



U.S. Department of
Transportation

**Federal Railroad
Administration**

A Radar Vehicle Detection System for Four- Quadrant Gate Warning Systems and Blocked Crossing Detection

Office of Research
and Development
Washington, DC 20590



NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. Any opinions, findings and conclusions, or recommendations expressed in this material do not necessarily reflect the views or policies of the United States Government, nor does mention of trade names, commercial products, or organizations imply endorsement by the United States Government. The United States Government assumes no liability for the content or use of the material contained in this document.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 2012		3. REPORT TYPE AND DATES COVERED Final Report July 2011 – May 2012
4. TITLE AND SUBTITLE A Radar Vehicle Detection System for Four-Quadrant Gate Warning Systems and Blocked Crossing Detection				5. FUNDING NUMBERS
6. AUTHOR(S) and FRA COTR Author and principal investigator: Thomas N. Hilleary COTR: Tarek Omar, D.Sc.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) ByStep, LLC 330 West 47 th Street, Suite 217 Kansas City, Missouri 64112				8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Research and Development 1200 New Jersey Avenue, SE Washington, DC 20590				10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FRA/ORD-12/24
11. SUPPLEMENTARY NOTES COTR: Tarek Omar, D.Sc.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the FRA Web site at www.fra.dot.gov/us/content/185 , or by calling (202) 493-1300.				12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words) The Wavetronix Matrix Radar was adapted for use at four-quadrant gate railroad crossings for the purpose of influencing exit gate behavior upon the detection of vehicles, as an alternative to buried inductive loops. Two radar devices were utilized, operating collaboratively, in order to realize a fully redundant system. Performance variables including vehicle size and location, vehicle occlusion, and radar positioning were evaluated, along with sensitivity to rain, snow, and other environmental conditions. Recommendations for utilization of the radars in conjunction with popular crossing warning system controllers are provided. Also included is a means for detecting vehicles that are stopped, stored, or deliberately placed in the crossing island, and rapidly communicating that information across cellular, PTC, ITCS, and ACSES, and other data networks.				
14. SUBJECT TERMS Microwave radar, vehicle detection, Wavetronix, four-quadrant gate, blocked railroad crossing, exit gates, obstacle detection, IODS, island radar,				15. NUMBER OF PAGES 68
				16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

METRIC/ENGLISH CONVERSION FACTORS

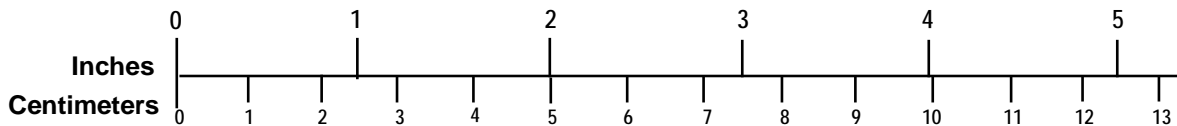
ENGLISH TO METRIC

LENGTH (APPROXIMATE)	
1 inch (in)	= 2.5 centimeters (cm)
1 foot (ft)	= 30 centimeters (cm)
1 yard (yd)	= 0.9 meter (m)
1 mile (mi)	= 1.6 kilometers (km)
AREA (APPROXIMATE)	
1 square inch (sq in, in ²)	= 6.5 square centimeters (cm ²)
1 square foot (sq ft, ft ²)	= 0.09 square meter (m ²)
1 square yard (sq yd, yd ²)	= 0.8 square meter (m ²)
1 square mile (sq mi, mi ²)	= 2.6 square kilometers (km ²)
1 acre = 0.4 hectare (he)	= 4,000 square meters (m ²)
MASS - WEIGHT (APPROXIMATE)	
1 ounce (oz)	= 28 grams (gm)
1 pound (lb)	= 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	= 0.9 tonne (t)
VOLUME (APPROXIMATE)	
1 teaspoon (tsp)	= 5 milliliters (ml)
1 tablespoon (tbsp)	= 15 milliliters (ml)
1 fluid ounce (fl oz)	= 30 milliliters (ml)
1 cup (c)	= 0.24 liter (l)
1 pint (pt)	= 0.47 liter (l)
1 quart (qt)	= 0.96 liter (l)
1 gallon (gal)	= 3.8 liters (l)
1 cubic foot (cu ft, ft ³)	= 0.03 cubic meter (m ³)
1 cubic yard (cu yd, yd ³)	= 0.76 cubic meter (m ³)
TEMPERATURE (EXACT)	
[(x-32)(5/9)] °F = y °C	

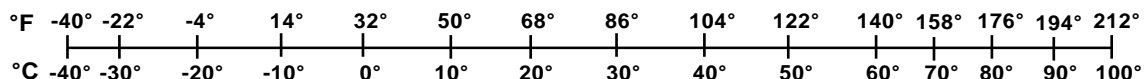
METRIC TO ENGLISH

LENGTH (APPROXIMATE)	
1 millimeter (mm)	= 0.04 inch (in)
1 centimeter (cm)	= 0.4 inch (in)
1 meter (m)	= 3.3 feet (ft)
1 meter (m)	= 1.1 yards (yd)
1 kilometer (km)	= 0.6 mile (mi)
AREA (APPROXIMATE)	
1 square centimeter (cm ²)	= 0.16 square inch (sq in, in ²)
1 square meter (m ²)	= 1.2 square yards (sq yd, yd ²)
1 square kilometer (km ²)	= 0.4 square mile (sq mi, mi ²)
10,000 square meters (m ²)	= 1 hectare (ha) = 2.5 acres
MASS - WEIGHT (APPROXIMATE)	
1 gram (gm)	= 0.036 ounce (oz)
1 kilogram (kg)	= 2.2 pounds (lb)
1 tonne (t)	= 1,000 kilograms (kg)
	= 1.1 short tons
VOLUME (APPROXIMATE)	
1 milliliter (ml)	= 0.03 fluid ounce (fl oz)
1 liter (l)	= 2.1 pints (pt)
1 liter (l)	= 1.06 quarts (qt)
1 liter (l)	= 0.26 gallon (gal)
1 cubic meter (m ³)	= 36 cubic feet (cu ft, ft ³)
1 cubic meter (m ³)	= 1.3 cubic yards (cu yd, yd ³)
TEMPERATURE (EXACT)	
[(9/5) y + 32] °C = x °F	

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price \$2.50 SD Catalog No. C13 10286

Updated 6/17/98

Contents

Executive Summary	1
1. Introduction	3
1.1 Background.....	4
2. Review of Vehicle Detection Technology Options.....	6
2.1 Infrared and Video Analytics.....	6
2.2 Microwave Radar.....	6
2.3 Buried or Embedded Detection Technologies	6
2.4 Buried Inductive Loops	7
2.5 Radar-Based Vehicle Detection.....	11
2.6 Wavetronix SmartSensor Matrix Radar.....	12
2.7 Radar-Based Detection System Cost	16
3. Hardware and Software Adaptation for Railroad Applications	18
3.1 Initial Tripod Tests	18
3.2 Generic Railroad Application Requirements.....	20
3.3 Summary of Necessary Railroad Application Adaptations and AREMA Compliance Requirements.....	22
4. System Performance Tests	23
4.1 Adaptation and Optimization Engineering Tasks.....	23
4.2 Test Site and Equipment.....	24
4.3 Test Methodology and Phases	27
5. Test Procedures and Results.....	28
5.1 Radar Mounting Height Sensitivity.....	28
5.2 Radar-to-Radar Interference Immunity	29
5.3 Snowfall Sensitivity Tests	29
5.4 Rainfall Sensitivity Tests.....	32
5.5 Vehicle Size and Location Tests.....	34
5.6 Comparative Radar Performance.....	37
5.7 Failsafe State Tests	44
5.8 Blocked Crossing Detection and Classification	45
6. Conclusion.....	48
7. Recommendations for Future Development and Evaluation	50
7.1 Future Research	50
7.2 Future Development	50
8. References	52
9. Acronyms, Abbreviations, and Definitions	54
Appendix A. Four-Quadrant Gates in Illinois.....	55

Illustrations

Figure 1. Crossing Clear Storage Distance	4
Figure 2. Wavetronix SmartSensor Matrix in Traffic Intersection Applications	13
Figure 3. Wavetronix SSM, Sixteen Radar Segment Detection Footprint	15
Figure 4. Wavetronix SSM Configuration Application and GUI	16
Figure 5. Initial Tripod Radar testing	18
Figure 6. Gate Mast Mounted Radar Detection Footprint	19
Figure 7. Dual, Complimentarily-Positioned Radar Footprints	19
Figure 8. Hinsdale BNSF Test Site	24
Figure 9. Inductive Loop Locations	25
Figure 10. Hinsdale Test Site Equipment Configuration	26
Figure 11. Low Radar Sensor Mounting and Bed Bounce Effect	28
Figure 12. Radar Mounted at 14.5 Ft versus 19.5 Ft	28
Figure 13. Radar Channel Set Conflict Detection and Resolution	29
Figure 14. Non-Traffic Area Established for Snowfall False Detection Tests	30
Figure 15. Snowfall False Detection Tests Example Outcomes	32
Figure 16. Example of the Rainfall False and Missed Detection Tests	33
Figure 17. Crossing Island Partitions for Vehicle Size and Location Tests	34
Figure 18. Vehicle Size and Location, Occlusion Testing	36
Figure 19. Anomalous Detection Analysis State Machine	38
Figure 20. An Auto is High Centered on Track 3 after a Mistaken Right Turn while in the Crossing Island	46
Figure 21. Cellular Dissemination of Blocked Crossing Alerts, with Automated Link to Real- time Visual Information	47

Tables

Table 1. Embedded Inductive Loop-Based Vehicle Detection System Cost.....	11
Table 2. SmartMatrix Radar State Approvals.....	14
Table 3. Radar-Based Vehicle Detection System Cost.....	17
Table 4. Outdoor Radar versus AREMA Class B Specifications.....	23
Table 5. Wavetronix Electronics Modules versus AREMA Class C Specifications.....	24
Table 6. Precipitation Events during Radar and Loop System Tests.....	31
Table 7. Comparative Loop versus Radar Test Summaries.....	41

Executive Summary

Detecting vehicles at railroad crossings is important for several reasons. Certain High Speed Rail and Quiet Zone corridors typically utilize four-quadrant gate railroad crossings, where there are entrance gates and exit gates for each lane of traffic. In the preferred operating mode, exit gates do not descend until it can be verified that doing so would not trap a vehicle on the tracks, inside the crossing island. But using buried loop vehicle detection presents several problems—they do not cover the entire crossing and they are prone to failure due to the extreme environment they must tolerate embedded in the roadway surface. When replacement is necessary, railroads must restrict the speed of locomotives until the loops are replaced and the road surface is reworked, generally by non-railroad contractors. Radars, by contrast, mounted above and outside the crossing, monitor the entire crossing island and provide uniquely redundant coverage by utilizing two radars positioned on opposite sides of the crossing.

The development and testing of a radar-based means of detecting vehicle presence at highway-rail grade crossings showed potential improvement in the areas of performance, reliability, safety, and life-cycle cost over the industry's conventional use of embedded inductive loop vehicle detectors at select locations.

A comprehensive series of validation tests contrasted the dual microwave radar system with the performance of inductive loops, also known as vehicle presence detectors. Tests that evaluated mounting location, vehicle size and location, environmental and meteorological performance, and failsafe scenarios demonstrated the dual-radar system's performance to be equal or superior to that of an array of embedded inductive loops in actual railroad crossing installations.

Over 4 months of testing involving more than 120,000 vehicles showed no missed detection events for either the loop system or the dual radar system.

Both systems experienced incidents where vehicles were inadvertently detected in both lanes rather than just one, especially when those vehicles were traveling through the crossing close to the centerline of the roadway. Overall, the radar system detection boundary was shown to be more precise than that of the loop system, as evidenced by the frequency of these adjacent lane detections: 406 for the radar system and 4,673 for the loop detection system. However, as a result of multipath reflections, the radar system did detect vehicles in the crossing in adjacent lanes (29 occurrences out of 120,130 vehicles or 0.024 percent). Additional research will determine whether increased delay settings can further minimize or eliminate these effects.

Tests also showed the radar system's ability to detect pedestrians and bicycles in some instances, although it has not been determined whether or how exit gates should be affected by their presence in the crossing island.

For reasons that were inconclusive, false detections by the loop system occurred 68 times (0.057 percent) while false detections by the radar system occurred 27 times (0.022 percent). For the purpose of providing an exit path for potentially trapped vehicles in four quadrant gate crossings, a false detection is generally considered to be an acceptable, 'right-side' failure, causing exit gates to ascend to the failsafe, raised position.

