From	To	Low	High	Low	High	Max	Max	
Light Rain	Dec 8, 2012	3.0	12:00am	3:00am	0.0/8 min	0.05/16 min	39.9	42.8	10.4	-	Light rain
	Dec 9, 2012	3.0	9:30am	12:30pm	0.01/15 min	0.06/5 min	39.2	39.9	11.5	-	Light rain
	Dec 20, 2012	7.5	12:00am	7:30am	0.02/20 min	0.18/30 min	41	44.1	24.2	33.4	Light rain
Heavy Rain	May 28, 2013	1.00	7:00pm	8:00pm	0	0	73.4	73.9	13.8	20.7	No Rain
		1.00	8:00pm	9:00pm	0.05/5 min	1.88/12 min	66.9	71.6	16.1	33.4	Torrential
		1.00	9:00pm	10:00pm	0	0	66.2	68	13.8	21.9	No Rain
	May 31, 2013	2.00	12:25am	2:25am	0.01/20 min	0.07/50 min	66	66.2	10.4	-	Light rain
		0.167	2:25am	2:35am	0.07/50 min	0.14/9 min	66.2	66.9	12.7	23	Torrential
		2.00	2:35am	4:35am	0.03/15 min	0.05/22 min	66.2	66.9	13.8	20.7	Light rain
	Jun 1, 2013	1.00	4:05pm	5:05pm	0.00/60 min	0.00/60 min	71.1	69.8	17.3	24.2	Light rain
		0.25	5:05pm	5:20pm	0.25/7 min	0.25/7 min	68	69.8	13.8	25.3	Torrential
		1.00	5:20pm	6:20pm	0.01/8 min	0.01/8 min	66	69.8	5.8	-	Light rain to no rain
	Jun 10, 2013	2.00	1:20am	3:20am	0.00/30 min	0.21/28 min	66.2	68	4.6	-	Light rain
		0.50	3:20am	3:50am	0.33/36 min	0.38/15 min	64.4	66	4.6	-	Torrential
		2.00	3:50am	5:50am	0.01/20 min	0.00/24 min	64.4	66.2	5.8	-	Light rain
Light Snow	Dec 28, 2012	0.33	10:20am	10:40am	0	0	30.2	32	8.1	-	Very light snow. Roadway partially covered with snow and no significant snow accumulation
	Dec 29, 2012	2	4:00am	6:00am	0	0	30.9	32	10.4	-	
	Dec 5, 2012	1	2:10pm	3:10pm	0	0	33.8	35.6	19.6	23	
	Jan 25, 2013	3.5	4:50am	8:20am	0.00/20 min	0.03/10 min	19	19.9	11.5	-	
Heavy Snow	Feb 1 and 2, 2013	8	10:00pm	6:00am	0.0/10 min	0.02/30 min	15.8	21.2	10.4	-	Roadway mostly covered with snow
	Feb 3 and 4, 2013	8	10:00pm	6:00am	0.0/10 min	0.01/8 min	21	23	10.4	-	Roadway mostly covered with snow
	Mar 5, 2013	9	9:00am	6:00pm	0.01/60 min	0.03 / 30 min	28.9	32	15	19.6	Freezing rain/ice falling and roadway partially covering with snow due to vehicle tire tracks
	Mar 5, 2013	6	6:00pm	12:00am	0.0/12 min	0.02/52 min	30	33.1	19.6	25.3	Freezing rain/ice continued and roadway partially covering with snow due to vehicle tire tracks. Camera covered with ice at the end of analysis period
	Feb 21 and 22, 2013	4	11:00pm	3:00am	0.0/25 min	0.05/34 min	24.1	26.6	19.6	25.3	Wet snow and flakes falling and road mostly covered with snow

Table 4. Selected Datasets for Fog Conditions

Weather Condition	Date	Hours	Local Time		Visibility (miles)		Temperature (◦F)		Wind (mph)	Gusts (mph)	Observation
			From	To	Low	High	Low	High	Max	Max	
Dense Fog	Jan 29, 2013	2	12:00am	2:00am	0.2	0.8	41	51.1	9.2	-	Dense fog and significantly reduced visibility from camera image
	Nov 21, 2012	3	4:00am	7:00am	0.1	0.2	37.9	39.9	4.6	-	
	Dec 3, 2012	3.5	12:30am	4:00am	0.1	0.2	46.4	50	3.5	-	

* Visibility in good weather conditions is reported as 10 miles.

Table 5. Selected Datasets for Windy Conditions

Weather Condition	Date	Hours	Local Time		Temperature (◦F)		Wind (mph)		Gusts (mph)		Observation
			From	To	Low	High	Low	High	Low	High	
Windy	Feb 11, 2013	8	7:00am	3:00pm	33.1	35.1	20	35.7	39.1	57.5	Image seems similar to good weather condition. No clear swaying because of wind
	Jan 19, 2013	4	8:00pm	12:00am	28	44.1	19.6	27.6	28.8	40.3	
	Dec 21, 2012	4	2:00am	6:00am	28.9	33.8	20.7	27.6	36.8	44.9	
	May 23, 2013	5	11:00am	4:00pm	46.4	51.1	21.9	33.4	27.6	41.4	

CHAPTER 5 ANALYSIS AND RESULTS

5.1 ANALYSIS OF RAIN DATA

A total of 13.5 hours of light rain and 13.9 hours of heavy rain was selected and analyzed for the rain conditions. To determine if a time period had heavy or light rain, the video images recorded at the crossing were used, along with data from the weather station. Figure 3 shows sample images of light and heavy rain conditions. In heavy rain, visibility is clearly reduced, and there is significant accumulation of water on the roadway.

(a) Light rain

(b) Heavy rain

Figure 3. Sample images of light and heavy rain conditions.

A summary of the results of the analysis for the rainy condition is shown in Table 6. The frequency of false calls increased when the precipitation intensity was the highest, reducing the visibility in the video images.

Table 6. Results from Rainy Conditions

Weather Condition	Date	Hours	Local Time		Activations		Trains	Measure of Performance				
								False	Missed		Stuck-on	Dropped
			From	To	Radars 1 and 2 (all zones)	Loops x 2 (all zones)			Single Radar	System-wide		
Light Rain	Dec 8, 2012	3.0	12:00am	3:00am	81	98	5	0.00%	0.00%	0.00%	0.00%	0.00%
	Dec 9, 2012	3.0	9:30am	12:30pm	1218	1240	7	0.08%	0.16%	0.00%	0.00%	0.00%
	Dec 20, 2012	7.5	12:00am	7:30am	621	620	31	5.80%	0.00%	0.00%	0.00%	0.00%
	Total	**13.5**	**n/a**		**1920**	**1958**	**43**	**1.93%**	**0.10%**	**0.00%**	**0.00%**	**0.00%**
Heavy Rain	May 28, 2013	1.0	7:00pm	8:00pm	424	420	5	1.18%	0.00%	0.00%	0.00%	0.00%
		1.0	8:00pm	9:00pm	336	222	3	27.08%	0.00%	0.00%	0.00%	0.00%
		1.0	9:00pm	10:00pm	177	186	5	0.56%	0.00%	0.00%	0.00%	0.00%
	May 31, 2013	2.0	1:25am	2:25am	52	54	6	3.85%	0.00%	0.00%	0.00%	0.00%
		0.167	2:25am	2:35am	19	2	1	78.95%	0.00%	0.00%	0.00%	0.00%
		2.0	2:35am	3:35am	6	6	1	0.00%	0.00%	0.00%	0.00%	0.00%
	Jun 1, 2013	1.0	4:05pm	5:05pm	542	512	4	0.92%	0.00%	0.00%	0.00%	0.00%
		0.25	5:05pm	5:20pm	141	96	1	24.82%	0.00%	0.00%	0.00%	0.00%
		1.0	5:20pm	6:20pm	378	366	4	0.00%	0.00%	0.00%	0.00%	0.00%
	Jun 10, 2013	2.0	1:20am	3:20am	19	20	4	0.00%	0.00%	0.00%	0.00%	0.00%
		0.5	3:20am	3:50am	15	0	0	100.00%	0.00%	0.00%	0.00%	0.00%
		2.0	3:50am	5:50am	119	134	4	0.00%	0.00%	0.00%	0.00%	0.00%
	Total	**13.9**	**n/a**		**2228**	**2018**	**38**	**7.58%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**

A detailed description of the errors for each radar and lane is shown in Tables 7 and 8. The results shown in Table 7 indicate that light rain conditions did not generate a significant change in the performance of the system, as observed in the light rain data from December 8 and 9 with 0.00% and 0.08% false calls, respectively. However, the false calls increased to 5.8% on December 20 mainly because of the calls generated when the gates were moving.

It is noted that the precipitation intensity was higher on December 20, compared with December 8 and 9 (up to 0.18 inch of rain on December 20, compared with up to 0.06 inch on December 9 and 8), which may have contributed to the increase in the frequency of false calls. On December 20, precipitation increased in the last 2 hours of the analysis period, and the system placed 19 of the 24 false calls when the gates were moving on Radar 2 Lane 1. Verification of the video images at the crossings showed the increase in precipitation, as reported by the weather station, but it did not seem enough to be classified as torrential rain.

In addition, similarities in the total number of calls by radar units and loops, as observed on December 20, are not an indication of the occurrence or errors. An explanation of why the total number of calls placed by the radar units plus the false calls minus the missed calls may not be equal to the number of loop calls is included in Section 2.1.

Table 7. Results from Light Rain Conditions by Radar and Lane

Date and Time (a)	Sensor (b)	Activations		Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not)					Missed Calls **	
		Radar (c)	Loop † (d)		Bicycles (f)	Pedestrians (g)	No Object (h)	Gates Moving (i)	Total (j)	Single Radar (k)	System-wide (l)
Dec 8, 2012 3 hours (12:00am - 3:00am)	Radar1Lane1	29	31	5	0	0	0	0	0	0	0
	Radar2Lane1	27	31		0	0	0	0	0	0	0
	Radar1Lane2	13	18		0	0	0	0	0	0	0
	Radar2Lane2	12	18		0	0	0	0	0	0	0
	Total	**81**	**98**	**5**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
Dec 9, 2012 3 hours (9:30am - 12:30pm)	Radar1Lane1	311	315	7	0	0	1	0	1	0	0
	Radar2Lane1	280	315		0	0	0	0	0	2	0
	Radar1Lane2	310	305		0	0	0	0	0	0	0
	Radar2Lane2	317	305		0	0	0	0	0	0	0
	Total	**1218**	**1240**	**7**	**0**	**0**	**1**	**0**	**1**	**2**	**0**
					0.00%	**0.00%**	**0.08%**	**0.00%**	**0.08%**	**0.16%**	**0.00%**
Dec 20, 2012 7.5 hours (12:00am - 7:30am)	Radar1Lane1	163	164	31	0	0	9	0	9	0	0
	Radar2Lane1	164	164		0	0	0	24	24	0	0
	Radar1Lane2	146	146		0	1	0	0	1	0	0
	Radar2Lane2	148	146		0	2	0	0	2	0	0
	Total	**621**	**620**	**31**	**0**	**3**	**9**	**24**	**36**	**0**	**0**
					0.00%	**0.48%**	**1.45%**	**3.86%**	**5.80%**	**0.00%**	**0.00%**

* The percentage of false calls is estimated as the number of false calls (total of column j) divided by the total number of calls placed by the radar units (total of column c).

** The percentage of missed calls is estimated as the ratio of the total of column k or *l* divided by the total of column d.

† Number of vehicles detected by loops is the total of column d divided by 2.

Results from specific periods of torrential rain are shown in Table 8; note that this table does not include the results from the supplemental data with light rain before and after the torrential rain. During periods of substantial traffic flow in the crossing and under torrential rain (such as on May 28 and June 1), false calls varied from 24.82% to 27.08%. However, when there was torrential rain but no traffic flow (May 31) or only one car (June 10), the radar units generated 15 false calls on each of these 2 days, which indicated that 78.95% and 100% of the calls were false, respectively. All false calls during torrential rain were generated when there were no objects in the crossing and the gates were in the upright position (column h in Table 8). These results contrast with results from good weather conditions, for which this type of false calls had a low frequency (0.15%).

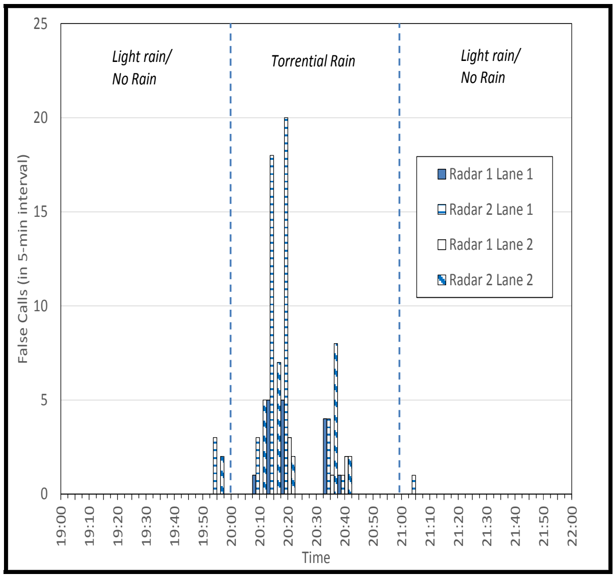
Table 8. Results from Heavy Rain Conditions by Radar and Lane (Torrential Rain Only)

Date and Time (a)	Sensor (b)	Activations		Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not)					Missed Calls **		Stuck-on Calls (m)
		Radar (c)	Loop † (d)		Bicycles (f)	Pedestrians (g)	No Object (h)	Gates Moving (i)	Total (j)	Not detected by subject radar in any lane (k)	Not detected by any radar in any lanes (l)	
May 28, 2013 1 hour (8:00pm - 9:00pm)	Radar1Lane1	77	60	5	0	0	16	0	16	0	0	0
	Radar2Lane1	111	60		0	0	46	0	46	0	0	0
	Radar1Lane2	65	51		0	0	7	0	7	0	0	0
	Radar2Lane2	83	51		0	0	22	0	22	0	0	2
	Total	**336**	**222**	**5**	**0**	**0**	**91**	**0**	**91**	**0**	**0**	**2**
					0.00%	**0.00%**	**27.08%**	**0.00%**	**27.08%**	**0.00%**	**0.00%**	**0.60%**
May 31, 2013 10 minutes (2:25am - 2:35am)	Radar1Lane1	3	1	1	0	0	2	0	2	0	0	0
	Radar2Lane1	13	1		0	0	9	0	9	0	0	0
	Radar1Lane2	1	0		0	0	1	0	1	0	0	0
	Radar2Lane2	2	0		0	0	3	0	3	0	0	0
	Total	**19**	**2**	**1**	**0**	**0**	**15**	**0**	**15**	**0**	**0**	**0**
					0.00%	**0.00%**	**78.95%**	**0.00%**	**78.95%**	**0.00%**	**0.00%**	**0.00%**
June 1, 2013 15 minutes (5:05pm - 5:20pm)	Radar1Lane1	38	26	1	0	0	6	0	6	0	0	0
	Radar2Lane1	30	26		0	0	3	0	3	0	0	0
	Radar1Lane2	31	22		0	0	6	0	6	0	0	0
	Radar2Lane2	42	22		0	0	20	0	20	0	0	0
	Total	**141**	**96**	**1**	**0**	**0**	**35**	**0**	**35**	**0**	**0**	**0**
					0.00%	**0.00%**	**24.82%**	**0.00%**	**24.82%**	**0.00%**	**0.00%**	**0.00%**
June 10, 2013 30 minutes (3:20am - 3:50am)	Radar1Lane1	2	0	0	0	0	2	0	2	0	0	0
	Radar2Lane1	2	0		0	0	2	0	2	0	0	0
	Radar1Lane2	10	0		0	0	10	0	10	0	0	0
	Radar2Lane2	1	0		0	0	1	0	1	0	0	0
	Total	**15**	**0**	**0**	**0**	**0**	**15**	**0**	**15**	**0**	**0**	**0**
					0.00%	**0.00%**	**100.00%**	**0.00%**	**100.00%**	**0.00%**	**0.00%**	**0.00%**

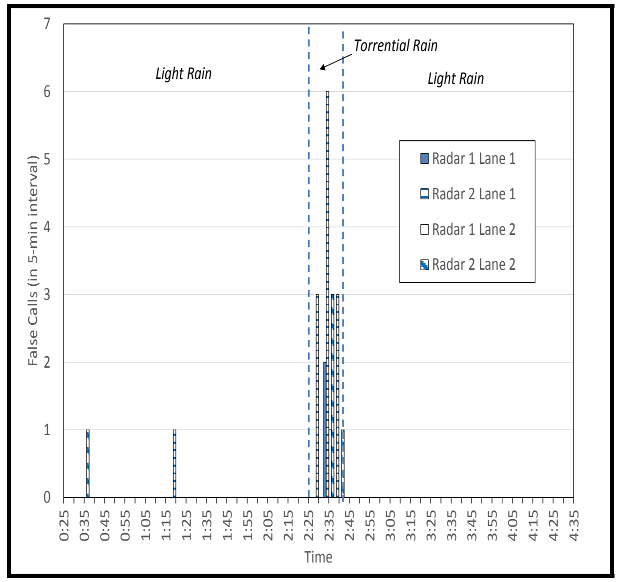
* The percentage of false calls is estimated as the number of false calls (total of column j) divided by the total number of calls placed by the radar units (total of column c).

† Number of vehicles detected by loops is the total of column d divided by 2.

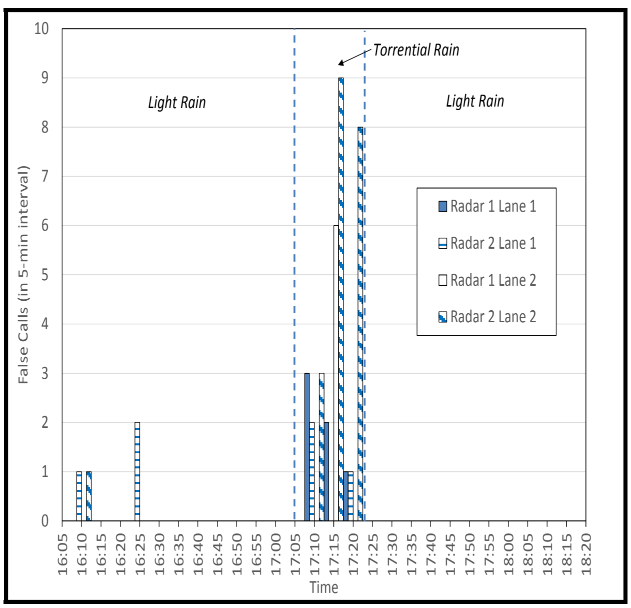
Figure 4 shows the sudden increase in false calls during brief periods with torrential rain, for which the number of false calls in 5-minute intervals is plotted over time for each radar and zone. The time frame in the horizontal axis includes periods before and after torrential precipitation to highlight the local and short effects of this weather condition on the system.



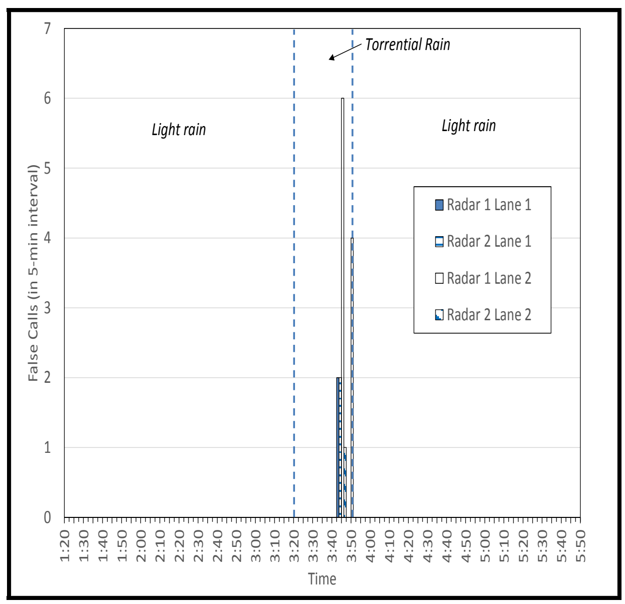
(a) Data from May 28



(b) Data from May 31



(c) Data from June 1



(d) Data from June 10

Figure 4. Frequency of false calls over time before, during, and after torrential rain.

In addition, the duration of the false calls in the heavy rain datasets is shown in Figure 5. Most of the false calls (53.2%) lasted for 2 seconds or less, but others remained on for a longer time, the longest being a call that lasted 117 seconds in Radar 2 Lane 2. On average, the longest false calls were observed in Radar 2 Lane 2, followed by those in Radar 1 Lane 1.

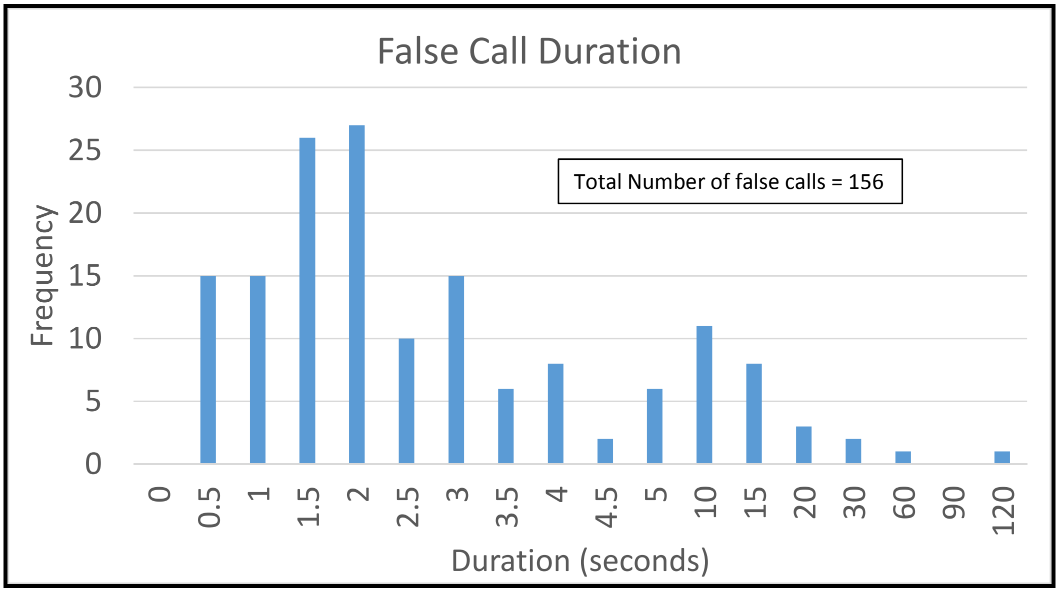
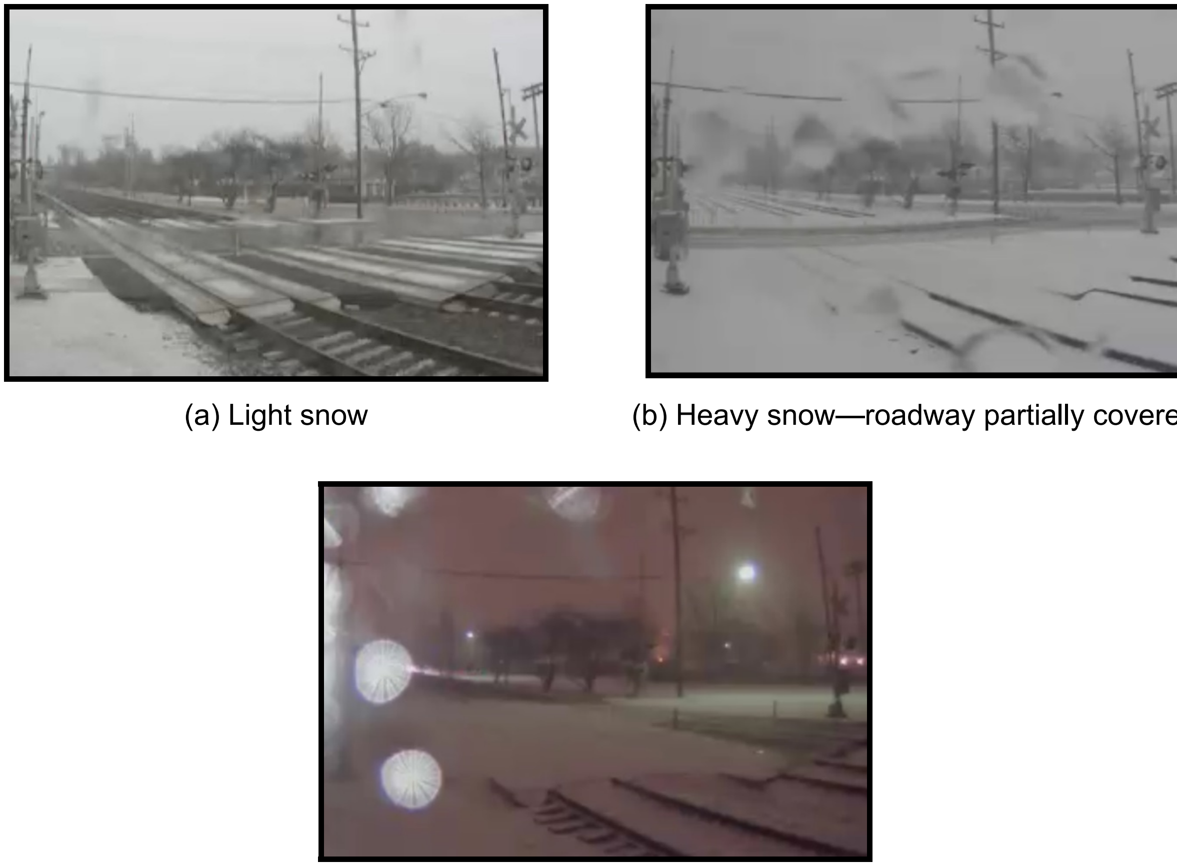


Figure 5. Distribution of false call duration in heavy rain datasets.

5.2 ANALYSIS OF SNOW DATA

A total of 6.8 hours of light snow and 35 hours of heavy snow were analyzed. Light snow refers to conditions in which snowfall is not accompanied with significant reduction in visibility or snow accumulation on the roadway. By contrast, heavy snow refers to conditions in which snow accumulation is significant and snow fully or partially covers the roadway. Heavy snow includes snowfall, ice, or freezing rain. Details on the specific conditions for each of the selected datasets are shown in Table 3. Sample images of light snow and heavy snow with the roadway fully and partially covered with snow are shown in Figure 6.



(a) Light snow

(b) Heavy snow—roadway partially covered

(c) Heavy snow—roadway completely covered

Figure 6. Sample images of light and heavy snow conditions.

A summary of the analysis of the snow data is shown in Table 9. The performance of the system in light and heavy snow was significantly different. However, the performance of the system in light snow was quite similar to the performance observed in good weather conditions. Specifically, false calls were 1.66% (compared with 0.96% in good weather), and missed calls by single radar were 0.2% (compared with 0.09% in good weather).

A total of 0.58% stuck-on calls was generated in light snow and are described in more detail in Table 10. No systemwide missed calls or dropped calls were observed in light snow conditions.

Table 9. Results from Snow Conditions

Weather Condition	Date	Hours	Local Time		Activations		Trains	Measure of Performance				
								False	Missed		Stuck-on	Dropped
			From	To	Radars 1 and 2 (all zones)	Loops x 2 (all zones)			Single Radar	System-wide		
Light Snow	Dec 28, 2012	0.33	10:20am	10:40am	151	160	0	0.00%	0.00%	0.00%	0.00%	0.00%
	Dec 29, 2012	2.0	4:00am	6:00am	27	36	3	3.70%	5.56%	0.00%	0.00%	0.00%
	Jan 5, 2013	1.0	2:10pm	3:10pm	406	396	6	3.20%	0.00%	0.00%	0.00%	0.00%
	Jan 25, 2013	3.5	4:50am	8:20am	1040	912	36	1.25%	0.11%	0.00%	0.58%	0.00%
	Total	**6.8**	**n/a**		**1624**	**1504**	**45**	**1.66%**	**0.20%**	**0.00%**	**0.37%**	**0.00%**
Heavy Snow	Feb 1 and 2, 2013	8.0	10:00pm	6:00am	438	538	15	3.88%	0.37%	0.00%	0.00%	0.00%
	Feb 3 and 4, 2013	8.0	10:00pm	6:00am	289	360	15	3.81%	5.28%	1.11%	0.00%	0.00%
	Mar 5, 2013	9.0	9:00am	6:00pm	2383	3216	58	4.11%	16.04%	13.50%	2.60%	0.00%
	Mar 5, 2013	6.0	6:00pm	12:00am	330	744	31	0.00%	18.01%	18.95%	0.00%	0.00%
	Feb 21 and 22, 2013	4.0	11:00pm	3:00am	98	108	14	12.24%	0.00%	0.00%	0.00%	0.00%
	Total	**35.0**	**n/a**		**3538**	**4966**	**133**	**3.90%**	**13.51%**	**11.66%**	**1.75%**	**0.00%**

The results observed in heavy snow were significantly different in terms of false, missed, and stuck-on calls. Overall, false calls increased to 3.9% for all heavy snow datasets together. On the dataset corresponding to February 21 and 22, for instance, false calls were 12.24% during periods of wet snow, when snow accumulation almost completely covered the roadway and tire marks were clearly visible on the surface.

System performance during heavy snow was significantly different in terms of missed calls. The percentage of vehicles missed by a single radar unit increased to 13.51% for all datasets combined (from 0.09% in good weather), and the percentage of systemwide missed calls (missed by both radar units) increased to 11.66% (from 0% in good weather). Most missed calls were generated on March 5, when the roadway was partially covered with snow accompanied by freezing rain/ice and snow partially covered the crossing.

In addition, stuck-on calls increased in heavy snow, with a frequency of 2.6% on March 5. Stuck-on calls were not observed in any other datasets selected for heavy snow conditions.

An additional breakdown of errors by radar and lane in light and heavy snow conditions and a breakdown of the types of false calls are shown in Tables 10 and 11, respectively.