Heavy rain or snow triggered false radar detections on 14 occasions during the 4-month study, the apparent result of the movement of significant accumulation of surface water. Increasing the

radar attenuation settings decreased false detection events, and it is thought that utilization of the radar's time integration (delay) settings may further decrease or eliminate rain-induced false detection events.

Categories were established for Stuck On and Dropped detection events, but the radar system did not register any occurrences of any meaningful duration. Ongoing research is intended to provide independent radar response times to verify that dropouts or detections that persist beyond those of inductive loops produce any consequences that would affect proper gate operation or crossing safety.

Estimates provided by contractors indicated a typical loop installation cost for a dual track crossing to be \$36,680, approximately 25 percent more than that of the dual radar system estimated at \$27,500. Estimates included materials, installation labor, underground boring for cable, and in the case of inductive loops, roadway milling and surfacing.

Generally, the lifetime of embedded loop systems is reported to be 4–6 years (yr), due to pavement movement caused by temperature extremes, loop distortion due to vehicle weight, and loop damage incurred as a result of pavement resurfacing and leveling. The radar system shows promise of a longer service and lower life cycle cost due to the non-embedded nature of the radar system and its relative ease of installation. The radar system Mean Time Between Failures (MTBF) is calculated at 10 yr. Due to its higher MTBF and significantly lower Mean Time To Repair (MTTR) of 6 hours (h), the radar system has an Availability of 99.99 percent. In contrast, loop systems have an Availability that ranges between 98.8 and 99.5 percent.

Additionally, utilizing the radar solution's inherent ability to sense vehicles that are moving or stationary, a low-cost means of detecting and communicating an alert pertaining to vehicles that are stored, disabled, or deliberately placed in the crossing island roadway was devised. Widespread notification of vehicles or other large obstacles that have remained motionless in the crossing island was shown to be possible utilizing any type of wired or wireless network, including Positive Train Control (PTC) and other train communication and control networks. The specific case of notification to handheld smartphones permitted the fastest possible dissemination of such an obstacle alert, especially effective when accompanied by an image of the crossing and a return Internet link, or shortcut that could connect the alert recipient to a real-time visual image of the crossing within 15 seconds (s). This form of alert dissemination could be used, for example, to notify local railroad maintainers and supervisors of a potentially obstructed crossing. In the same manner, the public cellular telephone network could be used to convey this information to centralized dispatch centers and crossing trouble desks.

Additional independent studies are underway at the Illinois Center for Transportation regarding a number of performance variables including radar response time, more in-depth research regarding the effects of rain and snow, and optimization of radar configuration settings.

1. Introduction

The North American railroad industry has expressed continued interest in non-embedded forms of highway vehicle detection for highway-rail grade crossing four-quadrant gate warning systems, in support of dynamic exit gate control operating modalities. The prospect of accurate, reliable longer life, lower cost, non-embedded detection has also engendered interest in radar-based systems for obstacle detection at crossings as a facet of Positive Train Control (PTC) enabled, communications-based crossing warning system activation, where assurance of a clear crossing island roadway may be one of the necessary crossing health messages communicated to the on-board system¹.

Four-quadrant gate crossing warning systems for high-speed rail and quiet zones frequently utilize a Dynamic Exit Gate Clearance Time operational mode². This system requires reliable vehicle presence detection in the crossing island to influence the behavior of exit gates, permitting vehicles in the crossing to clear the crossing island before exit gate descent. Vehicle detection in crossing islands has historically utilized inductive loops or magnetometer arrays buried in the roadway. While these legacy technologies generally perform satisfactorily where they have been tested and used, they have a limited service life and a susceptibility to damage due to temperature extremes, vehicle weight, and roadway resurfacing. When replacement is necessary, crossing roadway work is mandatory—subjecting the railroad to train speed restrictions and heightened safety risks that affect the motoring public and work crews⁵. Furthermore, buried detection technologies lack inherent system redundancy or a comprehensive process for measuring performance and reliability.

This project addresses the adaptation and testing of a commercial radar system utilized in highway and traffic intersection control (Intelligent Transport Systems, or ITS) for four-quadrant gate railroad crossing applications. Railroad application requirements identified in the course of the project, over and above those needed for ITS applications, included additional detection modalities, collaborative multi-radar operation, and methods utilized to achieve system redundancy, vitality, and comprehensive performance analysis.

In addition to offering the benefits of a detection system not embedded in the crossing roadway, it is anticipated that the radar-based approach could provide a reliable and economical means of detecting highway vehicles that may be stopped, stored, or deliberately placed in the crossing island. Crossing obstruction situations, thus detected, could be communicated to dispatchers and on-board systems via available wired or wireless networks, such as cellular or future PTC communication channels.

Although other forms of vehicle detection such as video, infrared, acoustic, and magnetometers have been selectively utilized, these technologies have not shown themselves to be sufficiently viable or cost effective and so have not generated use at the same level as the inductive loop technologies. Virtually all North American vehicle detection systems used at four-quadrant gate railroad crossings utilize buried inductive loops rather than those aforementioned forms of vehicle detection. Accordingly, this report describes the research and testing methods undertaken to develop, compare, and contrast the detection performance of a multiple radar detection system and a conventional embedded inductive loop detection system.

1.1 Background

1.1.1 Vehicle Detection in the Railroad Industry

Vehicle detection methods are used at select highway-rail intersections to influence exit gate behavior for four-quadrant gate warning systems, and as a supplemental safety measure (SSM) in quiet zones and at least one High-Speed Rail (HSR) corridor, the Northeast Corridor (NEC). Detecting vehicles that may be stopped, stored, or deliberately placed in the crossing island is considered an important safety factor in future communication-based crossing activation treatments implemented on fully deployed PTC infrastructure. Vehicle detection is also highlighted under the National Intelligent Transportation Systems (ITS) Architecture (V6.1⁸) as a key functional requirement for Advanced Railroad Grade Crossing operation. As discussed in this report, emerging radar-based detection technology holds potential for successful adaptation to highway-rail grade crossing applications, and offers distinct improvements over existing embedded vehicle detection solutions.

1.1.2 Railroad Crossing Geometry

The Manual on Uniform Traffic Control Devices (MUTCD) defines a Minimum Track Clearance Distance (MTCDD) for four quadrant gate warning systems as that area bounded by the entrance gate stop bar and the point where a vehicle exiting the crossing would be free of the exit gate arm. The MUTCD also defines a Clear Storage Distance of 6 feet (ft) between the rail nearest the entrance gate stop bar and the stop bar. This area is established to provide a small amount of space where vehicles may be stored (or safely positioned) if trapped in the crossing during warning system activation.

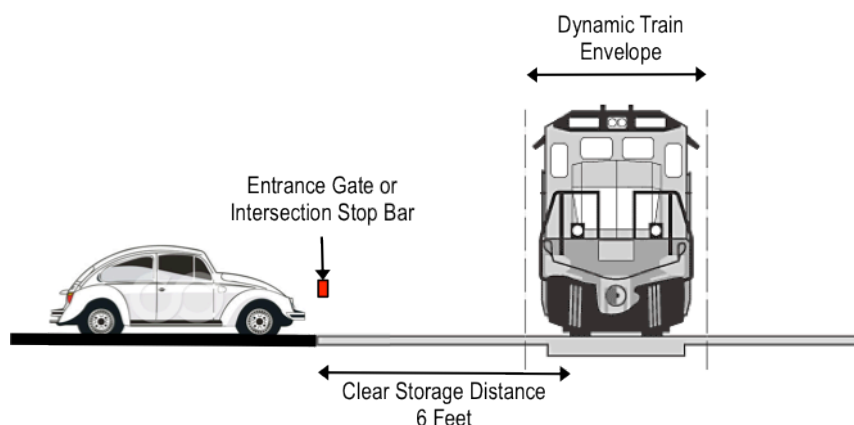


Figure 1. Crossing Clear Storage Distance

1.1.3 Exit Gate Operating Modes

The 2012 American Railway Engineering and Maintenance-of-Way Association's (AREMA) Communications and Signals (C&S) Manual Part 3.1.15 sets out operating criteria for crossing gate arms in a four-quadrant gate configuration. Two exit gate operating modes (EGOM) are described in the manual—*Timed* Exit Gate Operating Mode and *Dynamic* Exit Gate Operating Mode.

In Timed EGOM, the descent of exit gates is delayed few seconds after the entrance gates start downward motion to permit traffic to clear the crossing island. This operating mode is typically used as a backup to Dynamic EGOM or where there is a low risk of vehicle storage (queuing) in the crossing island. In Timed EGOM, the presence of vehicles that may be in the crossing island when the warning system is activated do not affect the descent of exit gates.

In Dynamic EGOM, exit gate operation is based on the presence of vehicles in the crossing island and within the MTCD. Ideally, vehicle presence detection systems for Dynamic EGOM avoid detection of the front ends of vehicles protruding beneath lowered entrance gates, as this would cause adjacent exit gates to ascend. Dynamic EGOM is to be used whenever there is a risk of traffic backing up or stopping on the crossing, for example, at intersections, bus stops, and driveways close to the crossing⁹. The selection of a specific operating mode is typically determined *based on an engineering study, with input from the affected railroad company*⁹. Increasingly, however, State agencies establish guidelines for the use of four-quadrant gates at crossings with train speeds in excess of 79 mph, indicating a general preference for Dynamic EGOM over Timed EGOM¹⁴.

1.1.4 Blocked Crossing Detection

Reliable and low life cycle cost methods for Intruder and Obstacle Detection Systems (IODS) are areas of continued interest. Most IODS research has focused on infrastructure-based systems that can communicate obstruction risks from wayside mounted sensory equipment to on-board (locomotive cab) annunciators. The latest FRA Needs Assessment Workshop ranked On Track Vehicle Detection as number 15 out of its top 33 research needs. A recently-proposed FRA rule mandating more widespread use of the toll-free telephone Emergency Notification System (ENS)¹² suggests that the optimum technology needed to move beyond dependence on the general public to place a telephone call to report a possible obstruction situation has not been envisioned or proven.

Although potential issues with bandwidth priorities have not been addressed, possible use of the PTC wireless communication infrastructure to communicate advance warning of potential crossing obstacles to on-board locomotive systems is also being contemplated.

2. Review of Vehicle Detection Technology Options

Numerous vehicle presence detection methods have been developed and implemented, with varying degrees of success and satisfaction. These have included technologies that utilize infrared light, video analytics, microwave, and buried (embedded) technologies such as magnetometers and inductive loops.

2.1 Infrared and Video Analytics

Visible and non-visible light emission and detection (e.g. infrared) operate at wavelengths that can be obscured easily by rain and snow, and occasionally overwhelmed by background sunlight. Despite the sophistication of video systems and the ability of analytic processing to recognize and classify vehicles, these systems are unreliable without sufficient light levels. As with infrared detection systems, the performance of video analytic systems may be impaired by the presence of rain, fog, snow, or the glare of bright background sunlight.

2.2 Microwave Radar

Microwave and ultra wideband radar systems have the advantage of operating at gigahertz (GHz) wavelengths that pass through rain, snow, and fog. They do not rely on visibility, ambient light levels, and are not affected by background sunlight. But to cover the large detection area at a crossing island, multiple radars and reflectors, or radars that feature mechanical or optical scanning, are required⁶. Additionally, the cost and complexity involved in the use of these earlier radar solutions have generally rendered them unsatisfactory, maintenance intensive, and cost prohibitive for railroad application. In fact, until recently, microwave radars operated on a Doppler process, detecting frequency shifts in emissions that were then reflected back to the radar detector. In essence, these Continuous Wave (CW) Doppler radar devices did not explicitly detect stopped vehicles, but instead utilized a counter technique that added vehicles coming into a detection zone and subtracted vehicles moving out of the detection zone. According to these systems, a non-zero counter value indicated that more vehicles had entered the detection zone than had left it, implying the continued presence of a stopped vehicle. Newer Frequency Modulated Continuous Wave (FMCW) radars and more advanced classification algorithms are better able to detect stationary vehicles, based on their reflection of returned radar energy and adaptive ‘learning’ of the detection environment. In a process called ‘washout,’ the radars maintain detection of stationary vehicles for a considerable period of time (e.g. 15–60 minutes) before beginning to treat those objects as part of the permanent ‘background’.

2.3 Buried or Embedded Detection Technologies

Magnetometers and buried inductive loops operate on simple physical principals: they detect changes in a magnetic field or inductance resulting from a proximate highway vehicle with sufficient metallic content. But these sensors are embedded in the roadway itself, a requirement that carries a number of disadvantages (detailed below). With a magnetometer, ‘hockey-puck’ sized detectors/transponders are set into core-drilled receptacles in the roadway. These devices detect the overhead passage of vehicles and wirelessly communicate the information to a local concentrator. This system introduces the complexity associated with a local wireless network—

which could impact reliability—and adds a battery maintenance responsibility to the life cycle cost of the detectors.