Table 10. Results from Light Snow Conditions by Radar and Lane

Date and Time (a)	Sensor (b)	Activations		Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not)					Missed Calls **		Stuck-on Calls (m)
		Radar (c)	Loop † (d)		Bicycles (f)	Pedestrians (g)	No Object (h)	Gates Moving (i)	Total (j)	Single Radar (k)	System-wide (l)	
Dec 28, 2012 20 minutes (10:20am - 10:40pm)	Radar1Lane1	39	39	0	0	0	0	0	0	0	0	0
	Radar2Lane1	34	39		0	0	0	0	0	0	0	0
	Radar1Lane2	38	41		0	0	0	0	0	0	0	0
	Radar2Lane2	40	41		0	0	0	0	0	0	0	0
	Total	**151**	**160**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
Dec 29, 2012 2 hours (4:00am - 6:00am)	Radar1Lane1	7	9	3	0	0	0	0	0	0	0	0
	Radar2Lane1	5	9		0	0	0	0	0	1	0	0
	Radar1Lane2	8	9		0	0	0	0	0	0	0	0
	Radar2Lane2	7	9		0	0	1	0	1	1	0	0
	Total	**27**	**36**	**3**	**0**	**0**	**1**	**0**	**1**	**2**	**0**	**0**
					0.00%	**0.00%**	**3.70%**	**0.00%**	**3.70%**	**5.56%**	**0.00%**	**0.00%**
Jan 5, 2013 1 hour (2:10pm - 3:10pm)	Radar1Lane1	107	104	6	0	1	0	0	1	0	0	0
	Radar2Lane1	101	104		0	0	0	10	10	0	0	0
	Radar1Lane2	98	94		0	1	0	0	1	0	0	0
	Radar2Lane2	100	94		0	1	0	0	1	0	0	0
	Total	**406**	**396**	**6**	**0**	**3**	**0**	**10**	**13**	**0**	**0**	**0**
					0.00%	**0.74%**	**0.00%**	**2.46%**	**3.20%**	**0.00%**	**0.00%**	**0.00%**
Jan 25, 2013 3.5 hours (4:50am - 8:20am)	Radar1Lane1	242	218	36	0	0	0	0	0	0	0	0
	Radar2Lane1	207	218		0	0	0	13	13	0	0	0
	Radar1Lane2	277	238		0	0	0	0	0	0	0	3
	Radar2Lane2	314	238		0	0	0	0	0	1	0	3
	Total	**1040**	**912**	**36**	**0**	**0**	**0**	**13**	**13**	**1**	**0**	**6**
					0.00%	**0.00%**	**0.00%**	**1.25%**	**1.25%**	**0.11%**	**0.00%**	**0.58%**

* The percentage of false calls is estimated as the number of false calls (total of column j) divided by the total number of calls placed by the radar units (total of column c).

** The percentage of missed calls is estimated as the ratio of the total of column k or l divided by the total of column d.

† Number of vehicles detected by loops is the total of column d divided by 2.

Table 10 shows that the distribution of the detection errors in light snow follows a similar trend to that in good weather. Radar 2 Lane 1 created false calls when the gates were moving or in the lowered position, and only a few missed calls were generated by Radar 1. It was also observed that no false or missed calls were found in December 28 dataset although the gates were not lowered because there were no trains during the 20-minute period analyzed, and the total traffic volume during this period was low (about 40 vehicles).

Each of the two radar units generated three stuck-on calls on January 25, and all of them occurred at a different time, indicating that the analysis for the two radar units combined will result in the same number of errors. For each radar, the three stuck-on calls happened within 5 minutes and were dropped after a second vehicle traveled over the zone. The video recordings showed no objects in the crossing during the stuck-on calls, so there was no clear reason for these events. Stuck-on calls by Radar 1 lasted between 7 and 15 seconds, whereas the stuck-on calls generated by Radar 2 lasted between 23 and 54 seconds.

By contrast, during heavy snow the frequency of false, missed, and stuck-on calls increased significantly. Table 11 shows that false activations were generated when no objects were on the crossing or when the gates were moving, and most of them were placed by Radar 2 Lane 1.

In heavy snow, missed calls increased in the two radar units and all zones, which indicated a widespread weather effect throughout the system. Missed calls were observed for a single radar unit at a time and also when the outputs from the two radar units were combined (systemwide). Visual verification of the missed calls did not show a particular trend in terms of the types of missed vehicles. It must be noted that missed calls did not increase in all datasets in the heavy snow conditions, but they were mostly limited to the two datasets from March 5. On March 5, many vehicles were simply not detected, and systemwide missed calls accounted for 13.5% in the first dataset, and 18.95% in the second dataset, as observed in Table 11. It is unclear why these missed calls occurred, but on March 5, there were snow and freezing rain/ice, unlike conditions for the other selected datasets. Moreover, the missed calls increased in the second dataset on March 5, when traffic volume was significantly lower, and ice accumulation on the radar units and the roadway could have been greater.

Table 11. Results from Heavy Snow Conditions by Radar and Lane

Date and Time (a)	Sensor (b)	Activations		Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not)					Missed Calls **	
		Radar (c)	Loop † (d)		Bicycles (f)	Pedestrians (g)	No Object (h)	Gates Moving (i)	Total (j)	Single Radar (k)	System-wide (l)
Feb 2, 2013 8 hours (10:00pm - 6:00am)	Radar1Lane1	115	144	15	0	0	1	0	1	0	0
	Radar2Lane1	127	144		0	0	2	14	16	0	0
	Radar1Lane2	101	125		0	0	0	0	0	0	0
	Radar2Lane2	95	125		0	0	0	0	0	2	0
	Total	**438**	**538**	**15**	**0**	**0**	**3**	**14**	**17**	**2**	**0**
					0.00%	**0.00%**	**0.68%**	**3.20%**	**3.88%**	**0.37%**	**0.00%**
Feb 4, 2013 8 hours (10:00pm - 6:00am)	Radar1Lane1	75	88	15	0	0	1	0	1	1	1
	Radar2Lane1	77	88		0	0	0	8	8	5	1
	Radar1Lane2	70	92		0	0	1	0	1	0	1
	Radar2Lane2	67	92		0	0	1	0	1	13	1
	Total	**289**	**360**	**15**	**0**	**0**	**3**	**8**	**11**	**19**	**4**
					0.00%	**0.00%**	**1.04%**	**2.77%**	**3.81%**	**5.28%**	**1.11%**
Mar 5, 2013 9 hours (9:00am - 6:00pm)	Radar1Lane1	622	871	58	0	0	9	2	11	206	93
	Radar2Lane1	854	871		0	0	40	10	50	95	95
	Radar1Lane2	564	737		0	0	15	6	21	8	125
	Radar2Lane2	343	737		0	0	9	7	16	207	121
	Total	**2,383**	**3,216**	**58**	**0**	**0**	**73**	**25**	**98**	**516**	**434**
					0.00%	**0.00%**	**3.06%**	**1.05%**	**4.11%**	**16.04%**	**13.50%**
Mar 5, 2013 6 hours (6:00pm - 12:00am)	Radar1Lane1	63	193	31	0	0	0	0	0	88	32
	Radar2Lane1	166	193		0	0	0	0	0	5	32
	Radar1Lane2	59	179		0	0	0	0	0	7	39
	Radar2Lane2	42	179		0	0	0	0	0	34	38
	Total	**330**	**744**	**31**	**0**	**0**	**0**	**0**	**0**	**134**	**141**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**18.01%**	**18.95%**
Feb 22, 2013 4 hours (11:00pm - 3:00am)	Radar1Lane1	26	28	14	0	0	1	0	1	0	0
	Radar2Lane1	37	28		0	0	0	11	11	0	0
	Radar1Lane2	16	26		0	0	0	0	0	0	0
	Radar2Lane2	19	26		0	0	0	0	0	0	0
	Total	**98**	**108**	**14**	**0**	**0**	**1**	**11**	**12**	**0**	**0**
					0.00%	**0.00%**	**1.02%**	**11.22%**	**12.24%**	**0.00%**	**0.00%**

* The percentage of false calls is estimated as the number of false calls (total of column j) divided by the total number of calls placed by the radar units (total of column c).

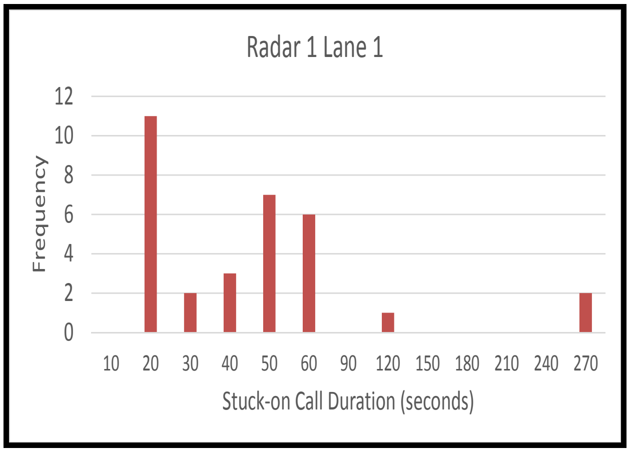
** The percentage of missed calls is estimated as the ratio of the total of column k or l divided by the total of column d.

† Number of vehicles detected by loops is the total of column d divided by 2.

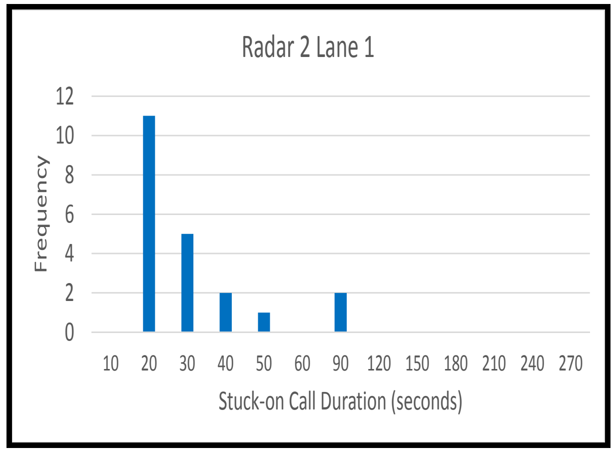
Given the increased frequency of missed calls in heavy snow, further analysis was conducted to find the actual number of vehicles (not calls) not detected by the radar units and their corresponding direction of travel, as well as a comparison of the duration of the activations from loops and radar units. Results of this analysis are included in the appendix of this report.

In terms of stuck-on calls, an increase in this type of call was observed in the heavy snow data of March 5. Stuck-on calls were found in the two radar units and all zones, which indicated widespread effects in the system. Although some of the stuck-on calls were terminated after a second vehicle left the crossing, others persisted after multiple vehicles had entered and left the crossing. Only three of the stuck-on calls occurred in both radar units simultaneously (one in Lane 1 and two in Lane 2), indicating that the two radar units combined had 59 errors (almost the same 62 errors as for the radar units individually). The average duration of stuck-on calls from the two radar units and in the two lanes was

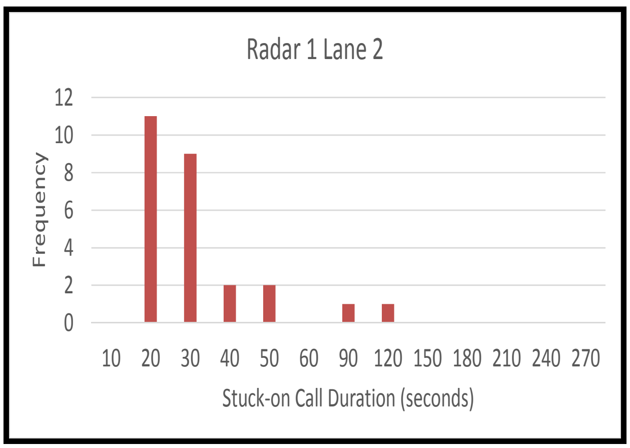
37 seconds, ranging between 10 and 270 seconds. The distributions of the stuck-on durations by lane and radar are shown in Figure 7.



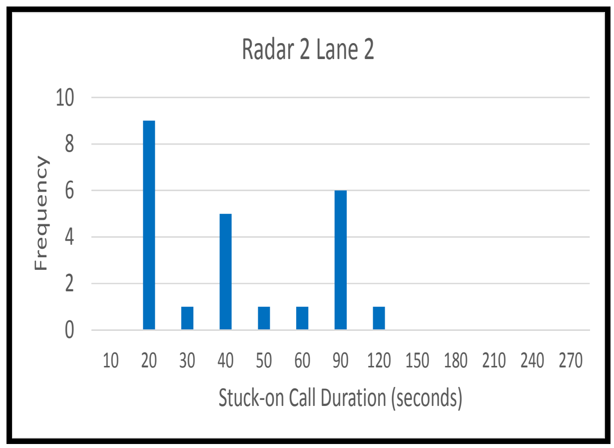
(a) Radar 1 Lane 1



(b) Radar 2 Lane 1



(c) Radar 1 Lane 2



(d) Radar 2 Lane 2

Figure 7. Distribution of stuck-on calls in heavy snow from March 5, 2013.

5.3 ANALYSIS OF FOG DATA

A total of 8.5 hours of dense fog from three different days was selected for analyzing this weather condition. Only periods with continuous dense fog were analyzed, as shown in the weather data in Table 3. Visibility ranged between 0.2 and 0.8 miles (visibility in clear conditions is 10 miles). Sample images of dense fog conditions are shown in Figure 8.

(a) Clear Conditions

(b) Dense Fog

Figure 8. Sample images of clear and dense fog conditions.

A summary of the analysis of dense fog is shown in Table 12. In general, the collected data show that the presence of fog did not affect the system in terms of missed, stuck-on, or dropped calls. However, in two of the three datasets, false calls increased to 11.54% and 27.27% but remained at 0% in the third dataset. It is also noted that the number of activations from radar units and loops was the same on the data from November 21, but the radar units had many false calls. The reason why the total number of calls placed by the radar units plus the false calls may not be equal to the number of loop calls is explained in Section 2.1.

Table 12. Results from Dense Fog Conditions

Weather Condition	Date	Hours	Local Time		Activations		Trains	Measure of Performance				
			From	To	Radars 1 and 2 (all zones)	Loops x 2 (all zones)		False	Missed: Single Radar	Missed: System-wide	Stuck-on	Dropped
Dense Fog	Jan 29, 2013	2.0	12:00am	2:00am	14	16	6	0.00%	0.00%	0.00%	0.00%	0.00%
	Nov 21, 2012	3.0	4:00am	7:00am	260	260	17	11.54%	0.00%	0.00%	0.00%	0.00%
	Dec 3, 2012	3.5	12:30am	4:00am	11	8	4	27.27%	0.00%	0.00%	0.00%	0.00%
	Total	**8.5**	**n/a**		**285**	**284**	**27**	**11.58%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**

The distribution of false calls by radar and lane, as well as the types of false calls observed in dense fog, is shown in Table 13. All false calls in dense fog occurred when the gates were moving or down, contrary to rain conditions, in which most false calls occurred when no objects were on the crossing. False calls caused by moving gates may be prevented by installing the radar units on poles separate from those holding the gates and by modifying the zones in a way that prevents gates from interfering with the detection even when the gates are moving.

In general, the analysis of fog data did not indicate any particular performance concerns.

Table 13. Results from Dense Fog Conditions by Radar and Lane

Date and Time (a)	Sensor (b)	Activations		Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not)					Missed Calls **		Stuck-on Calls (m)
		Radar (c)	Loop † (d)		Bicycles (f)	Pedestrians (g)	No Object (h)	Gates Moving (i)	Total (j)	Not detected by subject radar in any lane (k)	Not detected by any radar in any lanes (l)	
Jan 29, 2013 2 hours (12:00am - 2:00am)	Radar1Lane1	4	5	6	0	0	0	0	0	0	0	0
	Radar2Lane1	4	5		0	0	0	0	0	0	0	0
	Radar1Lane2	3	3		0	0	0	0	0	0	0	0
	Radar2Lane2	3	3		0	0	0	0	0	0	0	0
	Total	**14**	**16**	**6**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
Nov 21, 2012 3 hours (4:00am - 7:00am)	Radar1Lane1	52	64	17	0	0	0	0	0	0	0	0
	Radar2Lane1	78	64		0	0	0	30	30	0	0	0
	Radar1Lane2	64	66		0	0	0	0	0	0	0	0
	Radar2Lane2	66	66		0	0	0	0	0	0	0	0
	Total	**260**	**260**	**17**	**0**	**0**	**0**	**30**	**30**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**11.54%**	**11.54%**	**0.00%**	**0.00%**	**0.00%**
Dec 3, 2012 3.5 hours (12:30am - 4:00am)	Radar1Lane1	2	2	4	0	0	0	0	0	0	0	0
	Radar2Lane1	5	2		0	0	0	3	3	0	0	0
	Radar1Lane2	2	2		0	0	0	0	0	0	0	0
	Radar2Lane2	2	2		0	0	0	0	0	0	0	0
	Total	**11**	**8**	**4**	**0**	**0**	**0**	**3**	**3**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**27.27%**	**27.27%**	**0.00%**	**0.00%**	**0.00%**

* The percentage of false calls is estimated as the number of false calls (total of column j) divided by the total number of calls placed by the radar units (total of column c).

** The percentage of missed calls is estimated as the ratio of the total of column k or l divided by the total of column d.

† Number of vehicles detected by loops is the total of column d divided by 2.

5.4 ANALYSIS OF WIND DATA

A total of 21 hours of data was selected and analyzed for windy conditions. The dataset selection was based primarily on wind and gust records obtained from the weather station. Sustained wind speeds of 20 mph to 36 mph and gust speeds of 28 mph to 57 mph were registered at the weather station during the selected datasets. It was noted that the wind did not cause visible swaying or oscillation of the radar units, and no other weather events were observed from the video images.

A summary of the performance of the system in windy conditions is shown in Table 14. The results indicate that the frequency and type of errors in the selected datasets were similar to those of good weather conditions. False calls in the wind data were 0.59%, compared with 0.96% in good weather; and missed calls from a single radar unit were 0.07%, compared with 0.09% in good weather. No systemwide missed calls, stuck-on calls, or dropped calls were found in the datasets.

Table 14. Results from Windy Conditions

Weather Condition	Date	Hours	Local Time		Activations		Trains	Measure of Performance				
								False	Missed		Stuck-on	Dropped
			From	To	Radars 1 and 2 (all zones)	Loops x 2 (all zones)			Single Radar	System-wide		
Windy	Feb 11, 2013	8.0	7:00am	3:00pm	3921	3592	47	0.08%	0.00%	0.00%	0.00%	0.00%
	Jan 19, 2013	4.0	8:00pm	12:00am	635	670	12	0.63%	0.00%	0.00%	0.00%	0.00%
	Dec 21, 2012	4.0	2:00am	6:00am	104	124	6	5.77%	0.00%	0.00%	0.00%	0.00%
	May 23, 2013	5.0	11:00am	4:00pm	3024	2720	25	1.06%	0.18%	0.00%	0.00%	0.00%
	Total	**21.0**	**n/a**		**7684**	**7106**	**90**	**0.59%**	**0.07%**	**0.00%**	**0.00%**	**0.00%**

A breakdown of the false and missed calls by radar and lane is shown in Table 15. Similar to the results obtained in good weather conditions, the false calls in all datasets were generated when the gates were either moving or down. The missed calls generated by a single radar unit occurred in Radar 2, but their frequency was very low. In general, for this particular installation the wind did not affect the performance of the system.

Table 15. Results from Windy Conditions by Radar and Lane

Date and Time (a)	Sensor (b)	Activations		Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not)					Missed Calls **	
		Radar (c)	Loop † (d)		Bicycles (f)	Pedestrians (g)	No Object (h)	Gates Moving (i)	Total (j)	Single Radar (k)	System-wide (l)
Feb 11, 2013 8 hours (7:00am - 3:00pm)	Radar1Lane1	969	908	47	0	0	0	0	0	0	0
	Radar2Lane1	816	908		0	0	0	3	3	0	0
	Radar1Lane2	1,045	888		0	0	0	0	0	0	0
	Radar2Lane2	1,091	888		0	0	0	0	0	0	0
	Total	**3,921**	**3,592**	**47**	**0**	**0**	**0**	**3**	**3**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.08%**	**0.08%**	**0.00%**	**0.00%**
Jan 19, 2013 4 hours (8:00pm - 12:00am)	Radar1Lane1	188	193	12	0	0	0	0	0	0	0
	Radar2Lane1	171	193		0	0	0	4	4	0	0
	Radar1Lane2	137	142		0	0	0	0	0	0	0
	Radar2Lane2	139	142		0	0	0	0	0	0	0
	Total	**635**	**670**	**12**	**0**	**0**	**0**	**4**	**4**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.63%**	**0.63%**	**0.00%**	**0.00%**
Dec 21, 2012 4 hours (2:00am - 6:00am)	Radar1Lane1	27	29	6	0	0	0	0	0	0	0
	Radar2Lane1	26	29		0	0	0	4	4	0	0
	Radar1Lane2	25	33		0	0	0	0	0	0	0
	Radar2Lane2	26	33		0	0	2	0	2	0	0
	Total	**104**	**124**	**6**	**0**	**0**	**2**	**4**	**6**	**0**	**0**
					0.00%	**0.00%**	**1.92%**	**3.85%**	**5.77%**	**0.00%**	**0.00%**
May 23, 2013 5 hours (11:00am - 4:00pm)	Radar1Lane1	849	745	25	0	0	0	0	0	0	0
	Radar2Lane1	774	745		0	0	0	31	31	2	0
	Radar1Lane2	684	615		0	0	0	0	0	0	0
	Radar2Lane2	717	615		0	0	0	1	1	3	0
	Total	**3,024**	**2,720**	**25**	**0**	**0**	**0**	**32**	**32**	**5**	**0**
					0.00%	**0.00%**	**0.00%**	**1.06%**	**1.06%**	**0.18%**	**0.00%**

* The percentage of false calls is estimated as the number of false calls (total of column j) divided by the total number of calls placed by the radar units (total of column c).

** The percentage of missed calls is estimated as the ratio of the total of column k or l divided by the total of column d.

† Number of vehicles detected by loops is the total of column d divided by 2.

5.5 COMMENTS ON THE PERFORMANCE OF INDUCTIVE LOOPS

In the process of evaluating the performance of the radar vehicle detection system, the activations placed by the inductive loops were indirectly verified.

Because discrepancies between loop detectors and radar units were flagged as pointers for potential errors, a human observer (using the videos from the crossing) had to visually confirm that such discrepancies were in fact errors. If discrepancies were observed as a result of false loop activations or vehicles not detected by the loops but detected by the radar units, the loop errors were recorded and are reported in this section.

As described in Volume 3 of this study (Medina, Benekohal, and Ramezani, 2013), two very long stuck-on calls by the loops (lasting 6 and 8 hours) were observed in two different days in good weather conditions. The radar system detected seven motorcycles that the loops failed to detect.
In adverse weather conditions, the following two situations were observed in relation to loop performance:

- A call was generated by the loops in the two lanes after lighting struck near the crossing during heavy (torrential) rain (May 28 dataset). The call lasted 35 seconds before it dropped in the two lanes and the loop operation went back to normal.

- The loops failed to detect two motorcycles that were detected by the radar units (November 21 dataset). This dataset was one of those selected for dense fog analysis.

No additional detection errors by the loops were observed in the datasets selected for adverse weather analysis.

5.6 RESPONSE FROM VENDOR ON SYSTEM PERFORMANCE

The response from the system vendor (ByStep LLC/Island Radar Company LLC–Island Radar) to the results presented in this report are included in this section. The vendor comments (shown in italics) are added to the report as they can provide guidance on possible explanations for detection errors, as well as potential actions to reduce their frequency. The following is the transcript of the vendor response after examining the outcomes of the evaluation. It should be noted that these claims represent the opinion of the vendor and NOT that of the research team.

Vendor Claims Begin Here.

"In our opinion, the abnormally high number of missed detections and false detections during heavy snow and torrential rain conditions were the result of three distinct causal factors—inaccurate zone placement and dimensions, incorrect attenuation settings, and a latent queue forming feature originally established for traffic intersection applications.

<u>Missed and False Detections Due to Inaccurate Zone Positioning and Dimensioning</u>

Until very recently, zone settings have been an empirical process with final adjustments made by observing detection patterns of vehicles traveling through the crossing island. In recent observations made with improved zone placement and configuration tools, it has been found that zone positions and dimensions were not optimum, likely contributing to both false detection and missed detection outcomes.

<u>Missed Detections during Heavy Snow Conditions</u>

Prior to the commencement of this latest test phase, Island Radar adjusted the placement of zones and sensor sensitivity settings to optimize results.

- *Attenuation Setting:*

  In addition, there have been instances of false detection events due to gate movement and heavy rain. To minimize such false detection events, it has been Island Radar's practice to attenuate radar sensor sensitivity by applying between 4dB to 6 dB of attenuation. Based on substantial experience and because the crossing was outfitted with two sensors on opposing sides of the site, it was not expected this reduced sensitivity intended to minimize false detections would result in any missed detections.

- *Background Processing and the Effect of Attenuation on Detection Thresholds:*

  Until recently, the first phase of the radars' detection process ignored returned radar emissions that did were not at least 9dB greater than the radar "background" within the sensors' field of view. This 5 dB of applied attenuation intended to increase false detection immunity actually increased the absolute detection threshold to 14 dB above background (9dB plus 5dB).

- *The Effect of Tire Rutting in Slushy Snow on Detection Thresholds:*

  Until recently, the effect of "bright spots" that occur in the background as a result of periodic tire rutting that may occur in heavy, slushy snow also elevated this absolute detection threshold by an additional amount.

- *Overall Effect on Missed Detections:*

After reviewing results with Wavetronix, it is our belief that the combination of applied attenuation and increases in background levels due to slushy snow elevated the absolute detection threshold to a level where vehicles were missed altogether—despite the use of multiple radar sensors operating collaboratively.

Queue Forming Feature and Resulting False Detection Events

- *Original Purpose of the Queue Forming Feature:*

  Early in the development of Wavetronix radar sensors for traffic intersection use, a feature was included that effectively merged vehicles together into one very long, "virtual vehicle," thereby assuring presence detection across partially occupied radar detection zones. Until very recently, Island Radar was not aware of this feature and it did not occur to Wavetronix application engineers that the feature might be detrimental in railroad applications.

- *Effect of Queue Forming on Railroad Applications:*

  While the periodic merging of vehicles in the same lane has been observed in the past, it was assumed to be the result of the radars' attempts to estimate the length of vehicles. Further, a part of Island Radar's configuration procedure sought to minimize such occurrences by applying increased attenuation and delay settings—a practice that adversely contributed to current test phase outcomes.

  It is possible that vehicles located in close proximity but outside the crossing—as well as moving gates located outside established detection zones—may have been merged together across the crossing island from time to time as a result of the Queue Forming feature. The result of this phenomenon would have been a periodic and momentary false detection within an empty crossing island by a virtual vehicle that spanned the crossing island's detection zones.

Newly Applied Improvements

Newly available firmware upgrades to the radar sensors provide a number of improvements related to this test phase and to the use of the radar in railroad applications. These upgrades have been recently applied to the radar sensors at the test site.

- *Tracker Visibility When Establishing Detection Zones:*

  A firmware upgrade in the configuration application permits more accurate setting of detection zones and dimensions by showing the location of physical features within the detection footprint during the configuration step where zones are established. Recently applied to the radar sensors at the test site, this feature permitted what we believe to be a more accurate dimensioning and placement of the detection zones.

- *Heavy Weather Optimization:*

  Wavetronix has recently introduced a heavy Weather Optimization setting that provides faster and more dynamic processing of background levels. This improvement effectively reduces the signal-to-background-noise threshold to a point level that is lower than 9dB, responds to acute changes such as those caused by tire rutting in slushy snow, and does so without increasing the likelihood of false detection events.

- *Blinded Sensor Failsafe Awareness:*

  Another addition, although not directly related to the somewhat invalid outcomes of inclement weather test phase, allows the radar sensors to determine when radar segments are sufficiently 'blinded', for instance by a heavy coating of sleet or ice, and to promptly transition to a failsafe state.

- *Elimination of Queue Forming Feature in the Rail Version of the Radar:*

  Recent radar firmware has disabled the Queue Forming feature to minimize any false detection possibility due to vehicles in the same lane or due to the movement one or more crossing gates.

Vendor Recommendations

Based on our review and on the awareness of settings and features that would have provided significantly different outcomes, we recommend that relevant portions of the inclement weather test data be re-acquired and considered for inclusion in this study."

Vendor Claims End Here.

CHAPTER 6 ANALYSIS AND RESULTS OF THE RE-MODIFIED SYSTEM SETUP

The data presented in this section are based on a re-modified system configuration setup using datasets collected in winter, spring, and summer of 2014. The re-modified system was the result of further configuration changes made to the modified setup by the vendor, which were presented in previous sections. The modified setup itself was attained after the research team provided feedback to the vendor following the system initial installation. Throughout this project, all the changes to the system configuration setup have been exclusively performed by the system vendor. To maintain its independence as an evaluator, the research team deliberately avoided modifying the system configuration setup.

The need for data collection and analysis of the re-modified system emerged after discussing system performance results in adverse weather conditions with modified setup with the TRP. The TRP was concerned about the significant number of false and missed calls during heavy (or torrential) rain and snow. The vendor (ByStep LLC) provided explanations for the possible causes of the errors for the modified setup in adverse weather conditions. The vendor claimed that system performance could be improved and completed re-modification of the system configuration on January 30, 2014.

Thus, the objective of analyzing the data with the re-modified configuration was to assess system performance in adverse weather conditions, as well as to determine whether the configuration changes had any effects on system performance in good weather conditions.

The specific changes in the system configuration from the modified to the re-modified setup, as described by the vendor, were included in Section 5.6.

6.1 RECAPPING PREVIOUS SYSTEM PERFORMANCE

The evaluation of system performance in good and adverse weather conditions using the modified setup and data from 2012 and 2013 was described in detail in Volume 3 and previous chapters of this report. This section gives a brief overview of those results, which will serve as a benchmark to compare system performance with the re-modified setup.