2.4 Buried Inductive Loops

Of the aforementioned vehicle detection technologies, buried inductive loop systems are most typically utilized in crossing applications. Although they work satisfactorily, there are installation, performance, longevity, and maintenance issues that offer areas for improvement. Recently developed radar-based systems for traffic intersection and other ITS applications suggest that improvements in performance and life cycle cost factors over those of embedded detection technologies are possible.

2.4.1 Basic Operation of Inductive Loop Detection Systems

Vehicle detection for controlling traffic signals, highway ramp metering, and mechanical gates typically involves inductive loop sensors buried in the roadway. The inductance of coiled wire assemblies buried several inches in the roadway change when a vehicle with sufficient metallic content passes overhead within an allowable height, causing the loop detection system to issue a vehicle ‘call’ to a controller.

The railroad industry has historically chosen buried inductive loop detection systems for vehicle presence detection purposes, based on their demonstrated higher level of performance compared with video, infrared, Doppler microwave radar, and magnetometer systems. However, buried inductive loops are not completely satisfactory in crossing applications for four reasons: their relatively short life, the negative consequences of installing and maintaining an array of loop sensors buried in the railroad crossing island roadway, constrained areas for installation resulting in sensitivity issues, and lack of redundancy and system level performance monitoring.

2.4.2 Areas for Improvement for Inductive Loop Detection

2.4.2.1 Short Loop Life

Because they are buried in the roadway itself, buried inductive loops are subjected to environmental stress that can prematurely limit their useful life. Traffic industry studies²⁹ on the extent and causes of inductive loop failures do not provide meaningful mean time between failure (MTBF) data for preformed loops. Preformed loop assemblies, typically used in railroad crossing applications, are less subject to installation failures due to improper sealing, wire failure, and pavement deformation than the loops that were the subject of these FHWA studies.

Whether due to pavement failures, asphalt shifting, damage caused by freezing and thawing cycles, or road resurfacing, when any part of a loop—the ‘check loop’ (described below), home run cable, or subsurface junction boxes—experiences a failure, the entire loop and check loop assemblies must be replaced. Despite the failure cause, railroad engineering departments interviewed on this topic (BNSF and Union Pacific) estimate that loops can have a minimum useful lifetime of 4 to 6 yr, and can even last as much as 10 yr or more.

2.4.2.2 Loop Installation and Replacement Consequences

Based on local operating requirements, and absent any redundant or secondary detection system capability, the loop system installation or replacement process can create extended-period train delays while contractors are engaged in the installation or replacement process, which generally takes a minimum of 2–3 weeks to complete, as long as air and surface temperatures are above 40 °F. When a failed loop is replaced, a new loop can be saw-cut into the existing asphalt and sealed, or the loop area may be milled out so that the new loop may be set in place and asphalt layers applied. While more costly, the milled out replacement is preferred due to more precise placement and better environmental sealing of the loop assembly. Moreover, a failed loop assembly cannot be extracted intact from the roadway during a saw-cut or milling surface preparation, eliminating any possibility for post-failure analysis of the damaged loop.

2.4.2.3 Loop Availability

Loop Availability is derived from a combination of MTBF and mean time to repair (MTTR), and is most noticeably affected by the period of time necessary to replace failed loop components in the roadway as described above. For a loop MTBF of 4 to 10 yr and for a loop minimum MTTR of 2.5 weeks, loop Availability ranges between 98.8 and 99.5 percent.

2.4.2.4 Constrained Installation Area and Critical Sensitivity Tuning

Loop detectors must be isolated from one another and from proximate metallic structures such as the tracks that cut across a crossing island. The use of preformed concrete crossing panels further constrains available loop installation area between tracks in a double-track and triple-track corridors. The limited area where loops may be installed has two consequences: coverage limitations and a decrease of vertical sensitivity.

Due to decreased installation areas in preformed crossing panel islands, loops only cover a small portion of the island roadway. Tests have shown that very small motor vehicles, such as compacts and ultra-compacts, can occupy areas of a crossing island where loops are not responsive. In addition, when loops are installed between the tracks and the edge of the MTCD zone, protruding front ends of vehicles can be detected outside of the MTCD, causing exit gates to unnecessarily ascend in Dynamic EGOM configurations.

Vertical sensitivity of an inductive loop is limited to two-thirds of the length of the shortest side of a generally rectangular shaped loop. The available loop installation space between multiple tracks including the width of preformed crossing panels limits loop length to 24 inches (in), resulting in approximately 16 in of vertical height sensitivity. Consequently, installers typically increase the sensitivity of inner loops in order to adequately sense high-decked vehicles such as school buses and trailers. In addition, inner loops typically require vehicle ‘call’ extension to prevent intermittent vehicle detection between contiguously-spaced loops in a lane that would otherwise cause the lane’s exit gate to intermittently switch between ascending and descending directions (‘gate pumping’) in Dynamic EGOM configurations.

Tests have shown that the heightened sensitivity of interior loops can cause improper/unintended vehicle detection signals from adjacent lanes when a vehicle travels too close to the center of the roadway over the crossing island. In these cases, a vehicle is properly sensed in its particular

lane, but may also be detected in the opposing lane due to the loops' increased sensitivity and "V" shaped detection boundary.

Heightened sensitivity has also been shown to create a propensity for loops to freeze in the 'On' state, causing the associated exit gate associated with that loop's lane to remain in the raised position—a failsafe state that is defined by FRA as a partial activation failure.

2.4.2.5 Lack of Redundancy and System Level Performance Monitoring

Although buried inductive loops use co-located 'check loops' to monitor the detection system's health, they actually only verify the continuity of the system's home run cabling and the detector loop's ability to sense an energized check loop. Significantly, there is currently no way to comprehensively check or quantify the reliability of a buried inductive loop detector. Due to the physics governing the process of detecting changes in inductance resulting from an overhead vehicle's metallic content, multiple inductive loops cannot operate in close proximity. Consequently, there is no means of nesting or concentrically arranging loops to achieve redundant detection capability at zones within the crossing island.

The shortened equipment life and lack of loop detection system redundancy increase the likelihood that a crossing warning system will revert to a failsafe operational mode. Depending upon the railroad's signal engineering preferences, this failsafe operational mode may involve reverting to the more simplistic Timed Exit Gate Operating Mode behavior, or it may result in keeping the exit gates in the raised position until the train is detected on the crossing island.

2.4.2.6 Illinois Inductive Loop Experience – Loop Replacement, Re-Installation, and Reliability

The subject of an earlier research project which assessed the overall reliability of four-quadrant gate warning systems², Union Pacific Railroad (UP) installed four-quadrant gate systems at 69 locations between Springfield and Mazonia, IL, from 2000 to 2004. These sites used a popular exit gate management system (EGMS) along with an array of buried inductive loops to detect vehicles. This large concentration of four-quadrant gate sites operating with loops in a Dynamic EGOM serves as a useful body of actual experience from which to assess efficacy.

The loop installation process involves placing final lift layers of asphalt around the loops' junction boxes and home run cabling. UP's area manager of signal maintenance reports that 14 out of 69 sites (20 percent) required excavation and rework following the final asphalt layer installation. The exact cause of these initial loop system failures was not extensively researched. The junction boxes were excavated from the asphalt and reworked or replaced. UP believes that these failures were caused by manufacturing defects triggered or exacerbated by the application of asphalt and the presence of trapped moisture, an outcome that is only revealed after the irrevocable application of the hardened road surface.

When buried loops or their wiring components fail due to installation trauma or to environmental factors, they must be replaced. The replacement process involves surface saw cutting, which destroys the existing loops, making it impossible to do post-failure analysis. Since their initial installation, 8 out of the 69 sites (12 percent) have failed—due to factors that could not be analyzed—and have had to be replaced. It is, however, generally understood that periodic loop

failures are largely a function of pavement movement caused by seasonal temperature fluctuations and vehicle weight impacts and forces.

In another example of the consequences of permanently burying the vehicle detection system in the pavement, this particular Illinois corridor is currently undergoing high-speed passenger rail upgrades. As part of this upgrade process, concrete ties and new rail are being installed, necessitating the destruction and subsequent reinstallation of 100 percent of the buried loop vehicle detection systems.

It is also understood that the ambient electromagnetic effects of lightning storms can cause false loop detections ('calls') and other anomalous system behavior. As a result of these false calls, the exit gates can remain in the raised position until the next train to move through the crossing actually reaches the island itself—releasing the Island Relay (IR) and causing the exit gates to lower. Although the lowering of the gates did reset the falsely latched detection, the partial activation failure of the gates was noted and reported by the train crew, and required train speed restrictions at the crossing until a maintainer could physically investigate the report and clear the speed restriction.

2.4.3 Inductive Loop Detection System Cost

2.4.3.1 New Inductive Loop Systems

The cost estimate for a standard dual track, 6-loop inductive vehicle detection system was obtained from Railroad Controls Limited (RCL). Labor costs and the number of hours or days typically required for installation were provided as low-high ranges. The following system cost breakdown conservatively used the lower amounts from the ranges provided.

Table 1. Embedded Inductive Loop-Based Vehicle Detection System Cost

New Loop Installation Costs, Double-Track System with Six Embedded Loops				
Loop Materials	Quantity	Cost	Total	Notes¹
Preformed Loops	6	\$400	\$2,400	With integrated check loops
Junction Boxes	2	\$300	\$600	Mast base junction boxes
Loop Detector Electronics	2	\$4,500	\$9,000	Railroad type U1400, 4-Loop Detector
Cabling	600 ft	\$5/ft	\$3,000	Home run cable
Total Materials			\$15,000	
Loop Installation Labor	Quantity	Cost	Total	Notes²
Construction	3 days (d)	\$3,000	\$9,000	Four-man crew, \$3000–\$4000 per day, 2–5 d
Boring	200 ft	\$20/ft	\$4,000	\$20–\$75 per foot, allow one day for boring
Flagger	4 d	\$1,000/d	\$4,000	\$100/h, not including crew mobilization time
Total Installation Labor			\$17,000	
Roadway Surface				Notes³
Asphalt Milling, Overlay			\$4,680	3.5 in mill and overlay, 144 yd ²
Total Loop Installation			\$36,680	
¹ Estimates provided by Railroad Controls Limited, Ft. Worth, TX				
² Estimates provided by Railroad Controls Limited, Ft. Worth, TX				
³ Estimates provided by O'Donnell & Sons Contracting, Olathe, KS				

2.4.3.1 Loop Replacement Cost

Whether due to the initial installation yield, limited lifetime, or corridor upgrades, the reinstallation process for a single loop and lead in cable can cost up to \$25,000 for a saw-cut installation and \$34,000 for an installation involving asphalt milling and resurfacing (costs are based on 2012 quotes to the City of Olathe, KS). Even more important to the railroad is the time required to engage a contractor to perform this repair and replacement work, during which time train speed restrictions are generally in place.

2.5 Radar-Based Vehicle Detection

2.5.1 Current State of the Art

Non-embedded, microwave radar vehicle detection for traffic intersection control is increasingly popular, yielding inductive loop system performance levels without the drawbacks of in-roadway construction. Typically, these proven devices provide stop-bar detection for controlling traffic light phases (red, green, left-turn, right-turn), and for reducing dilemma zone risks (by extending

a green or yellow signal to permit approaching vehicles to safely proceed through an intersection, depending on their detected speed and distance).

Despite the obvious advantages of non-roadway installation, microwave radars designed for traffic intersection applications have not been adapted to, or qualified for, railroad application. For example, in a failed state, the failsafe mode to which a typical traffic intersection controller reverts is an ‘all red flashing’ mode. In this mode, the responsibility to prevent traffic contention for intersection space is ceded to the approaching motorists themselves. While adequate for an intersection, such a failsafe strategy is ineffective at a railroad crossing where one of the ‘vehicles’ is a locomotive with little ability to stop. Accordingly, any vehicle detection system adopted for railroad crossing applications must demonstrate higher levels of system performance validation and redundancy to satisfy the higher safety level expectations of railroad use.

2.5.2 Functional Expectations for a Radar-Based Vehicle Detection Solution

The objective of this crossing detection system development effort was to identify possible radars that have been successfully deployed in traffic intersection and highway applications, to adapt those technologies where necessary to meet the functional and environmental requirements of a railroad crossing application, and to test the result in actual installations.