Table 16 summarizes system performance in the different weather conditions, in terms of false, missed, stuck-on, and dropped calls. The light rain data analyzed before and after the periods of heavy rain (from Table 6) were combined with the data labeled as light rain in the same table, resulting in a total of 25.5 hours of light rain, and maintaining the duration of the heavy rain at 1.9 hours. The proportion of errors was also updated accordingly.

The number of activations by the radar units indicates the combined number of activations for the two units in the two zones, and for the loops the number of loop activations multiplied by two. A rough and conservative estimate of the traffic volume is half of the number of loop activations, as shown in Table 16.

Table 16. System Performance Using Datasets from the Modified Setup

Weather Condition	Hours	Activations		Trains	Measure of Performance				
						Missed			
		Radars 1 and 2 (all zones)	Loops x 2 (all zones)		False	Single Radar	System-wide	Stuck-on	Dropped
Good Weather	144	41,773	39,336	697	0.96%	0.09%	0.00%	0.00%	0.00%
Light Rain	25.5	3,637	3,656	76	1.37%	0.05%	0.00%	0.00%	0.00%
Heavy Rain	1.9	511	320	5	30.53%	0.00%	0.00%	0.00%	0.00%
Light Snow	6.8	1,624	1,504	45	1.66%	0.20%	0.00%	0.37%	0.00%
Heavy Snow	35.0	3,538	4,966	133	3.90%	13.51%	11.66%	1.75%	0.00%
Dense Fog	8.5	285	284	27	11.58%	0.00%	0.00%	0.00%	0.00%
Windy	21.0	7,684	7,106	90	0.59%	0.07%	0.00%	0.00%	0.00%

The following observations can be made from the results in Table 16:

- The system had the lowest frequency of errors in good weather, light rain, and windy conditions, and system performance in these conditions is comparable.
- False calls increased in heavy snow, dense fog, and heavy rain—heavy rain having the highest frequency.
- Missed calls increased in heavy snow, where vehicles were missed not only by a single radar unit, but also by both units at the same time, thus generating systemwide missed calls.
- Stuck-on calls increased in heavy snow, although the frequency of this error type remained lower than 2%. The heavy snow dataset had a combination of snow and ice, with the ice possibly building up on the radar units.

Based on these results, the evaluation of system performance after the vendor re-modified the system setup was focused on the conditions that had the most severe impact: heavy rain (highest frequency of false calls) and heavy snow (highest frequency of missed calls). The following section describes the new datasets collected in 2014.

6.2 DATASETS FOR THE RE-MODIFIED SETUP

Data collection started on January 31, 2014, immediately after the system setup was re-modified by the vendor (on January 30) and ended on July 15, 2014.

The dates, times, and characteristics of the snow and rain data are shown in Table 17. The selected good weather datasets consisted of six 24-hour periods from the following dates: February 11 and 23, March 30, April 6 and 17, and May 8.

Because periods of heavy rain were short, particular care was taken in selecting the beginning and ending times of the datasets using the weather station data and assessments based on video images from the crossing.

The characteristics of the selected datasets in terms of precipitation rates are similar to those observed in the datasets in the evaluation of the modified setup, making the comparisons between the two setups more meaningful. In the heavy snow dataset, there was a thin layer of ice on the lenses of the video camera, indicating possible ice buildup on the radar units. This condition was similar to that observed in the heavy snow dataset from the modified setup.

Table 17. Datasets to Evaluate the Re-Modified Setup

Weather Condition	Date	Hours	Local Time		Precipitation (in)		Temperature (◦F)		Wind (mph)	Gusts (mph)	Observation
			From	To	Low	High	Low	High	Max	Max	
Light Rain	19-Mar-14	6.0	5:00am	11:00am	0.01/30 min	0.11/17 min	44.1	45	10.4	16.1	Rain, no thunderstorm - short periods of heavier rain
	27-Mar-14	3.0	8:00pm	11:00pm	0.01/23 min	0.03/ 1 hr	48.9	50	23	42.6	Rain with ocassional lighting - not particularly heavy rain
	3-Apr-14	8.0	3:00am	11:00am	0.01/32 min	0.27/4 min	37.9	42.1	18.4	21.9	Periods of high rain intensity (mostly between 6am and 7am)
	13-Apr-14	6.0	4:00pm	10:00pm	0.00/30 min	0.19/9 min	46.9	63	18.4	28.8	Periods of high rain intensity (mostly between 6:20pm and 6:40pm)
	28-Apr-14	3.0	5:00am	8:00am	0.00/27 min	0.28/11 min	50	46.9	17.3	24.2	Relatively high intensity between 6:00am and 7:00am
	9-May-14	4.0	5:00am	9:00am	0.03/4 min	0.52/6 min	66.9	68	20.7	28.8	Relatively high intensity between 5:00am and 6:00am
	30-Jun-14	3.0	3:00am	6:00am	0.01/33 min	0.13/7 min	75	75.9	15	-	Rain with ocassional lighting - not particularly heavy rain
Heavy Rain	20-Feb-14	0.3	5:40am	6:00am	0.15/20 min	0.2 /9 min	35.1	35.6	6.9	-	Thunderstorm and rain
	3-Apr-14	0.3	6:50am	7:10am	0.22/16 min	0.22/16 min	39.9	39.9	12.7	21.9	Short period of heavy rain
	13-Apr-14	0.2	6:20pm	6:30pm	0.08/21 min	0.08/21 min	46.9	46.9	6.9	-	Short period of heavy rain
	28-Apr-14	0.2	6:40am	6:50am	0.08/60 min	0.08/60 min	48.9	48.9	13.8	-	Short period of heavy rain
	9-May-14	0.2	7:50am	8:00am	0.03/4 min	0.03/4 min	68	68	17.3	26.5	Short period of heavy rain
	7-Jul-14	0.5	1:30am	2:00am	0.11/9 min	0.34/8 min	73.9	81	24.2	36.8	Periods of heavy rain and thunderstorm
	8-Jul-14	0.2	6:00am	6:10am	0.13/29 min	0.13/29 min	73	73	18.4	29.9	Short period of heavy rain
	12-Jul-14	0.2	8:47am	9:00am	0.28/9 min	0.28/9 min	73	73	6.9	-	Short period of heavy rain
	12-Jul-14	0.3	9:35am	9:55am	0.7/14 min	0.7/12 min	72	73	15	-	Short period of heavy rain
Light Snow	Jan 31, 2014	6.0	8:00pm	2:00am	0.0/40 min	0.01/10 min	21.9	23	3.5	-	Slow snow buildup on roadway
	Feb 1, 2014	5.0	5:00am	10:00am	0.00/44 min	0.05/23 min	26.6	30	9.2	-	Snow completely covering the roadway
	Feb 5, 2014	14.0	12:00am	2:00pm	0.00/1 hr	0.01/10 min	24.1	25	21.9	33.4	Snow covering the road fully, then partially due to traffic
	17-Feb-14	6.0	6:00pm	12:00am	0.00/1 hr	0.01/ 8 min	24.8	28.9	18.4	25.3	No snowing, but roadway covered. Blowing snow due to wind
	1-Mar-14	4.0	3:30am	7:30am	0.00/1 hr	0.02/ 21 min	26.1	30	13.8	-	Very light snow. Possible frost at beginning of period
	11-Mar-14	2.0	10:00pm	12:00am	0.01/4 min	0.15/29 min	34	37	23	34.5	Rain transitioning to light snow
	12-Mar-14	10.0	12:00am	10:00am	0.00/1 hr	0.1 /8 min	28	33.1	24.2	39.1	Very light snow. Possible frost at beginning of period
Heavy Snow	17-Feb-14	6	10:00am	4:00pm	0.00/1 hr	0.15/2 min	23	24.8	19.6	28.8	Snow and ice. Camera blocked for about three hours due to ice (1pm to 4pm). Analysis conducted throughout that time also.

6.3 SYSTEM PERFORMANCE WITH THE RE-MODIFIED SETUP

The performance of the system with the re-modified setup was evaluated following the same procedure used for previous setups (initial and modified). Recall that the percentages of false and stuck-on calls were estimated as the total number of false or stuck-on calls divided by the total number of calls placed by the radar unit, whereas the percentages of missed and dropped calls were found as the ratio of total number of missed or dropped calls to the total number of loop calls.

6.3.1 Good Weather

System performance in good weather is shown in Table 18. These results are based on datasets that have more than 18,000 activations from the two loops combined (column *7* divided by 2). The overall frequency of false calls was 0.83% (the range was 0.31% to 1.70%). There were no systemwide (two radar units combined) missed calls, and the overall average of missed calls by one radar was 0.01% (the range was 0.00% to 0.04%). No stuck-on or dropped calls were found.

Table 18. Results from Good Weather with the Re-Modified Setup

Weather Condition (1)	Date (2)	Hours (3)	Local Time		Activations		Trains (8)	Measure of Performance				
								False (9)	Missed		Stuck-on (12)	Dropped (13)
			From (4)	To (5)	Radars 1 and 2 (all zones) (6)	Loops x 2 (all zones) (7)			Single Radar (10)	System-wide (11)		
Good Weather	Feb 11, 2014	24.0	12:00am	12:00am	7188	7416	134	0.31%	0.00%	0.00%	0.00%	0.00%
	Feb 23, 2014	24.0	12:00am	12:00am	4997	5130	58	0.60%	0.00%	0.00%	0.00%	0.00%
	March 30, 2014	24.0	12:00am	12:00am	3772	3846	59	1.70%	0.00%	0.00%	0.00%	0.00%
	April 6, 2014	24.0	12:00am	12:00am	4392	4344	59	1.50%	0.02%	0.00%	0.00%	0.00%
	April 17, 2014	24.0	12:00am	12:00am	8211	7628	135	0.76%	0.00%	0.00%	0.00%	0.00%
	May 8, 2014	24.0	12:00am	12:00am	8585	7880	134	0.73%	0.04%	0.00%	0.00%	0.00%
	Total	**144.0**	**n/a**		**37145**	**36244**	**579**	**0.83%**	**0.01%**	**0.00%**	**0.00%**	**0.00%**

Further details about the false and missed calls are shown in Table 19. The great majority of false calls were generated when the gates were moving (114 calls, or 0.31%) and caused by bicycles (105 calls, or 0.28%) and pedestrians (73 calls, or 0.2%). Only ten false calls, or 0.03%, were generated without any object being present in the crossing, and only five calls, or 0.01%, were caused by motorcycles. The four missed calls observed occurred in Radar 1 Lane 2. On three of the four occasions, the vehicles were missed when there was traffic in both directions, but the radar detected only vehicles in the southbound direction (Lane 1), missing the vehicle in the northbound direction (Lane 2).

Thus, it is concluded that in good weather conditions, the re-modified system configuration setup performed as well as the modified setup; in other words, the re-modifications did not deteriorate system performance.

Table 19. Results from Good Weather by Radar and Lane

Weather Condition (a)	Sensor (b)	Activations		Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not)						Missed Calls **	
		Radar (c)	Loop † (d)		Bicycles (f)	Motorcycles (g)	Pedestrians (h)	No Object (i)	Gates Moving (j)	Total (k)	Single Radar (l)	System-wide (m)
Good Weather 6 days (144 hrs)	Radar1Lane1	10730	9773	579	24	2	16	5	1	48	0	0
	Radar2Lane1	9482	9773		26	1	19	0	105	151	0	0
	Radar1Lane2	8407	8349		26	1	21	4	4	56	4	0
	Radar2Lane2	8526	8349		29	1	17	1	4	52	0	0
	Total	**37,145**	**36,244**	**579**	**105**	**5**	**73**	**10**	**114**	**307**	**4**	**0**
					0.28%	**0.01%**	**0.20%**	**0.03%**	**0.31%**	**0.83%**	**0.01%**	**0.00%**

* The percentage of false calls is estimated as the number of false calls (total of column k) divided by the total number of calls placed by the radar units (total of column c).

** The percentage of missed calls is estimated as the ratio of the total of column l or m divided by the total of column d.

† Number of vehicles detected by loops is the total of column d divided by 2.

6.3.2 Light and Heavy Rain

A summary of the performance of the re-modified system in light and heavy rain conditions is shown in Table 20. False calls were the only type of error observed in the rain datasets, with a frequency of 0.28% (range was 0.00% to 0.45%) in light rain and 2.30% (range was 0.00% to 16.00%, ignoring the case with very small sample size) in heavy rain. Datasets for the light rain condition were obtained from seven different days, and their combined duration was 33 hours, during which the traffic volume was near 4100 vehicles (~8150 loop activations). In contrast, datasets for the heavy rain condition were obtained from 9 days and only lasted 2.4 hours, when about 300 vehicles used the crossing in that time period. As described above, periods of heavy rain were carefully selected to only reflect that condition, preventing light and heavy rain from being mixed in the evaluation.

Table 20. Results from Rain Conditions with the Re-Modified Setup

Weather Condition (1)	Date (2)	Hours (3)	Local Time		Activations		Trains (8)	Measure of Performance				
								False (9)	Missed		Stuck-on (12)	Dropped (13)
			From (4)	To (5)	Radars 1 and 2 (all zones) (6)	Loops x 2 (all zones) (7)			Single Radar (10)	System-wide (11)		
Light Rain	March 19, 2014	6.0	5:00am	11:00am	2422	2304	52	0.45%	0.00%	0.00%	0.00%	0.00%
	March 27, 2014	3.0	8:00pm	11:00pm	481	524	11	0.21%	0.00%	0.00%	0.00%	0.00%
	April 3, 2014	8.0	3:00am	11:00am	1603	1648	45	0.36%	0.00%	0.00%	0.00%	0.00%
	April 13, 2014	6.0	4:00pm	10:00pm	1381	1448	15	0.28%	0.00%	0.00%	0.00%	0.00%
	April 28, 2014	3.0	5:00am	8:00am	864	784	32	0.00%	0.00%	0.00%	0.00%	0.00%
	May 9, 2014	4.0	5:00am	9:00am	1383	1340	33	0.07%	0.00%	0.00%	0.00%	0.00%
	June 30, 2014	3.0	3:00am	6:00am	88	102	8	0.00%	0.00%	0.00%	0.00%	0.00%
	Total	**33.0**	**n/a**		**8222**	**8150**	**196**	**0.28%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
Heavy Rain	Feb 20, 2014	0.33	5:40am	6:00am	40	52	1	0.00%	0.00%	0.00%	0.00%	0.00%
	April 3, 2014	0.33	6:50am	7:10am	76	72	7	2.63%	0.00%	0.00%	0.00%	0.00%
	April 13, 2014	0.17	6:20pm	6:30pm	32	36	2	0.00%	0.00%	0.00%	0.00%	0.00%
	April 28, 2014	0.17	6:40am	6:50am	43	50	2	0.00%	0.00%	0.00%	0.00%	0.00%
	May 9, 2014	0.17	7:50am	8:00am	113	100	4	0.00%	0.00%	0.00%	0.00%	0.00%
	July 7, 2014	0.5	1:30am	2:00am	9	4	1	55.56%	0.00%	0.00%	0.00%	0.00%
	July 8, 2014	0.2	6:00am	6:10am	25	28	1	16.00%	0.00%	0.00%	0.00%	0.00%
	July 12, 2014	0.2	8:47am	9:00am	82	98	0	6.10%	0.00%	0.00%	0.00%	0.00%
	July 12, 2014	0.3	9:35am	9:55am	188	176	2	0.00%	0.00%	0.00%	0.00%	0.00%
	Total	**2.4**	**n/a**		**608**	**616**	**20**	**2.30%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**

Additional details about the false calls in the heavy rain conditions are shown in Table 21. False calls occurred when there were no objects, when a pedestrian was present in the crossing, or when gates were moving. In total, there were 11 false calls without any object present, three false calls caused by pedestrians, and two caused by gates, accounting for 2.30% of the total activations in the 2.4 hours of data. The duration of the false calls without objects in the crossing ranged between 0.3 and 1.2 seconds, and all occurred within 10 seconds of each other. Video images showed that there was a combination of heavy rain and wind gusts when these false calls occurred.