Objectives for a radar-based crossing detection system, exclusive of the inherent advantages associated with non-embedded installation, include:

- Coverage of the entire crossing island requiring no complex mechanical or optical scanning
- Potential for multiple radars to operate collaboratively to achieve active redundancy and performance cross-checking, and a vital ‘no single point of failure’ architecture
- Ability to detect both moving and stopped highway vehicles
- Proven performance and satisfactory MTBF in related applications

2.6 Wavetronix SmartSensor Matrix Radar

A review of leading traffic radar suppliers resulted in the choice of Wavetronix™ and its recently introduced SmartSensor™ Matrix Radar (SSM). The company claims an installed base of more than 20,000 radar vehicle detection devices, primarily in traffic intersection and highway arterial monitoring applications. When approached regarding the possible adaptation of its technology to railroad uses, Wavetronix was poised to introduce its Matrix Radar technology for non-embedded stop bar detection at intersections. This device was found to contain certain features that made it particularly unique and attractive for railroad crossing installations, as indicated in the following subsections.

2.6.1 Large Detection Footprint

Of specific interest was the SSM radar sensor’s integration of 16 individual radars into a single weatherproof enclosure, providing a quarter-circle shaped, 15,386 ft² coverage pattern that measured 90° x 140 ft—large enough to cover a typical railroad crossing in its entirety with no scanning or mechanical apparatus.

2.6.2 Encoded Emissions Permit Multiple, Redundant Radars

The SSM radar sensor uses encoded emissions to permit multiple radars to operate without interference at a traffic intersection (Figure 2) where multiple radars (one per approach) would typically operate in close proximity. For railroad application, this capability would permit multiple radars (typically two) to operate from opposing points of view on the same detection zones at a crossing to achieve active redundant operation. Mounted on or near each entrance (or exit) gate mast at the edge of the MTC zone, each radar can individually monitor the entire crossing island, detecting stopped or moving vehicles in up to 16 zones and up to 10 lanes, fulfilling the vitality, redundancy and performance cross-checking capabilities notably lacking in buried loop detection systems.



Figure 2. Wavetrionix SmartSensor Matrix in Traffic Intersection Applications

2.6.3 Ability to Detect Moving and Stopped Vehicles

Because the SSM radar sensors are based on Frequency Modulated Continuous Wave (FMCW) rather than just Continuous Wave (CW) emissions, they do not rely on Doppler-shift detection and are therefore capable of detecting stopped vehicles, fulfilling another important objective of a radar-based solution. Differentiation from objects that are always stationary (poles, buildings, etc.) is accomplished by sophisticated algorithms that continuously ‘learn’ the sensors’ environment and begin to ignore objects that have remained stationary for longer than 15 minutes (min) (the SSM radar’s default “washout” setting).

2.6.4 Long Life, High Mean Time between Failures

Calculated Mean Time Between Failures (MTBF) for the SSM radar sensor is greater than 10 yr, a not unexpected longevity given that the solid-state device is safely mounted above and just outside of the crossing island and therefore not subject to the trauma of in-road installation and post-installation lift layers of hot asphalt. It should be noted that this MTBF is a calculated value based on a prediction model (MIL-HDBK-217), and is not intended as a guarantee of field failure rates; nor is it supported by actual field experience.

2.6.5 Intuitive Configuration Application and Graphic User Interface

Lastly, owing to the commercialization of the SSM radar sensor in existing traffic management applications, the manufacturer developed a new set of configuration applications, making setup and alignment relatively easy. These support applications permitted real-time visual verification of the radar's positioning and detection zones, although a completely railroad-centric paradigm would be preferred.

2.6.6 Additional Technical Aspects of the Wavetronix Radar

The SSM radar sensor was chosen for the application because of its performance history, its ability to detect stopped and moving vehicles, and its 16-radar implementation which provides a quarter-circle shaped detection zone—large enough to completely cover a typical crossing from a vantage point at the top of an entrance (or exit) gate mast. The following detailed information provided by the manufacturer, Wavetronix, and current users, provides additional technical detail about the SSM radar sensor chosen for use in the railroad crossing application.

2.6.6.1 SmartSensor Matrix State Approvals

The SSM radar is a relatively new Wavetronix product first manufactured and marketed in 2010. Literature searches did not identify any third-party validation studies or reports for the SSM product, although independent research has been conducted on several other Wavetronix traffic radars which share core technology with the SSM radar^{21,22,23,24}. Currently, four States have completed testing and evaluation of the SSM and have added the product to their respective lists of approved product and vendors for ITS applications.

Table 2. SmartMatrix Radar State Approvals

State	Approval Certificate	Approval Date
Alabama ²⁵	PEB 2250	October 4, 2010
Florida ²⁶	66013653209011	December 8, 2010
Pennsylvania ²⁷	WAV-002P	June 13, 2012
Ohio ²⁸	n/a	August 23, 2011

2.6.6.2 FMCW versus CW Radar in Stopped Vehicle Detection

Radar gained a reputation for not being able to detect stopped vehicles because early systems used filters to reduce return signal reflections from background objects such as trees and poles, but that also filtered out stopped vehicles. Conventional, non-pulsed Continuous Wave (CW) radar systems have a difficult time detecting stopped vehicles because those vehicles are indistinguishable from the background of the 'scene' when they have no velocity.

The SSM radar sensor is able to detect both stopped and moving vehicles because of its ability to sense the power difference between return signals from a vehicle and those from other roadway objects. The use of a Frequency Modulated Continuous Wave (FMCW), rather than a straight CW signal, allows the sensor to separate objects in range even when they are not in motion.

Unlike CW modulation, the FMCW radar is able to detect the range to objects in its field of view. It does this by sending out electromagnetic waves that are swept from a starting frequency

to an end frequency (known as the bandwidth). It then receives return or reflected waves some time later after they have bounced off objects in the field of view. When the returned waves are mixed with the original waves, a signal is generated with a frequency proportional to the distance that the returned waves traveled. Therefore, objects farther away will have a signal with a higher frequency than objects that are closer. Because of the continuing change in emitted frequencies (frequency modulation), the device can sense stationary objects as well as those that are moving.

The ability to distinguish between two closely spaced objects depends on the difference between the start and stop frequencies, also called the bandwidth. The more bandwidth used, the closer together two objects can be and still be differentiated from each other. The SSM radar sensor uses a bandwidth of about 250 megahertz (limited by the FCC), which gives a resolving distance of 2 ft or less between objects.

2.6.6.3 Field of View—One Beam versus Multiple Beam Radars

A radar sensor's field of view is determined by its beam width. If the beam width is large, the radar is able to detect objects farther away from the front-looking angle of the sensor. In essence, it can detect—better than a sensor with a smaller beam width—objects that are farther to the right or left of the front of the sensor. The downside of having a larger beam width is that the radar cannot detect objects as far away as a sensor with a narrower beam width can. A radar with only one antenna and beam cannot determine how far to the left or right an object is relative to the front of the sensor. In order to get this information, the sensor needs more than one beam. (Author's note: mechanical or optical steering of a single beam to cover a large area, while used in aviation radar applications, is deemed too complex for railroad applications due to increased cost and excessive maintenance requirements).

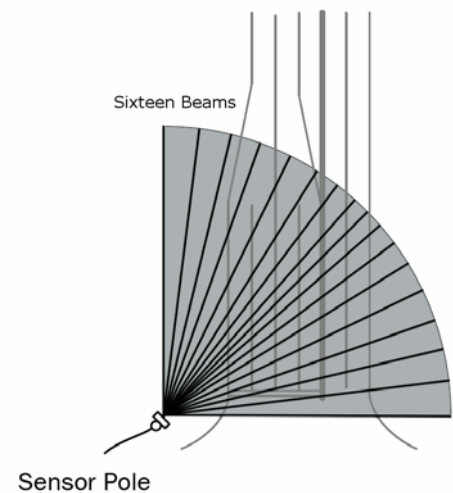


Figure 3. Wavetronix SSM, Sixteen Radar Segment Detection Footprint

The SSM radar sensor uses an array of 16 radar beams spread out over an arc of 90 degrees. Using these 16 radar elements, the SSM radar sensor is able to detect both the range and the angle to an object. By using 16 beams, which increases the angle over which the sensor detects objects, the sensor is able to have narrower individual beam widths; this effectively increases the detection range to over 140 ft from the sensor.

Using this architecture the SSM radar sensor can accurately detect vehicles within a 140-ft arc of 90 degrees (Figure 3). This means that the SSM radar sensor can continuously monitor a 15,386 ft² area for vehicles in multiple lanes containing multiple detection zones.

2.6.6.4 Vehicle Classification and Tracking Algorithms

In order to ensure accurate vehicle detection, the SSM radar sensor utilizes tracking algorithms. Since the SSM radar sensor is not limited, as a loop detector is, to looking at a fixed point in a roadway, it can detect and track objects well before they get to the location of interest on the roadway. Tracking helps the sensor reduce detection reliability issues—such as may result from

a larger vehicle closer to the sensor occluding the view of a vehicle farther out. Tracking also allows the sensor to detect aberrant behavior such as U-turns and lane changes within the detection area. This feature is thought to be of value in light of the unpredictable or aberrant driver behavior that may result from the activation of the crossing warning system and concern about possible vehicle entrapment.

2.6.6.5 User Interface for Detection Zone Setup and Verification

Set up and configuration of the SSM radar sensor is accomplished using a configuration application. The setup software, known as SmartSensor Manager (Figure 4), utilizes a graphical user interface (GUI) that gives the user a 2-D view of the traffic as seen by the sensor. This visual allows easy placement of lanes and detection zones, as well as configuration of output channels.

This same software is used to verify that the sensor's placement and configuration will give the desired performance. This is possible because the user interface displays detected traffic, zone, and channel status in real time.

The SSM radar was initially developed for single radar use at each multilane approach of a traffic intersection. Accordingly, the configuration application deals with just one radar at a time. The crossing application envisioned by this development anticipates the use of two radars, each detecting vehicles in identical lanes and zones, but from opposite 'viewpoints' at the crossing. A recommendation for future optimization is a configuration application from which both radars may be operated simultaneously, minimizing any deviation between radars that would result from individually configured lanes and detection zones.

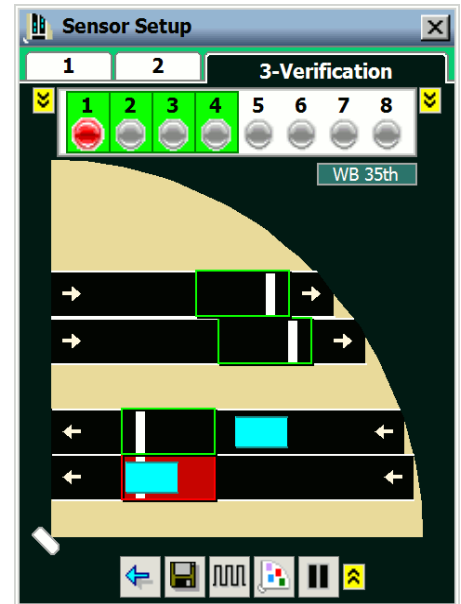


Figure 4. Wavetronix SSM Configuration Application and

2.7 Radar-Based Detection System Cost

Because of the non-embedded nature of the radar vehicle detection system, installation time and labor is considerably less than for an inductive loop system.

2.7.1 New Radar Detection System Cost Estimate

Table 3. Radar-Based Vehicle Detection System Cost

New Radar Detection System Installation Costs, Double-Track System with 6 Embedded Loops				
Radar Materials	Quantity	Cost	Total	Notes¹
Radar Sensor	2	\$6,400	\$12,400	WX-SS-300 SmartSensor-Rail
Radar Mast Extension	2	\$300	\$600	
Junction Boxes	2	\$200	\$400	Mast Base Junction Boxes
Radar Electronics	1	\$4,500	\$4,500	VDR24, Two Radar, Four Zone
Mast Cable	2	\$200	\$400	with Weatherproof Connector
Cabling	600 ft	\$2/ft	\$1,200	Home run Cable
Total Materials			\$19,500	
Radar Installation Labor	Quantity	Cost	Total	Notes²
Construction	1 d	\$3,000	\$3,000	Four man crew, \$3000–\$4000 per day, 1–2 d
Boring	200 ft	\$20/ft	\$4,000	\$20-\$75 per foot, allow one day for boring
Flagger	1 d	\$1,000/d	\$1,000	\$100/h, not including crew mobilization time
Total Installation Labor			\$8,000	
Total Radar Installation			\$27,500	
¹ Estimates provided by Wavetronix and the Island Radar Company				
² Estimates provided by Rob Aanenson, Vice President Engineering, Railroad Controls Limited				

2.7.2 Cost Comparison, Radar System versus Loop System

As Table 1 shows, the cost of a new inductive loop detection system for a dual-track, six-loop system is estimated to be \$36, 680. In contrast, as shown in Table 3, installation of a dual radar system to detect vehicles within the same type of crossing is estimated to be \$27,500, or 25 percent less than the cost for a loop based system.

3. Hardware and Software Adaptation for Railroad Applications

3.1 Initial Tripod Tests

The SSM radar sensor was initially field tested and evaluated for possible use in railroad crossing motor vehicle detection applications. Railroad officials were interested in the changes and modifications that would be necessary to adapt the radar from the traffic intersection control applications for which it was initially designed to railroad crossing applications with different (more) requirements for effective use (Section 2.5.2). Of particular interest were the following capabilities:

- Coverage of the entire crossing island requiring no complex mechanical or optical scanning
- Ability to utilize multiple radars operating collaboratively, to achieve active redundancy and performance cross-checking, and a vital ‘no single point of failure’ architecture
- Ability to detect both moving and stopped vehicles
- Proven performance and satisfactory MTBF in related applications



Figure 5. Initial Tripod Radar

Although a minimum of two radars working collaboratively is envisioned for purposes of redundancy and vitality, a single SSM radar sensor was initially deployed on a 15-foot tripod mount, to gather initial performance data (Figure 5). The setup and configuration application provided nearly automatic lane detection with minimal adjustment necessary to define lane widths and stop bar locations. Existing vehicle classification and detection algorithms functioned satisfactorily. Examination of the performance and detection data from these initial field tests identified three detection situations that needed to be evaluated and possibly modified in consideration of the SSM radar sensor's use in railroad crossing applications. These detection performance cases include the following:

- Approach-dependent detection latencies
- The possibility for vehicle occlusion
- Reverse direction filtering of vehicles in designated lanes of travel

3.1.1 Approach-Based Detection Latencies

The SSM radar sensor detection pattern, 90° x 140 ft, completely covers most crossing island detection boundaries defined by the MTCD zone (Figure 6). Any vehicle within the 15,386 ft² arc area is detected and tracked by the SSM radar sensor. During the initial field tests, it was noted that vehicles entering the detection zones from the arc side were detected 0.5 to 1.0 seconds (s) sooner than vehicles entering the detection zone from the straight side, radii, or the

detection footprint arc. According to the manufacturer, the early detection occurs because vehicles entering the detection zones from the arc side of the detection footprint are actually ‘seen’ by the radar sensor well beyond the 140-ft range and tracked all the way into the crossing. Vehicles entering the detection footprint from the radius side need to travel 1–2 ft before they present a sufficient radar cross-section to be classified by the sensor.

The observed radii-entry latency is not deemed critical to the application given the proposed use of redundant, complementarily positioned radars for system redundancy and radar cross-checking. In this topology (Figure 7), each of the two radars offers an arc entry approach to oncoming vehicles entering the crossing. Both radars can register a detection event in the radar sensors’ common detection zones, providing fast response despite direction of vehicle travel, and also providing detection redundancy.

3.1.2 Vehicle Occlusion

Designed to err on the side of false detections rather than missed detections, Wavetronix detection algorithms strive to track vehicles traveling in any direction, even if they are temporarily blocked, or ‘occluded’ by a larger, taller vehicle in the radar sensor’s foreground. While the SSM radar sensor’s occlusion compensation ‘remembered’ vehicles that were temporarily hidden behind a larger foreground vehicle, there were instances where an occluded vehicle was not seen by the single SSM radar sensor mounted on a 15-ft tripod.

Although rare, and mitigated by an intended installation height of 18–20 ft rather than the initial tripod installation height of 15 ft, vehicle occlusion is not deemed to be critical to the intended application for the following reasons:

- Dual, complementarily positioned radars (Figure 7) essentially eliminate the possibility that a larger, taller vehicle could hide a small vehicle since there are multiple vantage points.
- If occlusion *were* to occur, it would be because there is an occluding vehicle, which would itself be sensed in the crossing island, permitting the crossing controller to react in

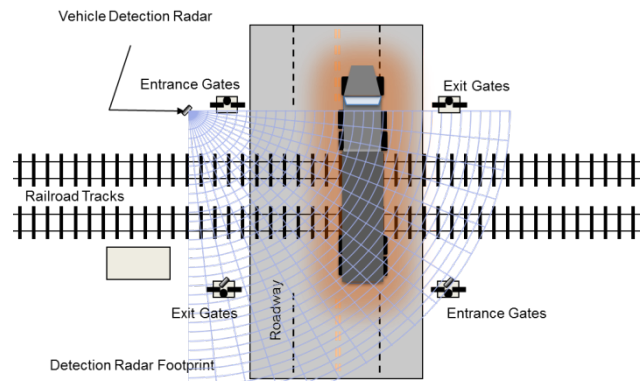


Figure 6. Gate Mast Mounted Radar Detection Footprint

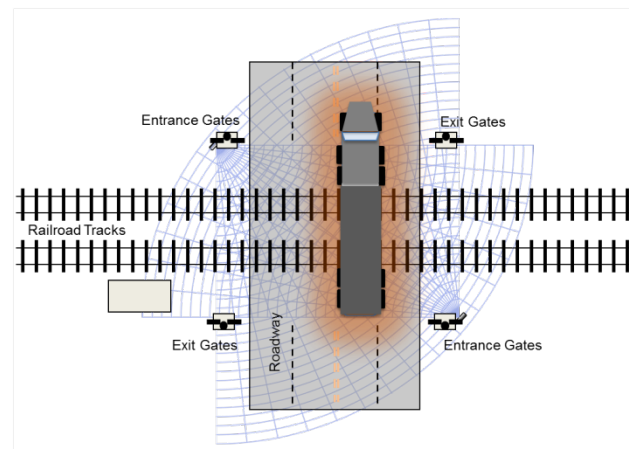


Figure 7. Dual, Complimentarily-Positioned Radar Footprints

accordance with Dynamic EGOM requirements. Although not a national operational standard, current Illinois guidelines recommend an exit gate strategy whereby all exit gates are raised if a vehicle is detected in any one lane for more than 4 s ('bi-directional timeout') (See Appendix A, Four-Quadrant Gates in Illinois). Configured in this manner, the exit gate in the *occluding vehicle* lane would remain in the raised position, and 4 s later the exit gate in the *occluded vehicle* lane would also be raised.

3.1.3 Reverse Direction Filtering

To prevent the typical SSM radar sensor from falsely detecting vehicle occupancy in a left-hand turn at a traffic intersection when the lane is 'clipped' by a left-turning vehicle from a cross-bound lane, the Wavetronix detection algorithms intentionally filter out vehicle flow in the reverse direction. Although important for traffic intersection applications—to prevent false left hand turn lane clipping—this filtering prevented the SSM radar sensor, as currently designed, from detecting vehicles that may have reversed direction or executed a U-turn within the crossing island.

This irregular driver behavior must be accommodated in the crossing application. It was determined that in order to establish a 'bi-directional lane' detection modality, changes in the detection algorithms by Wavetronix would be necessary.

3.2 Generic Railroad Application Requirements

In addition to the suggested changes discussed in Section 3.1, there were additional modifications of a more general nature shown to be necessary in order to fully adapt the SSM radar and its support electronics to the requirements of the railroad industry, which differ in several areas from the requirements for traffic intersection control applications.

3.2.1 AREMA Compliant Electrical Characteristics

Notably, review of the technical properties of the SSM radar sensor and its electronic modules showed that they did not conform to the AREMA power supply and interface isolation requirements necessary to assure no adverse effects on the operation of the crossing warning equipment. Ground isolation and dielectric breakdown specifications set out in AREMA 11.5.1 for Class C equipment require 2000 volts RMS of isolation between all inputs and outputs and the power supply from which the crossing warning system operates. The power supply ground for the SSM radar and support electronics is connected to earth ground for protection from external transient and surge voltages and is therefore not isolated. Furthermore, the output contact closures that signal vehicle presence detection are isolated but only to a level of 1500 volts—less than the AREMA isolation requirement of 2000 volts for Class C equipment.

It was therefore determined that changes to the power supply and output isolation circuitry would be required to make the device meet railroad requirements.

3.2.2 Detection and Failsafe States

Like any system, electronic presence detection equipment can sometimes fail and there may be rare situations where the detection process is inconclusive and indicates a level of uncertainty

regarding the presence or absence of a highway vehicle. In these situations, it is necessary for the system to revert to a ‘failsafe’ state—safely assuming that a vehicle is present (a false detection is preferable to a missed detection). However, the standard output circuit states used by the traffic intersection control industry, including those in the SSM sensor and its support electronics, rely on a ‘closed’ contact output to indicate vehicle presence and an ‘open’ contact to indicate a clear state. This is not consistent with railroad failsafe conventions. For instance, a severed connection between the detection system outputs and the crossing controller inputs would be interpreted by the crossing controller as an open contact, or continuous ‘clear’ condition.

Additionally, the Wavetronix equipment failsafe state forces all detection outputs to the ‘presence’ state without supplying a separate set of electrical contacts to indicate healthy operation or a failsafe condition. Most railroad crossing controllers prefer to use a separate, static ‘HealthCheck OK’ circuit associated with each sensor.

It was therefore determined that changes to invert the vehicle presence output from a closed contact to an open contact state and to establish separate ‘HealthCheck OK’ circuitry would be required to fully conform the device to railroad operating requirements.

3.2.3 Railroad Vitality

Although vitality is not an explicit requirement for crossing warning system components, an aspect of vitality is beneficial for the intended crossing application and a desirable improvement over other forms of vehicle detection. The conventional Wavetronix equipment is questionable as far as vital operation is concerned, but the implementation of two radars, each with a separate output circuitry, establishes an architecture by which both radars independently detect the presence of vehicles in all lanes and detection zones. Each radar has the additional responsibility of regularly communicating operational health information to its own dedicated output module. Dual radar sensors operating in this combined and independent manner satisfy the basic vitality criteria of ‘no single point of failure’.

It was therefore determined that changes would be required to permanently combine the outputs of a dual-radar implementation with separate and redundant circuit paths from each sensor to achieve a no single point of failure architecture.

3.2.4 Active Redundant Operation

The SSM radar sensors were designed to permit up to eight devices to operate in the same vicinity, so that an entire traffic intersection could be outfitted with radar-based vehicle detection. In a traffic intersection application, the radars are pointed away from one another, each trained on its respective approach lanes to the intersection. But reflections from vehicles would reach other radars, so it was necessary for the manufacturer to create separate ‘channels’ to ensure that a maximum of eight radars operating in close proximity would not interfere with one another. This design feature was used in the railroad crossing application where it was envisioned that a minimum of two radars would sense vehicles in the same lanes and detection zones from opposite sides of the crossing, and therefore not interfere with one another.

Consideration was given to comparing the outputs of multiple radars to assure that both devices were operating identically. However, while the dual radar topology with both radars’ detection

outputs combined provides redundant operation, it is not anticipated that the radars will detect each vehicle with 100 percent synchronicity. Differences in response times due to approach direction (Section 3.1.1) and the possibility of vehicle occlusion (Section 3.1.2) will cause slight performance variances between multiple radars.

Therefore, it was determined that individual logs for detection events be maintained by the system, and a calculated percentage of co-incident detection events be continuously updated. An empirically determined percentage of minimum co-incident detection events may be thus established and used as a system metric, for instance, when deviations suggest that the mechanical positioning of the radars or detection zone boundaries may need adjustment. A satisfactorily performing, dual radar system may achieve a typical co-incident detection percentage of 98.9 percent. If a radar sensor was inadvertently repositioned, or one of the radar's detection zones misconfigured, the co-incident percentage would be significantly reduced.

3.3 Summary of Necessary Railroad Application Adaptations and AREMA Compliance Requirements

As detailed in the foregoing sections, and in preparation for formal testing of the Wavetronix radar in crossing applications, the following modifications were designed and implemented on the SSM radar sensor:

- Bi-directional lane detection modality (Section 3.1.3)
- AREMA compliant power supply and output relay interfaces (Section 3.2.1)
- Normally-open failsafe output functionality (Section 3.2.2)
- Establishment of a vital, 'no single point of failure' circuit architecture (Section 3.2.3)
- Dual radar, collaborative operation with co-incident detection tracking (Section 3.2.4)

Other operational characteristics noted in the previous sections, such as arc side detection latency (Section 3.1.1) and vehicle occlusion (Section 3.1.2), did not need modification by Wavetronix since their effects were mitigated by the use of two or more complementarily positioned radars operating on the same crossing island lanes and detection zones.

4. System Performance Tests

4.1 Adaptation and Optimization Engineering Tasks

As described in the preceding sections, hardware and software adaptations were implemented to conform the radar devices to railroad crossing operation and to achieve compliance with AREMA specifications for Class B equipment (Radar Sensor – Wayside Outdoor) and Class C equipment (Radar electronics – Wayside Signal Enclosures).