On the other hand, in the light rain datasets, most of the false calls were generated when the crossing gates were moving (either up or down), as shown in Table 22. This was the case for 20 out of the 23 false calls observed. The remaining three false calls were caused by one pedestrian and two calls being generated without any object present in the crossing. Calls caused by moving gates were more common for Radar 1 Lane 2.

The comparison of the modified and re-modified setups is presented later in this chapter.

Table 21. Results from Heavy Rain Conditions by Radar and Lane

Date and Time *(a)*	Sensor *(b)*	Activations		Trains *(e)*	False Calls * (including bicycles and peds that radars detected but loops did not)					
		Radar *(c)*	Loop † *(d)*		Bicycles *(f)*	Motorcycles *(g)*	Pedestrians *(h)*	No Object *(i)*	Gates Moving *(j)*	Total *(k)*
Feb 20, 2014 20 min (5:40am - 6:00am)	Radar1Lane1	9	12	1	0	0	0	0	0	0
	Radar2Lane1	8	12		0	0	0	0	0	0
	Radar1Lane2	11	14		0	0	0	0	0	0
	Radar2Lane2	12	14		0	0	0	0	0	0
	Total	**40**	**52**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
April 3, 2014 20 min (6:50am - 7:10am)	Radar1Lane1	16	16	7	0	0	0	0	0	0
	Radar2Lane1	15	16		0	0	0	0	0	0
	Radar1Lane2	23	20		0	0	0	0	2	2
	Radar2Lane2	22	20		0	0	0	0	0	0
	Total	**76**	**72**	**7**	**0**	**0**	**0**	**0**	**2**	**2**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**2.63%**	**2.63%**
April 13, 2014 10 min (6:20pm - 6:30pm)	Radar1Lane1	7	8	2	0	0	0	0	0	0
	Radar2Lane1	6	8		0	0	0	0	0	0
	Radar1Lane2	10	10		0	0	0	0	0	0
	Radar2Lane2	9	10		0	0	0	0	0	0
	Total	**32**	**36**	**2**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
April 28, 2014 10 min (6:40am - 6:50am)	Radar1Lane1	12	12	2	0	0	0	0	0	0
	Radar2Lane1	10	12		0	0	0	0	0	0
	Radar1Lane2	10	13		0	0	0	0	0	0
	Radar2Lane2	11	13		0	0	0	0	0	0
	Total	**43**	**50**	**2**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
May 9, 2014 10 min (7:50am - 8:50am)	Radar1Lane1	23	24	4	0	0	0	0	0	0
	Radar2Lane1	19	24		0	0	0	0	0	0
	Radar1Lane2	36	26		0	0	0	0	0	0
	Radar2Lane2	35	26		0	0	0	0	0	0
	Total	**113**	**100**	**4**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
July 7, 2014 30 min (1:30am - 2:00am)	Radar1Lane1	3	2	1	0	0	0	1	0	1
	Radar2Lane1	3	2		0	0	0	1	0	1
	Radar1Lane2	0	0		0	0	0	0	0	0
	Radar2Lane2	3	0		0	0	0	3	0	3
	Total	**9**	**4**	**1**	**0**	**0**	**0**	**5**	**0**	**5**
					0.00%	**0.00%**	**0.00%**	**55.56%**	**0.00%**	**55.56%**
July 8, 2014 10 min (6:00am - 6:10am)	Radar1Lane1	5	7	1	0	0	0	1	0	1
	Radar2Lane1	3	7		0	0	0	0	0	0
	Radar1Lane2	9	7		0	0	0	2	0	2
	Radar2Lane2	8	7		0	0	0	1	0	1
	Total	**25**	**28**	**1**	**0**	**0**	**0**	**4**	**0**	**4**
					0.00%	**0.00%**	**0.00%**	**16.00%**	**0.00%**	**16.00%**
July 12, 2014 13 min (8:47am - 9:00am)	Radar1Lane1	15	29	0	0	0	0	0	0	0
	Radar2Lane1	16	29		0	0	0	0	0	0
	Radar1Lane2	25	20		0	0	2	1	0	3
	Radar2Lane2	26	20		0	0	1	1	0	2
	Total	**82**	**98**	**0**	**0**	**0**	**3**	**2**	**0**	**5**
					0.00%	**0.00%**	**3.66%**	**2.44%**	**0.00%**	**6.10%**
July 12, 2014 20 min (9:35am - 9:55am)	Radar1Lane1	32	34	2	0	0	0	0	0	0
	Radar2Lane1	25	34		0	0	0	0	0	0
	Radar1Lane2	67	54		0	0	0	0	0	0
	Radar2Lane2	64	54		0	0	0	0	0	0
	Total	**188**	**176**	**2**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**

* The percentage of false calls is estimated as the number of false calls (total of column k) divided by the total number of calls placed by the radar units (total of column c).

† Number of vehicles detected by loops is the total of column d divided by 2.

Table 22. Results from Light Rain Conditions with the Re-Modified Setup

Date and Time (a)	Sensor (b)	Activations: Radar (c)	Activations: Loop † (d)	Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not): Bicycles (f)	Motorcycles (g)	Pedestrians (h)	No Object (i)	Gates Moving (j)	Total (k)
Mar 27, 2014 3 hrs (8:00pm - 11:00pm)	Radar1Lane1	149	146	11	0	0	0	0	0	0
	Radar2Lane1	139	146		0	0	0	0	1	1
	Radar1Lane2	96	116		0	0	0	0	0	0
	Radar2Lane2	97	116		0	0	0	0	0	0
	Total	**481**	**524**	**11**	**0**	**0**	**0**	**0**	**1**	**1**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.21%**	**0.21%**
April 3, 2014 8 hrs (3:00am - 11:00am)	Radar1Lane1	392	393	45	0	0	0	0	0	0
	Radar2Lane1	308	393		0	0	0	0	0	0
	Radar1Lane2	442	431		0	0	0	1	5	6
	Radar2Lane2	461	431		0	0	0	0	0	0
	Total	**1,603**	**1,648**	**45**	**0**	**0**	**0**	**1**	**5**	**6**
					0.00%	**0.00%**	**0.00%**	**0.06%**	**0.31%**	**0.37%**
April 13, 2014 6 hrs (4:00pm - 10:00pm)	Radar1Lane1	427	421	15	0	0	0	0	0	0
	Radar2Lane1	360	421		0	0	0	0	1	1
	Radar1Lane2	296	303		0	0	1	0	1	2
	Radar2Lane2	298	303		0	0	1	0	0	1
	Total	**1,381**	**1,448**	**15**	**0**	**0**	**2**	**0**	**2**	**4**
					0.00%	**0.00%**	**0.14%**	**0.00%**	**0.14%**	**0.29%**
April 28, 2014 3 hrs (5:00am - 8:00am)	Radar1Lane1	209	169	32	0	0	0	0	0	0
	Radar2Lane1	160	169		0	0	0	0	0	0
	Radar1Lane2	242	223		0	0	0	0	0	0
	Radar2Lane2	253	223		0	0	0	0	0	0
	Total	**864**	**784**	**32**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
May 9, 2014 4 hrs (5:00am - 9:00am)	Radar1Lane1	321	312	33	0	0	0	0	0	0
	Radar2Lane1	265	312		0	0	0	0	1	1
	Radar1Lane2	395	358		0	0	0	0	0	0
	Radar2Lane2	402	358		0	0	0	0	0	0
	Total	**1,383**	**1,340**	**33**	**0**	**0**	**0**	**0**	**1**	**1**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.07%**	**0.07%**
June 30, 2014 3 hrs (3:00am - 6:00am)	Radar1Lane1	17	23	8	0	0	0	0	0	0
	Radar2Lane1	16	23		0	0	0	0	0	0
	Radar1Lane2	27	28		0	0	0	0	0	0
	Radar2Lane2	28	28		0	0	0	0	0	0
	Total	**88**	**102**	**8**	**0**	**0**	**0**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
Mar 19, 2014 6 hrs (5:00am - 11:00am)	Radar1Lane1	580	565	52	0	0	0	0	0	0
	Radar2Lane1	497	565		0	0	0	0	3	3
	Radar1Lane2	663	587		0	0	0	0	6	6
	Radar2Lane2	682	587		0	0	0	0	2	2
	Total	**2,422**	**2,304**	**52**	**0**	**0**	**0**	**0**	**11**	**11**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.45%**	**0.45%**

* The percentage of false calls is estimated as the number of false calls (total of column k) divided by the total number of calls placed by the radar units (total of column c).

† Number of vehicles detected by loops is the total of column d divided by 2.

6.3.3 Light and Heavy Snow

A summary of system performance in the selected light and heavy snow datasets is shown in Table 23. In these conditions, errors were less than 1% for false and stuck-on calls. There were no systemwide missed calls or dropped calls. Missed calls were limited to vehicles not detected by one of the radar units at a time, so the redundancy provided by the second radar unit prevented systemwide missed calls by detecting those vehicles.

Among the light and heavy snow datasets, the results from March 11 and 12 in the light snow condition had the greatest proportion of errors (0.84% false calls, 2.17% missed calls, and 0.29% stuck-on calls). However, based on the weather condition details from that day (see Table 17), neither precipitation nor temperature were the most extreme compared with other datasets. On March 11 and 12, light rain transitioned to light snow; thus, there was potential for ice accumulation on the radar units and the crossing location, which could have influenced system performance. On the other hand, there was significant ice accumulation in the heavy snow dataset, as evidenced in the video images by the camera lenses being almost completely covered with ice, but the error frequency in that dataset was not particularly high (0.29% false calls and 0.28% missed calls). Based on these results, there was no conclusive evidence to support the idea that ice accumulation was a significant factor on system performance.

Table 23. Results from Snow Conditions with the Re-Modified Setup

Weather Condition	Date	Hours	Local Time		Activations		Trains	Measure of Performance				
			From	To	Radars 1 and 2 (all zones)	Loops x 2 (all zones)		False	Missed: Single Radar	Missed: System-wide	Stuck-on	Dropped
Light Snow	Jan 31-Feb 1, 2014	6.0	8:00pm	2:00am	705	828	15	0.43%	0.00%	0.00%	0.00%	0.00%
	Feb 1, 2014	5.0	5:00am	10:00am	915	924	15	0.33%	0.32%	0.00%	0.11%	0.00%
	Feb 5, 2014	14.0	12:00am	2:00pm	4957	3888	63	0.18%	0.26%	0.00%	0.00%	0.00%
	Feb 17, 2014	6.0	6:00pm	12:00am	2015	2088	47	0.00%	0.05%	0.00%	0.00%	0.00%
	March 1, 2014	4.0	3:30am	7:30am	148	186	9	0.68%	0.00%	0.00%	0.00%	0.00%
	March 11-12, 2014	12.0	10:00pm	10:00am	2381	1794	55	0.84%	2.17%	0.00%	0.29%	0.00%
	Total	**47.0**	**n/a**		**11121**	**9708**	**204**	**0.32%**	**0.55%**	**0.00%**	**0.07%**	**0.00%**
Heavy Snow	Feb 17, 2014	6.0	10:00am	4:00pm	2732	2542	21	0.29%	0.28%	0.00%	0.00%	0.00%
	Total	**6.0**	**n/a**		**2732**	**2542**	**21**	**0.29%**	**0.28%**	**0.00%**	**0.00%**	**0.00%**

Additional details of the results of the heavy snow conditions are shown in Table 24. False calls were generated exclusively by pedestrians in the crossing; thus, the detection zones were not triggered by adverse weather conditions. Some single radar missed calls are observed in column I, but the second radar unit detected the missed vehicles, thus preventing systemwide missed calls.

In one of the seven cases there were two vehicles in the crossing at the same time, one in each direction. One of the radar units missed the southbound vehicle (Radar 1 Lane 1), but it properly detected the northbound vehicle. The other radar (Radar 2) detected both of the vehicles and thus prevented a systemwide missed call. In the remaining six cases there was only one vehicle in the crossing at a given time.

Table 24. Results from Heavy Snow Conditions by Radar and Lane

Date and Time (a)	Sensor (b)	Activations		Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not)						Missed Calls **	
		Radar (c)	Loop † (d)		Bicycles (f)	Motorcycles (g)	Pedestrians (h)	No Object (i)	Gates Moving (j)	Total (k)	Single Radar (l)	System-wide (m)
Feb 17, 2014 6 hrs (10:00am - 4:00pm)	Radar1Lane1	705	623	21	0	0	1	0	0	1	1	0
	Radar2Lane1	791	623		0	0	1	0	0	1	3	0
	Radar1Lane2	578	648		0	0	2	0	0	2	2	0
	Radar2Lane2	658	648		0	0	4	0	0	4	1	0
	Total	**2,732**	**2,542**	**21**	**0**	**0**	**8**	**0**	**0**	**8**	**7**	**0**
					0.00%	**0.00%**	**0.29%**	**0.00%**	**0.00%**	**0.29%**	**0.28%**	**0.00%**

* The percentage of false calls is estimated as the number of false calls (total of column k) divided by the total number of calls placed by the radar units (total of column c).

** The percentage of missed calls is estimated as the ratio of the total of column l or m divided by the total of column d.

† Number of vehicles detected by loops is the total of column d divided by 2.

Details for light snow conditions are shown in Table 25. False calls in light snow were below 1% for each of the datasets and were found most often in the dataset from March 11 and 12 because of an increase in detections generated when the gates were moving (16 detections). Overall, the effects of light snow conditions were not widespread in the selected datasets.

Missed calls also increased for the March 11 and 12 dataset, where a total of 39 missed calls from a single radar unit was found. This type of error happened on both radar units but did not generate any systemwide missed calls because of the detections made by the second radar unit.

In the light snow condition there were 53 single radar missed calls. In 13 of them there were vehicles occupying the crossing in both directions, and in 3 out of the 13 there were two vehicles traveling close to each other in the same direction that were missed by a single radar unit. All other missed call cases involved only missing one vehicle by a single radar unit.

In the same dataset there was also an increase in stuck-on calls, to seven cases. The duration of the stuck-on calls ranged between 30 seconds and 3 minutes. In four of those cases, the calls were terminated without any object being in the crossing, in two cases the calls ended after the first vehicle went over the zone, and in one case the movement of the gates caused the call termination. All stuck-on calls occurred at different times in the dataset, except for two that happened simultaneously with Radar 1 Lane 2 and Radar 2 Lane 1 after a plow truck left the crossing. This stuck-on call lasted about 1 minute and 40 seconds and was terminated without any object being present in the crossing.