The radar sensor had undergone environmental testing in advance of its release for use in traffic intersection, highway, and ITS applications. These tested parameters compared favorably with the requirements set out in AREMA C&S Manual 11.5.1, and in fact indicated that the radar had undergone more severe levels of testing than those established by the AREMA manual (Table 4).

Table 4. Outdoor Radar versus AREMA Class B Specifications

Parameter	AREMA Class B Requirement	SSM Radar Sensor Tested Specification	Comparative Rating
Operating Temperature	-40 °F to +160 °F	-40 °F to +175 °F	Exceeds
Relative Humidity (%)	0% to 95% Non-Condensing	0% to 95% Non-Condensing	Meets
Vibration	0.1" p-p 2.0 g p	0.5 g up to 30 Hz (NEMA TS-2-2003)	Equivalent
Mechanical Shock	10 g p	10 g 11ms half sine wave (NEMA TS-2-2003)	Exceeds
Dielectric Strength	3000 Vrms	300V positive and negative	Not applicable - no exposed conductive surfaces other than earth ground
Abrasive Environment	Yes	Yes, plus resistance to corrosion, fungus, moisture deterioration, and UV rays	Exceeds
Weatherability	Not Tested/Established	UL 746C weatherability	Exceeds
NEMA 250 Compliance	Not Tested/Established	Watertight External icing (clause 5.6) Hosedown (clause 5.7) 4X corrosion (clause 5.10) Gasketing (clause 5.14)	Exceeds
FCC	Not Tested/Established	FCC CFR 47, Part 15 section 15.249	Exceeds
Electromagnetic Compatibility	50kHz-88MHz 150uV/m 88MHz-216MHz 250uV/m 216MHz-1000MHz 350uV/m	Per IEC 61000-4-5 class 4	Exceeds

Similarly, the electronics modules to which the radars connect were designed by Wavetronix to comply with prevailing ITS and Traffic Intersection control equipment operating specifications (Table 5). Isolation and dielectric withstand levels differ between the two industries, so initial radar and network equipment was installed using a separate, isolated, UPS-backed power system. Connections between the Wavetronix equipment and the railroad crossing bungalow equipment

were further isolated with mechanical relays (XR and IR signals) and EGMS isolated inputs (for detection zones and health check signals).

Table 5. Wavetronix Electronics Modules versus AREMA Class C Specifications

Parameter	AREMA Class C Requirement	Wavetronix Electronics	Comparative Rating
Operating Temperature	-40 °F to +160 °F	Initially -29 °F to +165 °F, modified to comply with AREMA Class C requirements	Meets
Relative Humidity (%)	0% to 95% Non-Condensing	0% to 95% Non-Condensing	Meets
Vibration	0.07" p-p 1.5 g p	0.5 g up to 30 Hz (NEMA TS-2-1998)	Equivalent
Mechanical Shock	10 g p	10 g 11ms half sine wave (NEMA TS-2-1998)	Exceeds
Dielectric Strength	2000 Vrms	Modified to comply with AREMA Class C requirements	Meets
Abrasive Environment	No	No	Meets
Electromagnetic Compatibility	50kHz-88MHz 150uV/m 88MHz-216MHz 250uV/m 216MHz-1000MHz 350uV/m	Per IEC 61000-4-5 class 4	Exceeds

4.2 Test Site and Equipment

A pair of SSM radars was modified according to the findings in Section 3 and initially installed at a BNSF crossing site in Olathe, KS. An event recorder and remote accessibility network were also installed to prototype and test the equipment that would be installed at the formal test site in Illinois.

The formal test site for the radar evaluation was a triple-track Metra location in Hinsdale, IL, a western suburb of Chicago (Figure 8). Located at the junction of South Monroe Street and Hinsdale Avenue, this site experiences moderate vehicular and railroad traffic—2,350 vehicles and 156 trains per day. Construction was completed at the site in November 2011



Figure 8. Hinsdale BNSF Test Site

to install new preformed crossing panels and buried inductive loops. Between November 2011 and May 2012, the period during which the radar detection system was being evaluated, exit gates were not installed at the crossing based on an agreement between the State of Illinois and the BNSF Railway.

This permitted the Exit Gate Management System (EGMS) at the formal test site to be used solely for the purpose of detecting vehicles via its connected buried inductive loop array. Eight inductive loop detectors were installed beneath the roadway, four for each lane of the crossing (Figure 9). Each lane's four detection loops were programmatically combined within the EGMS, which then provided to the event recorder a single detection signal for each entire lane of traffic.

Two modified Wavetronix SSM radar sensors were installed—one atop each exit gate mast. Initially, the radar sensors were mounted at a height of 14.5 ft, considerably lower than the recommended height of 18–22 ft. It was determined that additional tests should be considered for radar performance at this lower height before relocating the sensors to their intended position.

Radars were grounded at the mast bases and the radar communication cables were run into the crossing equipment bungalow, using a junction box at each mast base to connect to home run cabling. The Wavetronix electronics rack was mounted in the bungalow along with the following equipment (Figure 10):

- An outdoor video camera with 4GB of local flash memory storage
- An interface to the EGMS inductive loop array
- Isolated interfaces to the crossing controller's Island Relay and Crossing Relay signals
- An event recorder/comparator to compare detection signals from the combined radar and the combined loop detection subsystems for each lane of traffic
- Network interfaces to permit remote configuration and remote retrieval of event recorder data and stored video clips and image sequences

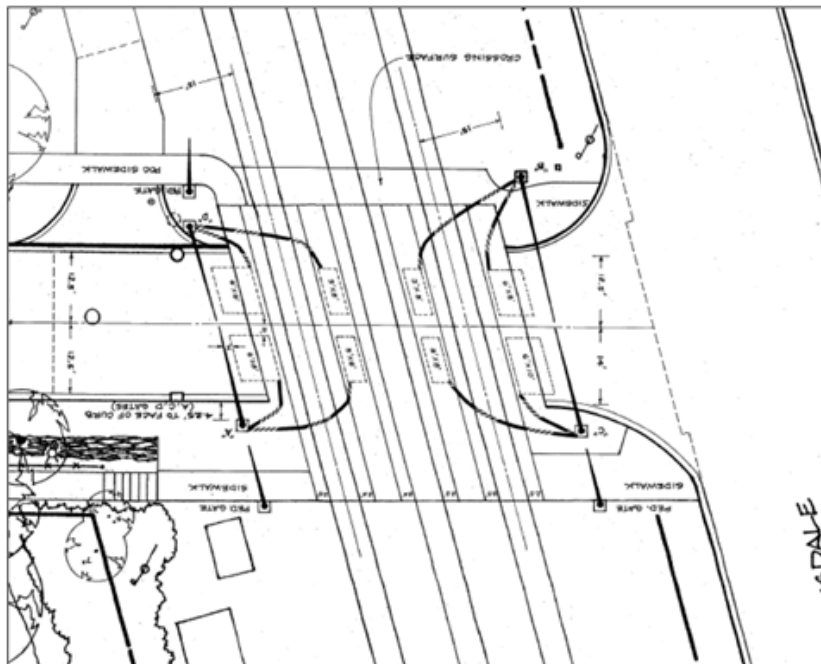


Figure 9. Inductive Loop Locations

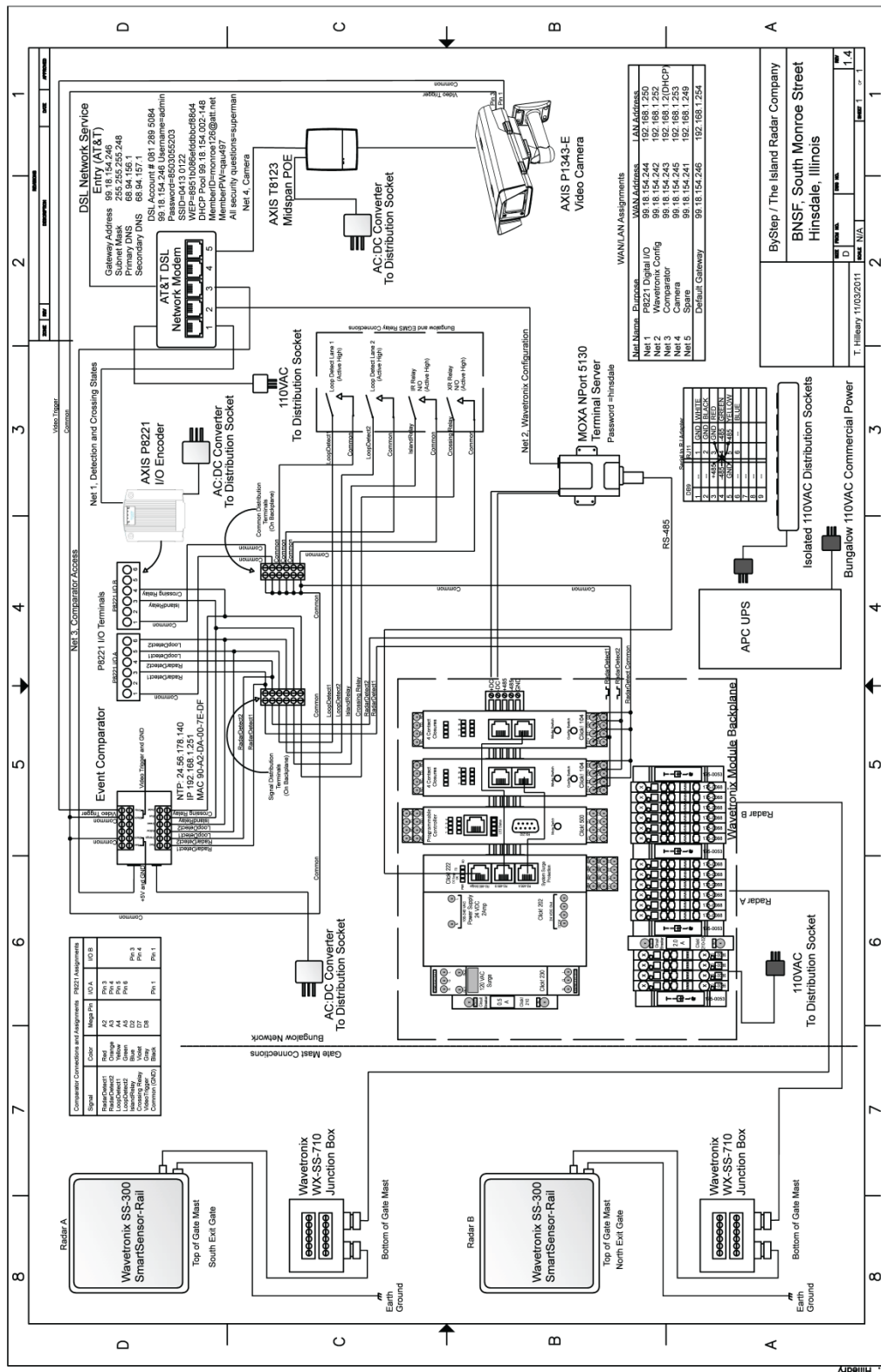


Figure 10. Hinsdale Test Site Equipment Configuration

4.3 Test Methodology and Phases

Field tests were devised and conducted to assess the performance of the radar detection system and validate its potential use as a primary or secondary vehicle detection component for influencing exit gate behavior or detecting potential blocked crossing situations. Tests included the following categories:

- Radar mounting height sensitivity
- Radar-to-radar interference immunity
- Radar snow, slush, and rain sensitivity
- Comparative detection performance, varying vehicle size and location in the crossing island
- Comparative detection performance, extended term test, normal vehicle speeds
- Radar failsafe and health check tests
- Radar blocked crossing detection, notification, and remote accessibility

The following section provides more detail about each test phase, including the test procedure, acceptance criteria, and results. It should be noted that many of the tests involved on-site evaluation and the placement of vehicles of varying sizes in different locations within the crossing island.

The longer-term, comparative tests collected detection data and associated video records over a 4-month period. These records were analyzed and compared to discover false or missed detection events as well as any substantial difference in response between the loop detector and the radar detector subsystems.

The event and video data archive compiled during this 4-month period was also used to capture radar performance during naturally occurring snow and rainfall events that may have induced false or missed detections.

5. Test Procedures and Results

5.1 Radar Mounting Height Sensitivity

Initial installations at the Hinsdale site did not include mast extensions that would have positioned the radar sensors at their optimum height of 18–22 ft (per Wavetronix guidelines). Rather, the radars were initially mounted at a height of 14.5 ft at the top of the exit gate masts. It was determined that this performance should be examined relative to that of a raised height to verify whether the mast extensions were actually necessary.

Initial performance at the lower height showed that certain vehicles (two and three axle single unit trucks with top-side ladders, equipment racks, or empty truck beds) created echoes that bounced back and forth between metal surfaces on the roof frame before some energy returned to the radar. Because distance from the sensor is calculated from the time it takes emitted energy to return to the sensor, this delayed return radar signal was sometimes of sufficient magnitude and persistence to be interpreted as a ‘phantom’ object several feet distant from the real object (Figure 11).

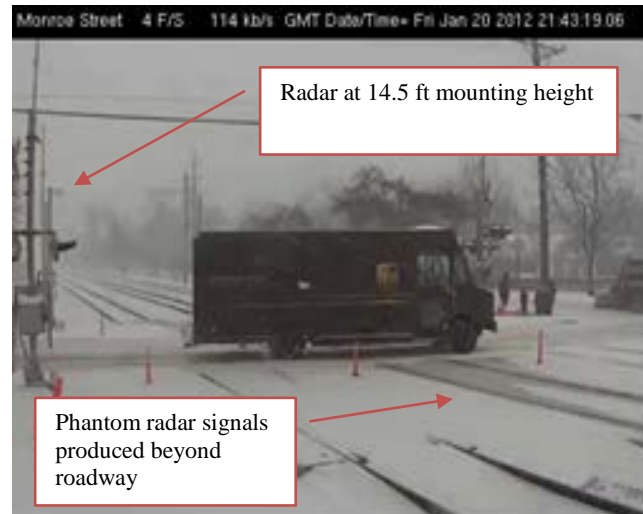


Figure 11. Low Radar Sensor Mounting and Bed Bounce Effect

5.1.1 Procedure and Acceptance Criteria

Discussions with the manufacturer verified that this condition (referred to by Wavetronix as ‘bed bounce’, for an empty truck bed) could occur, but Wavetronix was unable to confirm whether or not this condition was aggravated by radar sensor mounting height and the low angle of incidence of the emitted radar signals.

Notably, after installation of mast extensions that elevated the radar sensors to a preferred height of 19.5 ft (Figure 12), similar vehicles did not produce noticeable phantom radar tracer signals.



Figure 12. Radar Mounted at 14.5 Ft versus 19.5 Ft

5.1.2 Results and Analysis

Comparative tests (described later) conducted on more than 120,000 vehicles evidenced 27 instances of ‘bed bounce’ phantom vehicle detection, a rate of 0.022 percent. It is anticipated that these false detection events may be further minimized or eliminated altogether through the use of higher radar sensors and the adjustment of attenuation and delay settings. It should be noted that, like the buried inductive loop’s periodic detection—due to heightened sensitivity—of vehicles in an adjacent lane (Section 2.4.2.3), phantom object detection of this sort by the radar only occurs when there is already a vehicle in the crossing. Therefore, it appears that there are minimal safety implications.

5.2 Radar-to-Radar Interference Immunity

The proposed system is comprised of two or more radars, providing redundancy and radar cross-checking functions absent in other popular vehicle detection technologies. It is therefore important that multiple radars do not interfere with one another and that any potential interference be self-correcting by the radar system itself, through a process by which radar channel sets are assigned and adjusted semi-automatically.

5.2.1 Procedure and Acceptance Criteria

This test verifies the radars’ ability to sense potential interference from additional radars trained on the same detection area, and to automatically adjust channelization to permit multiple radars to operate without interference. The test is set up by intentionally programming the two radars’ channel sets to the same channel.

The radar devices should promptly communicate a channel contention and permit an automated correction procedure to separate the channel sets.

5.2.2 Results and Analysis

When the radar configuration application is invoked, it first searches the site for connected radars. Before permitting the configuration of any connected radar, the configuration application attempts to confirm any channel conflicts. In the test case illustrated in Figure 13, a warning message was displayed, offering the opportunity to automatically resolve and optimize channel set selections for the multiple radars.

5.3 Snowfall Sensitivity Tests

Prior highway experience (i.e. not at railroad crossings) with the SSM radar by the Illinois Department of Transportation evidenced periodic false detection events due to snowfall conditions, especially those involving heavy ground accumulation of slush and plowed snow. Two forms of snowfall sensitivity were tested at the railroad-crossing site—false detections and missed detections.

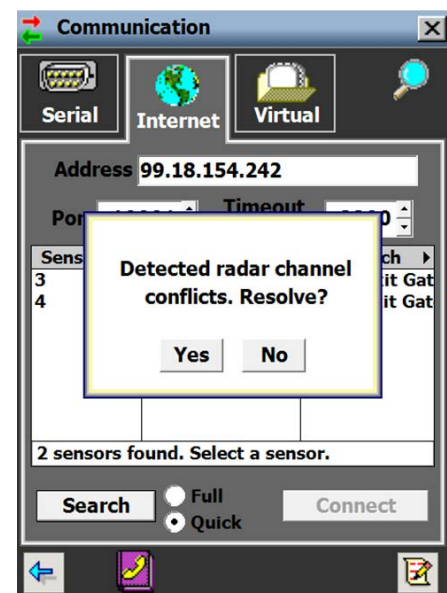


Figure 13. Radar Channel Set Conflict Detection and Resolution

Described in greater detail in Section 5.6, the long-term comparative performance tests involved equipment that could digitally record detection events for radar and loop detector subsystems, and also trigger a visual record of detection events from a camera with a view of the entire crossing island. The ability to trigger video records based on various criteria was utilized to structure snowfall and rainfall tests, which are described in greater detail below.

5.3.1 Procedure and Acceptance Criteria

5.3.1.1 Snowfall-Induced False Detections

To test for snow and slush false detection sensitivity, a test was devised to capture any detection events during heavy snowfall conditions in a zone where no vehicles were expected to be traveling. Using the large area west of the crossing roadway comprised of crossing panels, asphalt road surface, and rails, a special detection zone was established (shown in red, Figure 14). This area was chosen because it was identical to the roadway, crossing panel, and rail surface of the roadway lanes over the crossing. The camera was programmed to store a video record of any object detected in this zone. In this manner, unless snowfall and related conditions created false detection events, the only recorded detection events would be train traffic or pedestrian traffic that were reasonably expected to periodically traverse the area.

5.3.1.2 Snowfall-Induced Missed Detection

To test for missed detection events, comparative test data accumulated between January 20 and April 30 was examined for instances of missed detection events, under the assumption that all radars and all loops would not simultaneously miss detection of a vehicle. Therefore, any missed detection event by one of the radars would be revealed as an anomalous detection event.

During this period, there were five precipitation periods that included snow in excess of trace amounts (Table 6). Only one snowfall event on January 20 exceeded 5 inches (in) of accumulation, far fewer snow storms than normal for the region.

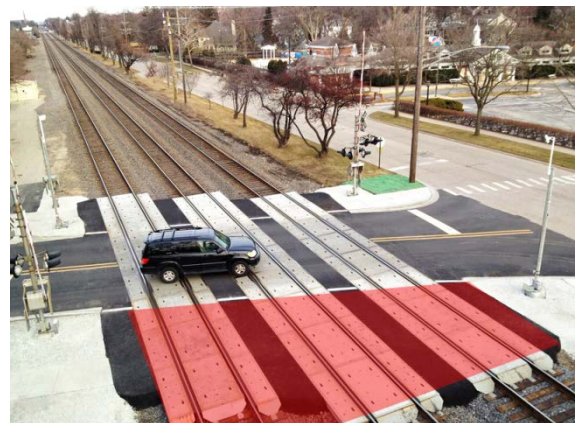


Figure 14. Non-Traffic Area Established for Snowfall False Detection Tests

Table 6. Precipitation Events during Radar and Loop System Tests

Hinsdale Illinois, precipitation days greater than trace amounts		
Date	Precipitation	Precipitation Type
January 20, 2012	5.18"	Snow
January 22, 2012	.44"	Snow
January 23, 2012	.25"	Rain-Snow Mixture
February 16, 2012	.21"	Snow
February 24, 2012	.24"	Snow
March 2, 2012	.19"	Rain
March 8, 2012	.21"	Rain
March 12, 2012	.28"	Rain
March 23, 2012	.89"	Rain
March 30, 2012	.25"	Rain
April 1, 2012	.21"	Rain
April 14, 2012	.87"	Rain
April 15, 2012	.82"	Rain
April 28, 2012	.20"	Rain
April 30, 2012	.39"	Rain

Initial tests conducted at the Olathe, KS, site showed that general attenuation settings of 3–6 decibels (dB) were sufficient to adequately attenuate snowfall reflections yet not negatively affect vehicle detection, especially at the close ranges dealt with in a crossing island application. Attenuation was conservatively set at 4 dB across the entire detection footprint for both radar sensors.

It was anticipated that a small percentage of false detections could occur, given prior observations by the State of Illinois in traffic intersection applications—it is not known, however, whether attenuation settings were addressed in those trials. It is highly important that no missed detections occur under any circumstances, but especially in the primary use case where heavy precipitation may limit visibility and possibly increase the likelihood of vehicles getting trapped in the crossing island upon crossing warning system activation (Brian Vercruyse, Illinois Commerce Commission, personal communications, November 30, 2011).

5.3.2 Results and Analysis

5.3.2.1 Snowfall-Induced False Detection Results

The majority of the Snowfall-Induced False Detection test data was gathered during a 5.1–5.4-in snowfall on January 20, 2012. As described in the foregoing, an isolated detection zone was established in an area of the crossing where vehicle traffic would not be found. By triggering a video image sequence for any detection event triggered in this zone, it was reasoned that only trains or pedestrians would cause, and therefore be captured in, the image record. Any detection event captured on video that did not evidence a train, pedestrian, or other visible physical object was assumed to be the result of snowfall.

The test ran from 3 p.m. until 12 midnight during which there was an accumulation of 5.1–5.4 in of snow. Upon examination of the video and event recorder records, 68 image capture events

had occurred. Of these, 65 were trains (as expected). One triggered event was due to a ‘bed bounce’ occurrence from a UPS truck in lane 1, directly adjacent to the specially established, non-trafficked detection zone (the radar had not yet been raised to its ideal height of 19.5 ft). The other two occurrences involved a jogger and a family pulling a sled across the non-trafficked detection zone (Figure 15).



Figure 15. Snowfall False Detection Tests Example Outcomes

During the course of subsequent long-term comparative vehicle studies that ran until April 30 (>120,000 vehicles), there were two events for which the radar system was apparently triggered by snowfall, most likely from surface accumulation of slush. There were no similar snowfall-induced false detection events observed for the loop system. It should be noted that that mild winter season in 2011 was not typical for the Chicago area. East coast locations, for instance, received snowfalls of 20 in or more, and may have yielded different false and missed detection results. Additional testing for more typical precipitation levels is warranted and recommended.

5.3.2.2 Snowfall-Induced Missed Detection Results

Over the course of the comparative vehicle studies, there were no missed detection events for the loop system or the radar system that were attributable to precipitation. Given the use of two complementarily positioned radar sensors, this result was expected. Further research providing greater detail about the relative response times for two radars operating in this collaborative fashion is necessary, if for no other reason than to justify the need for two radars rather than one.

5.4 Rainfall Sensitivity Tests

5.4.1 Procedure and Acceptance Criteria

Preliminary testing at the BNSF crossing site in Olathe showed that dense rainfall could produce false detection events. According to the manufacturer, these events were the result of the physical rippling movement of water accumulating at the surface level. In limited testing, attenuating the radar gain by 3–6 dB eliminated this phenomenon.

5.4.1.1 Rainfall-Induced False Detection

The long-term comparative data tests described below in Section 5.6 provided data that was used for rainfall sensitivity tests. Under the assumption that all radars and all loops would not simultaneously produce a false detection at the same time and in the same zone location, an anomalous detection event would be created and recorded in the event recorder and on video. Examination of the visual record produced for any anomalous detection event would reveal whether a rainfall-induced false detection had occurred.

5.4.1.2 Rainfall-Induced Missed Detection

The long-term comparative radar performance tests described below in Section 5.6 provided data that was used for rainfall sensitivity tests. Under the assumption that all radars and all loops would not simultaneously miss a vehicle detection event, an anomalous detection event would be created and recorded in the event recorder and on video. Examination of the visual record produced for any anomalous detection event would reveal whether a rainfall-induced false detection had occurred.

5.4.2 Results and Analysis

5.4.2.1 Rainfall-Induced False Detection Results

Over the course of the comparative vehicle studies (Figure 16) there were 12 events (out of a total of more than 120,000) for which the radar system was apparently triggered by rain, most likely from surface accumulations. There were no similar rainfall-induced false detection events observed for the loop system.