Table 25. Results from Light Snow Conditions by Radar and Lane

Date and Time (a)	Sensor (b)	Activations: Radar (c)	Activations: Loop † (d)	Trains (e)	False Calls * (including bicycles and peds that radars detected but loops did not): Bicycles (f)	Motorcycles (g)	Pedestrians (h)	No Object (i)	Gates Moving (j)	Total (k)	Missed Calls **: Single Radar (l)	System-wide (m)	Stuck-on Calls (n)
Feb 17, 2014 6 hrs (4:00pm - 10:00pm)	Radar1Lane1	634	482	47	0	0	0	0	0	0	1	0	0
	Radar2Lane1	614	482		0	0	0	0	0	0	0	0	0
	Radar1Lane2	412	562		0	0	0	0	0	0	0	0	0
	Radar2Lane2	355	562		0	0	0	0	0	0	0	0	0
	Total	**2,015**	**2,088**	**47**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.05%**	**0.00%**	**0.00%**
Mar 1, 2014 4 hrs (3:30pm - 7:30pm)	Radar1Lane1	39	44	9	0	0	0	0	0	0	0	0	0
	Radar2Lane1	35	44		0	0	0	0	1	1	0	0	0
	Radar1Lane2	35	49		0	0	0	0	0	0	0	0	0
	Radar2Lane2	39	49		0	0	0	0	0	0	0	0	0
	Total	**148**	**186**	**9**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.68%**	**0.68%**	**0.00%**	**0.00%**	**0.00%**
Feb 5, 2014 14 hrs (12:00am - 2:00pm)	Radar1Lane1	1040	1000	63	0	0	1	0	0	1	0	0	0
	Radar2Lane1	958	1000		0	0	0	0	0	0	0	0	0
	Radar1Lane2	1235	944		0	0	3	0	0	3	7	0	0
	Radar2Lane2	1724	944		0	0	5	0	0	5	3	0	0
	Total	**4,957**	**3,888**	**63**	**0**	**0**	**9**	**0**	**0**	**9**	**10**	**0**	**0**
					0.00%	**0.00%**	**0.18%**	**0.00%**	**0.00%**	**0.18%**	**0.26%**	**0.00%**	**0.00%**
Feb 1, 2014 5 hrs (5:00am - 10:00am)	Radar1Lane1	219	216	15	0	0	0	0	0	0	0	0	0
	Radar2Lane1	212	216		0	0	0	0	0	0	2	0	1
	Radar1Lane2	219	246		0	0	1	0	0	1	1	0	0
	Radar2Lane2	265	246		0	0	2	0	0	2	0	0	0
	Total	**915**	**924**	**15**	**0**	**0**	**3**	**0**	**0**	**3**	**3**	**0**	**1**
					0.00%	**0.00%**	**0.33%**	**0.00%**	**0.00%**	**0.33%**	**0.32%**	**0.00%**	**0.11%**
Jan 31, 2014 6 hrs (8:00pm - 2:00am next day)	Radar1Lane1	192	213	15	0	0	0	0	0	0	0	0	0
	Radar2Lane1	184	213		0	0	0	0	3	3	0	0	0
	Radar1Lane2	163	201		0	0	0	0	0	0	0	0	0
	Radar2Lane2	166	201		0	0	0	0	0	0	0	0	0
	Total	**705**	**828**	**15**	**0**	**0**	**0**	**0**	**3**	**3**	**0**	**0**	**0**
					0.00%	**0.00%**	**0.00%**	**0.00%**	**0.43%**	**0.43%**	**0.00%**	**0.00%**	**0.00%**
Mar 11, 2014 12 hrs (10:00pm - 10:00am next day)	Radar1Lane1	536	439	55	0	0	1	1	0	2	9	0	1
	Radar2Lane1	634	439		0	0	0	0	15	15	13	0	2
	Radar1Lane2	551	458		0	0	0	0	1	1	9	0	1
	Radar2Lane2	660	458		0	0	1	1	0	2	8	0	3
	Total	**2,381**	**1,794**	**55**	**0**	**0**	**2**	**2**	**16**	**20**	**39**	**0**	**7**
					0.00%	**0.00%**	**0.08%**	**0.08%**	**0.67%**	**0.84%**	**2.17%**	**0.00%**	**0.29%**

* The percentage of false calls is estimated as the number of false calls (total of column k) divided by the total number of calls placed by the radar units (total of column c).

** The percentage of missed calls is estimated as the ratio of the total of column l or m divided by the total of column d.

† Number of vehicles detected by loops is the total of column d divided by 2.

6.4 COMPARISON OF MODIFIED AND RE-MODIFIED SETUPS

This section compares the results obtained with the re-modified setup, presented above, with the results from the system with the modified configuration, summarized in Table 16. The comparison is shown in Table 26, where the difference between the two setups is highlighted.

Table 26. Comparison of Modified (Previous) and Re-Modified (Latest) Setups

Weather Condition *(1)*	System Setup *(2)*	Hours *(3)*	Activations		Trains *(6)*	Measure of Performance				
			Radars 1 and 2 (all zones) *(4)*	Loops x 2 (all zones) *(5)*		False *(7)*	Missed		Stuck-on *(10)*	Dropped *(11)*
							Single Radar *(8)*	System-wide *(9)*		
Good Weather	Modified (Previous)	144.0	41773	39336	697	0.96%	0.09%	0.00%	0.00%	0.00%
	Re-Modified (Latest)	144.0	37145	36244	579	0.83%	0.01%	0.00%	0.00%	0.00%
	Difference	0.0	-4628	-3092	-118	**-0.13%**	**-0.08%**	**0.00%**	**0.00%**	**0.00%**
Light Rain	Modified (Previous)	25.5	3637	3656	76	1.37%	0.05%	0.00%	0.00%	0.00%
	Re-Modified (Latest)	33.0	8222	8150	196	0.28%	0.00%	0.00%	0.00%	0.00%
	Difference	7.5	4585	4494	120	**-1.09%**	**-0.05%**	**0.00%**	**0.00%**	**0.00%**
Heavy Rain	Modified (Previous)	1.9	511	320	5	30.53%	0.00%	0.00%	0.00%	0.00%
	Re-Modified (Latest)	2.4	608	616	20	2.63%	0.00%	0.00%	0.00%	0.00%
	Difference	0.5	97	296	15	**-27.90%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
Light Snow	Modified (Previous)	6.8	1624	1504	45	1.66%	0.20%	0.00%	0.37%	0.00%
	Re-Modified (Latest)	47.0	11121	9708	204	0.32%	0.55%	0.00%	0.07%	0.00%
	Difference	40.2	9497	8204	159	**-1.34%**	**0.35%**	**0.00%**	**-0.30%**	**0.00%**
Heavy Snow	Modified (Previous)	35.0	3538	4966	133	3.90%	13.51%	11.66%	1.75%	0.00%
	Re-Modified (Latest)	6.0	2732	2542	21	0.29%	0.28%	0.00%	0.00%	0.00%
	Difference	-29.0	-806	-2424	-112	**-3.61%**	**-13.23%**	**-11.66%**	**-1.75%**	**0.00%**

Based on the results shown in Table 26, the performance of the system in the re-modified setup improved in some of the conditions and maintained low frequency of errors in others. In good weather, system performance did not show any significant changes. Similar results were observed during light rain and to some extent in light snow, where errors had a slight reduction in the re-modified setup.

On the other hand, significant improvements were observed in the two critical conditions observed in the modified setup: heavy rain and heavy snow. In heavy rain, the frequency of false calls was reduced from 30.5% to 2.6% using datasets that were comparable in time, vehicular and train volume, and in the intensity of the weather condition. In heavy snow, system performance improved in terms of false, missed, and stuck-on calls. False calls were reduced to 0.3% from 3.9%, missed calls by a single radar unit were reduced to 0.3% from 13.5%, and systemwide missed calls and stuck-on calls were completely prevented compared with 11.7% and 1.75% in the modified setup, respectively. However, it is noted that the sample size for the comparison of heavy snow was smaller in the re-modified setup (6 hours from a single day) compared with the 35 hours from 5 days analyzed in the modified setup. For the heavy snow condition, the research team was focused on potential ice accumulation because that seemed to be a common factor among the datasets with highest error frequencies in the previous setup.

Further details on the comparison between the two setups in terms of false calls are shown in Table 27. The most significant changes were observed in heavy rain and heavy snow, as mentioned above. In heavy snow, the system with the re-modified setup eliminated false calls generated without objects in the crossing and also those when the gates were moving, and the few false calls found were caused by pedestrians. Similarly, in heavy rain, the re-modified setup reduced false calls without any objects in the crossing from 30.5% to 1.8%, which was the most significant reduction of false calls.

Table 27. Comparison of False Calls from Modified (Previous) and Re-Modified (Latest) Setups

Weather Condition *(a)*	System Setup *(b)*	False Calls (including bicycles and peds that radars detected but loops did not)					
		Bicycles *(c)*	Motorcycles *(d)*	Pedestrians *(e)*	No Object *(f)*	Gates Moving *(g)*	Total *(h)*
Good Weather	Modified (Previous)	0.04%	0.00%	0.19%	0.15%	0.59%	0.96%
	Re-Modified (Latest)	0.28%	0.01%	0.20%	0.03%	0.31%	0.83%
	Difference	0.24%	0.01%	0.01%	-0.12%	-0.28%	-0.13%
Light Rain	Modified (Previous)	0.00%	0.00%	0.08%	0.52%	0.77%	1.37%
	Re-Modified (Latest)	0.00%	0.00%	0.02%	0.01%	0.24%	0.28%
	Difference	0.00%	0.00%	-0.06%	-0.51%	-0.53%	-1.09%
Heavy Rain	Modified (Previous)	0.00%	0.00%	0.00%	30.53%	0.00%	30.53%
	Re-Modified (Latest)	0.00%	0.00%	0.49%	1.81%	0.33%	2.63%
	Difference	0.00%	0.00%	0.49%	-28.72%	0.33%	-27.90%
Light Snow	Modified (Previous)	0.00%	0.00%	0.18%	0.06%	1.42%	1.66%
	Re-Modified (Latest)	0.00%	0.00%	0.13%	0.02%	0.18%	0.32%
	Difference	0.00%	0.00%	-0.06%	-0.04%	-1.24%	-1.34%
Heavy Snow	Modified (Previous)	0.00%	0.00%	0.00%	2.26%	1.64%	3.90%
	Re-Modified (Latest)	0.00%	0.00%	0.29%	0.00%	0.00%	0.29%
	Difference	0.00%	0.00%	0.29%	-2.26%	-1.64%	-3.61%

6.5 RESPONSE FROM VENDOR ON SYSTEM PERFORMANCE

The findings from the re-modified setup were sent to the vendor. The vendor did not have further comments and was appreciative of including all of the findings in this volume.

CHAPTER 7 CONCLUSIONS

This report presents an evaluation of a microwave radar system for vehicle detection at a railroad grade crossing with four-quadrant gates in the following adverse weather conditions: rain (light and torrential), snow (light and heavy), dense fog, and wind.

7.1 MODIFIED SETUP AND INTERMEDIATE CONCLUSIONS

The evaluation of the modified setup was based on data from 2012 and 2013 and after the system was "modified" by the vendor following feedback on the performance from the initial setup. The results of the system with the modified setup showed that system performance was sensitive to some weather events, and the effects of such events varied significantly. In torrential rain, the false calls increased significantly. When traffic was using the crossing in torrential rain (such as on May 28 and June 1), false calls increased to 24.82%–27.08%. However, when there was only one vehicle (on May 31) or no traffic flow (on June 10) in torrential rain, the radar units generated 15 false calls on each of those two days. All false calls registered in torrential rain were generated when there were no objects in the crossing and the gates were in the upright position. Missed, stuck-on, or dropped calls were not affected by light or heavy rain.

Snow datasets were divided into light and heavy snow, based on the extent of snow accumulation on the roadway and the type of precipitation. The system was not severely affected by light snow, but errors increased significantly in heavy snow. For all heavy snow datasets combined, false calls increased to 3.9%, missed calls by a single radar unit were 13.51%, and missed calls by the two radar devices working as a combined unit were 11.66%. The most severe effects were found during freezing rain/ice, with significant snow accumulation, and when the roadway was partially covered with snow. The missed calls were not observed in all datasets with heavy snow but were generated mainly in periods of freezing rain/ice. In addition, one of the datasets showed 2.6% stuck-on calls, with durations that ranged between 10 seconds and 270 seconds.

In dense fog, the false calls increased to 11.58%, and all false calls were generated when the gates were moving or in the down position.

Wind did not affect system performance in any of the four types of errors evaluated in this study. Thus, the frequency of false, missed, stuck-on, and dropped calls was similar to the frequency observed in good weather.

In summary, the performance of the system with the modified setup was affected by different types of weather events, and the intensity and characteristics of the weather condition affected the frequency of errors. Performance degradation in short periods of heavy (torrential) rain was greater in magnitude than in periods of light rain, and the effects of freezing rain/ice with snow accumulation were more significant than the effects during light snowfall. Lastly, dense fog increased false calls when the gates were moving or in the down position.

7.2 RE-MODIFIED SETUP AND FINAL CONCLUSIONS

The re-modified system was the result of further configuration changes made to the modified setup by the vendor. The need for a re-modified system emerged after the results from adverse weather were made known to the vendor, particularly the false and missed calls during heavy (or torrential) rain and snow.

Results of the performance evaluation showed that the re-modified setup reduced the frequency of errors in heavy rain and heavy snow conditions, while maintaining good performance in good weather, light rain, and light snow conditions.

In heavy rain, the false calls with the re-modified setup were reduced to 2.6% compared with 30.5% in the modified setup conditions. This reduction was the result of a significant decrease in false calls without objects in the crossing.

In heavy snow, the most critical error frequency in the modified setup was the systemwide missed calls (11.7%). The re-modified setup eliminated those missed calls. False calls were also reduced from 3.9% to 0.3% by preventing activations without objects in the crossing and from the gates being lowered or raised.

More favorable conditions (good weather, light rain, and light snow) had less than 1% false calls and practically no missed, stuck-on, or dropped calls.

Results from this evaluation show that the performance of the detection system improved after re-modification.

The redundancy obtained by having two units sensing the same areas in the crossing reduced the frequency of systemwide missed calls, as expected. This redundancy is strongly recommended to avoid missing vehicles.

Installations using this detection system are recommended to be tested at crossings with a greater number of tracks or where longer detection zones are needed, as well as locations with multiple lanes in a given direction of traffic.

Further monitoring is also recommended to build confidence in system performance at other locations and under different weather conditions.

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APPENDIX

For the data from the modified setup, further analysis of missed vehicles and the duration of the activations by the radar units are included in this appendix. For the data from the re-modified setup such analysis was not needed because the frequency of missed calls was lower and there were no systemwide missed calls.

Missed Vehicles and Missed Calls in the Modified Setup

Missed calls have been reported for all conditions and are estimated as a function of the total number of activations by the loops. However, because the frequency of missed calls was very high during two of the heavy snow datasets, it was decided to determine the number of *missed vehicles* in addition to the number of *missed calls*.

The number of missed calls and the number of missed vehicles may be different because of the following two situations: (1) multiple missed vehicles traveling close to each other could have generated a single loop call that was missed, and (2) a single missed vehicle could have activated the two loop zones, thus creating two missed calls for the radar units. Thus, depending on the frequencies of these two situations, the number of missed calls can be different from the number of missed vehicles.

If the number of missed vehicles is reported, the percentage of errors must be estimated based on the actual number of vehicles using the crossing, rather than on the number of calls generated by the loops. Table A-1 shows the analysis of missed calls and missed vehicles from the March 5 datasets. The actual number of vehicles in the selected time periods was obtained by watching the videos and tallying vehicles by direction, as shown in column d. It is noted that in the first dataset, the total number of vehicles is greater than the number of loop calls, but that was not the case in the second dataset. This is because of the greater traffic volume in the first dataset, where vehicles closely following each other placed one single long call in the loops. In the second dataset, with lower volumes, the time between consecutive vehicles was more likely to be long enough to create separate loop calls. In addition, under lower vehicle volumes, there was a tendency for drivers to drive between the two lanes, which often resulted in a single vehicle creating loop calls in the two directions of traffic and thus inflating the total number of loop calls (as shown in columns d and e).

Table A-1. Missed Calls and Missed Vehicles in Heavy Snow Conditions by Radar and Lane

Date and Time (a)	Sensor (b)	Lane (c)	Actual Number of Vehicles (manually counted) (d)	Loop activations (e)	Missed Calls *		Missed Vehicles †					
					Single Radar (f)	System-wide (g)	Single Radar (h)				System-wide (i)	
Mar 5, 2013 9 hours (9:00am - 6:00pm)	Radar1Lane1	SB Vehicle (Lane 1)	977	871	206	93	Radar 1	269	SB Vehicle	262	SB Vehicle (Lane 1)	78
	Radar2Lane1				95	95			NB Vehicle	7		
	Radar1Lane2	NB Vehicle (Lane 2)	746	737	8	125	Radar 2	318	SB Vehicle	93	NB Vehicle (Lane 2)	105
	Radar2Lane2				207	121			NB Vehicle	225		
	Total	**Lane 1 + Lane 2**	**1723**	**1608**	**516**	**434**	**587**				**183**	
					16.04%	**13.50%**	**34.07%**				**10.62%**	
Mar 5, 2013 6 hours (6:00pm - 12:00am)	Radar1Lane1	SB Vehicle (Lane 1)	162	193	88	32	Radar 1	96	SB Vehicle	82	SB Vehicle (Lane 1)	17
	Radar2Lane1				5	32			NB Vehicle	14		
	Radar1Lane2	NB Vehicle (Lane 2)	111	179	7	39	Radar 2	37	SB Vehicle	4	NB Vehicle (Lane 2)	35
	Radar2Lane2				34	38			NB Vehicle	33		
	Total	**Lane 1 + Lane 2**	**273**	**372**	**134**	**141**	**133**				**52**	
					18.01%	**18.95%**	**48.72%**				**19.05%**	

* The percentage of missed calls is estimated as the ratio of the total of column f or g divided by the total of column e* 2.

† The percentage of missed vehicles is estimated as the total of columns h or i divided by the total of column d.

From Table A-1, it is observed that Radar 1 missed more vehicles traveling in Lane 1 (southbound), and Radar 2 showed the same trend with vehicles traveling in Lane 2 (northbound). Thus, each radar missed more vehicles in the direction with the most restricted angle, for which the available time to track and identify vehicles could have been reduced.

Regarding systemwide missed vehicles, more vehicles were missed in the northbound direction, where vehicles entered the crossing after turning from Hinsdale Avenue onto Monroe Street. The percentage of missed vehicles was greater in the second dataset (columns h and i) of March 5, following the same trend observed for missed calls in columns f and g. In the first dataset, systemwide missed vehicles were 10.62% of the total number of vehicles using the crossing, and the percentage of missed vehicles by a single radar unit only was 34.07%. In the second dataset, these percentages increased to 19.05% systemwide and 48.72% for the vehicles missed by a single radar only. It is noted that the systemwide missed vehicles are different from those reported as missed by a single radar only; thus, the values from column i are not included in column h (the same applies to columns f and g).

Duration of Loop and Radar Calls and Effects of Removing Short Calls (<0.5 seconds) in the Modified Setup

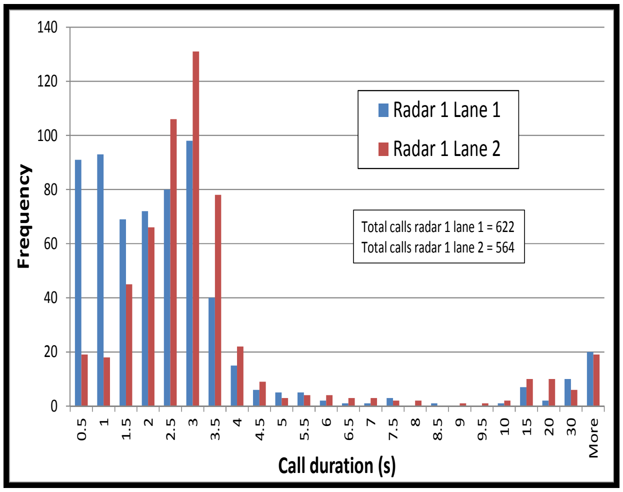
In the process of verifying potential missed calls and missed vehicles, it was observed that the activations from the radar units were in general significantly shorter than those from the loops. This finding was further investigated to determine the distribution of all calls placed by each system for the heavy snow datasets. Figures A-1 and A-2 show the duration of the calls for the same datasets analyzed above in Table A-1.

The average loop call duration for the first dataset from March 5 was 5.46 and 4.69 seconds for Lanes 1 and 2, respectively. The duration of the loop calls was shorter in the second dataset (4.57 and 3.56 seconds in Lanes 1 and 2, respectively), when the traffic volume was lower, because there were fewer cases of multiple vehicles detected by the same loop call. In contrast, the average duration of the radar calls, excluding the stuck-on calls, was between 1.24 and 3.15 seconds for any given zone and radar in the same datasets.

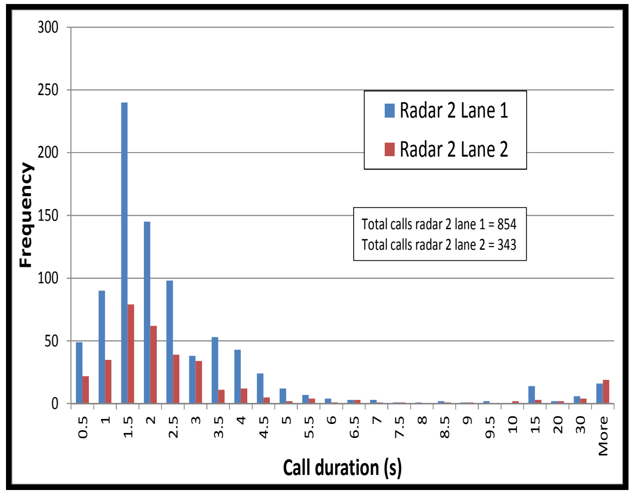
The distribution of the call durations from Figures A-1 and A-2 also shows the occurrence of radar calls shorter than 0.5 seconds. At a railroad grade crossing, calls that are too short may not effectively operate exit gates, and filters to eliminate short calls can be set in place. Thus, the impact of truncating very short calls from the datasets (shorter than 0.5 seconds) was estimated. Results for this analysis are shown in Table A-2, where a new set of values under the column “Truncated Data Missed Calls” is shown, along with the frequency of missed vehicles in the original dataset.

From Table A-2, it can be observed that the percentage of missed vehicles by a single radar unit and systemwide increased slightly when calls shorter than 0.5 seconds were removed from the data. This indicates that some vehicles were detected only by very short calls, increasing the potential of missed calls and inadequate operation of gates.

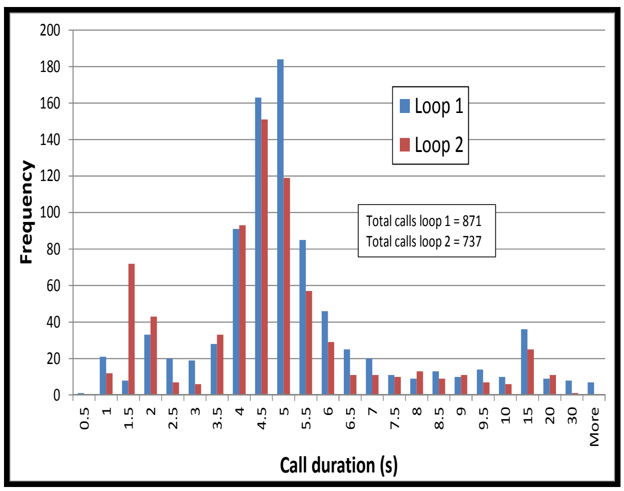
In addition, the research team determined the frequency of missed calls that occurred when vehicles in the two directions of traffic were occupying the crossing at the same time. On the first dataset from March 5 (9am to 6pm), this was the case in 8 out of the 269 missed calls by Radar 1, in 30 out of the 318 missed calls by Radar 2, and in 20 out of the 183 systemwide missed calls. On the other hand, on the second dataset from March 5 (6pm to 12am), this situation was not observed in the missed calls by a single radar unit, but it was observed in 6 out of the 52 systemwide missed calls. These results indicate that vehicles occupying the two lanes at the same time happened approximately between 3% and 12% of the missed calls by a single radar unit or the systemwide missed calls. It should be noted that these figures are for the modified setup and do not represent the system performance in the re-modified setup.



(a) Radar 1

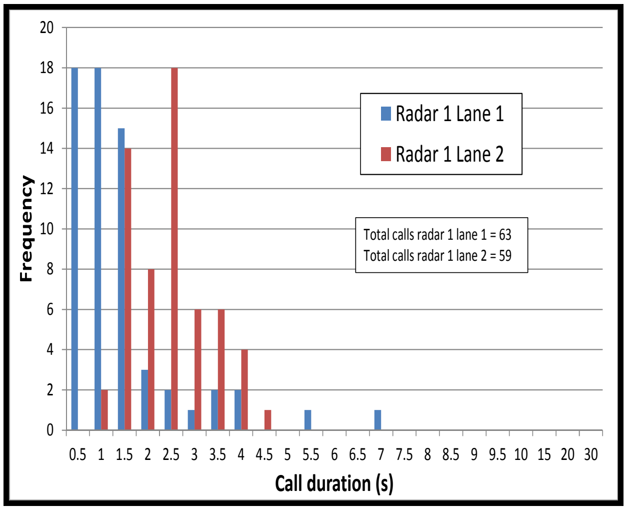


(b) Radar 2

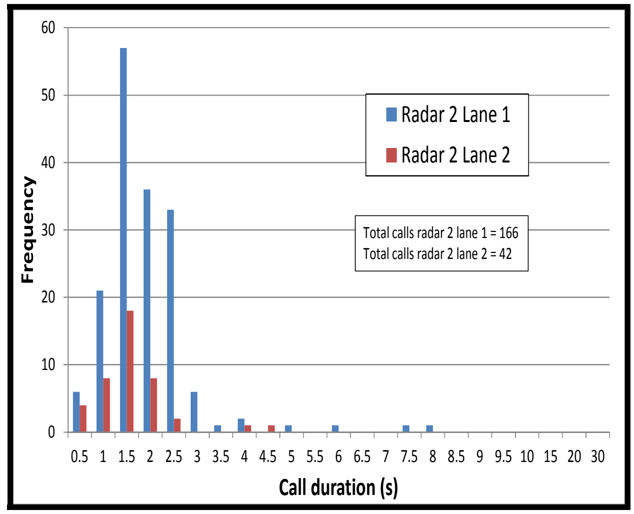


(c) Loops

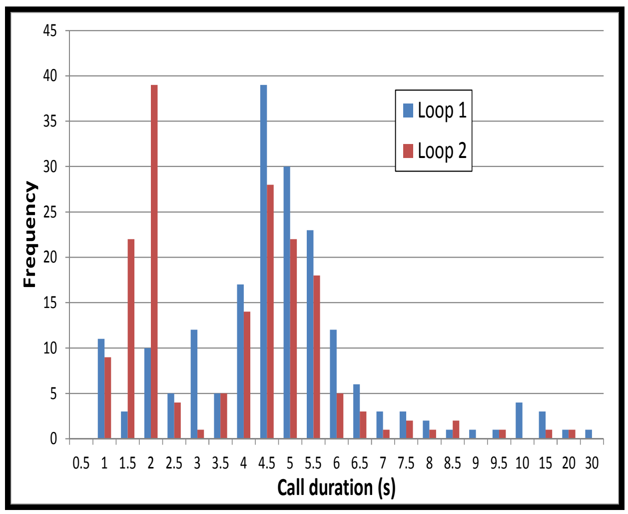
Figure A-1. Duration of calls from loops and radar units—
March 5 from 9 a.m. to 6 p.m. (heavy snow).



(a) Radar 1



(b) Radar 2



(c) Loops

Figure A-2. Duration of calls from loops and radar units—
March 5 from 6 p.m. to 12 midnight (heavy snow).

Table A-2. Missed Vehicles and Truncated Data Missed Vehicles in Heavy Snow Conditions by Radar and Lane

Date and Time (a)	Sensor (b)	Lane (c)	Actual Number of Vehicles (manually counted) (d)	Missed Vehicles †						Truncated Data Missed Vehicles † (removing calls shorter than 0.5 sec)					
				Single Radar (e)				System-wide (f)		Single Radar (g)				System-wide (h)	
Mar 5, 2013 9 hours (9:00am - 6:00pm)	Radar1Lane1	SB Vehicle (Lane 1)	977	Radar 1	269	SB Vehicle	262	SB Vehicle (Lane 1)	78	Radar 1	296	SB Vehicle	287	SB Vehicle (Lane 1)	108
	Radar2Lane1					NB Vehicle	7					NB Vehicle	9		
	Radar1Lane2	NB Vehicle (Lane 2)	746	Radar 2	318	SB Vehicle	93	NB Vehicle (Lane 2)	105	Radar 2	314	SB Vehicle	91	NB Vehicle (Lane 2)	112
	Radar2Lane2					NB Vehicle	225					NB Vehicle	223		
	Total	**Lane 1 + Lane 2**	**1723**	**587**				**183**		**610**				**220**	
				34.07%				**10.62%**		**35.40%**				**12.77%**	
Mar 5, 2013 6 hours (6:00pm - 12:00am)	Radar1Lane1	SB Vehicle (Lane 1)	162	Radar 1	96	SB Vehicle	82	SB Vehicle (Lane 1)	17	Radar 1	103	SB Vehicle	91	SB Vehicle (Lane 1)	21
	Radar2Lane1					NB Vehicle	14					NB Vehicle	12		
	Radar1Lane2	NB Vehicle (Lane 2)	111	Radar 2	37	SB Vehicle	4	NB Vehicle (Lane 2)	35	Radar 2	38	SB Vehicle	6	NB Vehicle (Lane 2)	37
	Radar2Lane2					NB Vehicle	33					NB Vehicle	32		
	Total	**Lane 1 + Lane 2**	**273**	**133**				**52**		**141**				**58**	
				48.72%				**19.05%**		**51.65%**				**21.25%**	

† The percentage of missed vehicles is estimated as the total of columns e, f, g, or h divided by the total of column d.