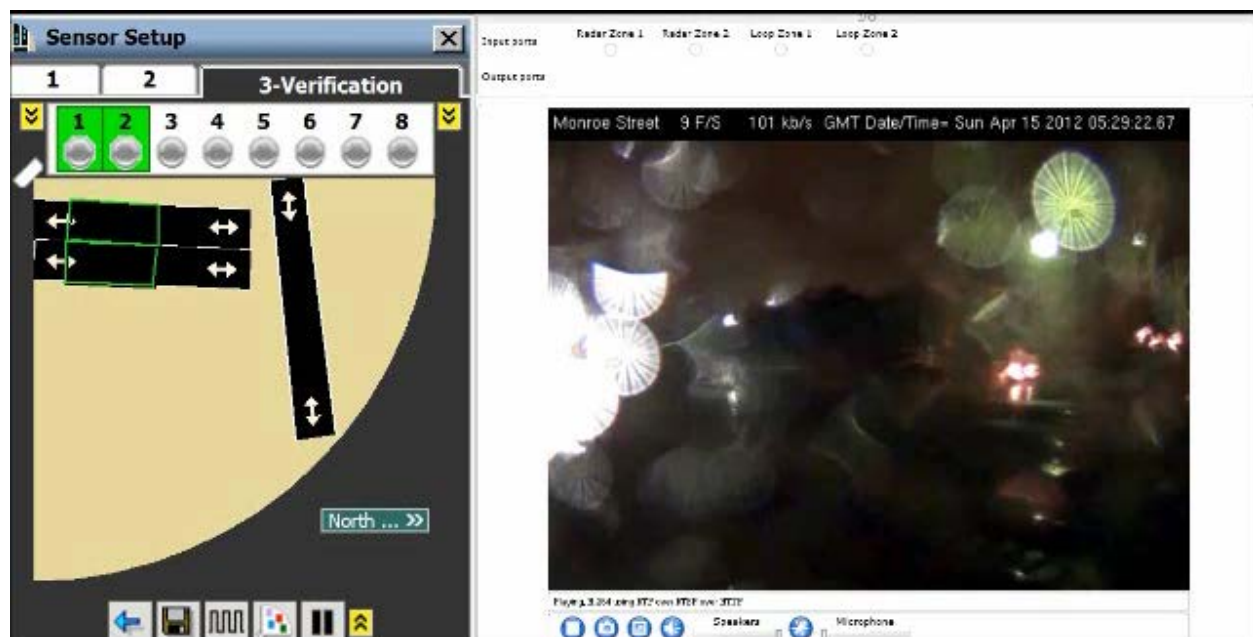


Figure 16. Example of the Rainfall False and Missed Detection Tests

According to the manufacturer, rainfall-induced false detections can occur due to random movement of surface water during extremely high volume rainfall events. For a detection to occur, reflective peaks and ripples on the surface of pooled water must be of sufficient magnitude and duration to trigger a detection state. Prior experimentation determined that attenuation settings of 4–6 dB minimized rainfall-induced false detections; however, no integration delay parameter was applied. The manufacturer has since advised that setting a 200 to 300 millisecond (msec) delay parameter for each of the zones may further reduce rainfall-induced false detections. Thus configured, a detection event would have to persist uninterrupted for the entire delay period in order to be registered; there is a low probability of this occurring at a typical crossing location due to the randomness of surface water movement and the short duration of peaks and ripples that presumably cause these false detection events. Additional testing utilizing the delay parameter set at 200 to 300 msec is therefore recommended to verify this hypothesis.

5.5 Vehicle Size and Location Tests

Location tests were conducted to verify the radar system ability to detect vehicles regardless of where they may be located in the crossing, and regardless of potentially aberrant driver behavior (e.g. reversals of heading and direction of travel). Under the strict supervision of BNSF personnel, vehicles of several sizes were temporarily placed at various locations on the crossing island, especially in areas where continuous loop detector coverage might have been questionable.

The test crossing was partitioned into 12 sections representing areas where vehicles could be located (Figure 17). It should be noted that areas where the grade crossing surface projects beyond the roadway, outside the MTCD zone, have been included (called ‘aprons’ for the purpose of this report). This addition was made in response to recent occurrences at the test crossing where a vehicle executed a right turn in the middle of the crossing, was driven off the crossing panel surface, and for several minutes remained high-centered on the track itself (see section 5.8.1.1, High Centered Vehicle Incident).

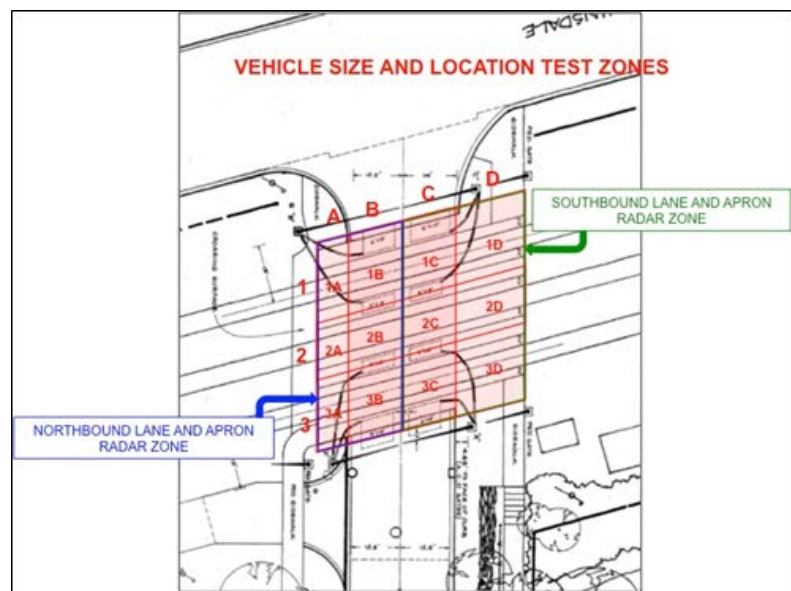


Figure 17. Crossing Island Partitions for Vehicle Size and Location Tests

5.5.1 Procedure and Acceptance Criteria

5.5.1.1 Vehicle Location

Test vehicles were slowly driven onto the crossing island into each of the 12 designated partitions, pausing for 60 s, long enough to simulate a vehicle being operated in the crossing island during a warning system activation and long enough to simulate an obstructing vehicle (for the purposes of subsequent blocked crossing tests and implementation recommendations). Of specific interest were the following vehicles classes:

- Sedan
- Sub Compact (e.g. Smart Car)
- SUV or 15 Passenger Van
- Single-unit combination truck with trailer (e.g. railroad Boom Truck with loaded trailer)

Of specific interest were the following locations within the crossing island:

- Partially within the MTCD zone but on the roadway
- Straddling the crossing roadway centerline
- Partially within or outside the MTCD to the right or left of roadway lanes (where possible on extended width crossing panel crossing installations)

It was expected that vehicles would be detected within one second of entering the detection zone and that the detection would persist for as long as the vehicle remained anywhere—even partially—within an established detection zone.

5.5.1.2 Vehicle Size

Test vehicles were driven slowly onto the crossing island, stopped for 60 s mid-way (long enough to simulate an obstructing vehicle), and then driven off the crossing island. Detection by one or both radar sensors as well as the inductive loop system should occur when a vehicle or portion thereof is inside the MTCD and should clear when the vehicle completely exits the MTCD zone.

5.5.1.3 Vehicle Length

Test vehicles were driven slowly onto the crossing island, stopped for 60 s mid-way (long enough to simulate an obstructing vehicle), and then driven off the crossing island. Detection by one or both radar sensors as well as the inductive loop system should occur when the vehicle or portion thereof is inside the MTCD and should clear when the vehicle completely exits the MTCD zone.

5.5.1.4 Vehicle Occlusion

One large test vehicle was driven slowly onto the crossing island, stopped for 60 s mid-way (long enough to simulate an obstructing vehicle), and then driven off the crossing island. Simultaneously, a smaller vehicle was driven in a similar manner from the opposite direction. The radar sensors should detect both vehicles even though the smaller vehicle is occluded by the

larger one from the perspective of at least one of the two radar sensors. Vehicle pair combinations included:

- Sub Compact (e.g. Smart Car)
- SUV or 15 Passenger Van
- Single-unit combination truck with trailer (e.g. railroad Boom Truck with loaded trailer)

5.5.1.5 Vehicle Speed

Test vehicles were driven through the crossing island at normal crossing speed, approximately 25–30 mph. Detection by one or both radar sensors as well as the inductive loop system should occur when the vehicle or portion thereof is inside the MTCD and should clear when the vehicle completely exits the MTCD zone. Vehicles employed for this test included:

- Sedan
- Sub Compact (e.g. Smart Car)
- SUV or 15 Passenger Van

5.5.2 Results and Analysis

A near-field wireless link and display was used to provide an indication of loop and radar system outputs inside the vehicles being tested. In essence, vehicles of varying sizes were tested throughout the crossing island to discover any locations where either the radar detection system or the loop detection system could not ‘see’ the vehicles (Figure 18).



Figure 18. Vehicle Size and Location, Occlusion Testing

Except for the instance when an ultra-compact (Smart Car) was slowly moved across a preformed crossing panel where no loops could be located, both systems properly detected vehicles of all sizes. When the ultra-compact vehicle remained stationary on one of the crossing panels, the loop system could not maintain detection of the vehicle, while the radar system continued to detect the presence of the vehicle.

Vehicle occlusion tests were conducted utilizing an ultra-compact and a passenger large van in one case, and a sedan and combination truck in another. As expected, due to the use of complimentary positioned radars sensors, the smaller vehicles in both cases were detected and tracked as they slowly proceeded through the crossing in opposite directions.

It was found that very slow moving vehicles take additional time to be detected by the radar sensors at the extreme edges of the detection zones. Traveling at less than 1 ft per s, smaller vehicles, on occasion, were detected after they had traveled almost 2–3 ft into the detection zones, but were detected in less time at normal crossing speeds. This increased distance,

however, was still at the boundary of the MTCD and within the Track Storage Distance between the rails and the crossing gates.

5.6 Comparative Radar Performance

5.6.1 Procedure

A comparative test, the most data-intensive of the test categories, was established to monitor and record detection events from the radar detection subsystem and to compare those events on a continuous basis with similar detection events signaled by the loop subsystem of the site's EGMS system. Four contiguous EGMS loop outputs per lane were combined into one occupancy detection signal for each lane of traffic. Similarly, two detection zones were established for each of the two radar sensors mounted atop the crossing's exit gate masts—one zone per radar for each lane of traffic. Ideally, and with sufficient allowances for minimal signal latencies, each of the two subsystems was expected to detect the same vehicles in their respective lanes, whether moving or stationary.

An Event Comparator, a small microprocessor-based event analyzer, was installed—and was able to detect situations where detection events from each of the two subsystems differ sufficiently that they may be characterized as 'potentially anomalous'. Utilizing a similar evaluation methodology as prior studies, four categories of potentially anomalous events were recognized (Medina et. al. 2008, 2009, 2011)^{3,4}.

1. **Missed detection events:** An instance where the radar detection subsystem does not respond to a detection event from the buried inductive loop system. A missed detection of a vehicle inside the MTCD (Minimum Track Clearance Distance) zone during a crossing warning system activation would not affect exit gate position or have an adverse safety effect. A missed detection results if there is no corresponding radar detection event within 1.5 s of a loop detection event.
2. **False detection events:** An instance where the radar detection subsystem records a detection event that the buried inductive loop system does not. A false detection results if the radar detection subsystem records a detection event that is not corroborated by the loop detection system within 1.5 s.
3. **Stuck detection events:** An instance where the radar detection subsystem and the buried inductive loop system record detection events, but the radar system detection persists longer than that of the loop system. A stuck detection results if the radar detection subsystem persists more than 3 s longer than a loop system detection event.
4. **Dropped detection events:** An instance where the radar detection subsystem and the buried inductive loop system record detection events but the radar system detection clears sooner than that of the loop system. A dropped detection results if the radar detection clears more than 3 s before the loop detection system signals a clear state.

Upon recognition of a potentially anomalous detection event, the Event Comparator was programmed to trigger a video camera trained on the crossing to record and remotely store clips from a continuously running video stream from a point in time 4 s before the detection event to 6 s after the detection event. From time to time, these pre-trigger and post-trigger time constants were altered to improve image content and conserve network bandwidth. Video clips were

periodically downloaded and manually analyzed to determine the underlying cause of the potential detection anomaly.

During the passage of a train over the crossing, both loop and radar detectors register numerous detection events. It was desirable to prevent these train detection events from unnecessarily consuming event recorder and video storage space. Therefore, Island Relay (IR) and Crossing Relay (XR) signals from the bungalow systems were used to capture vehicle behavior between crossing activation and train arrival, and to mask detection output signals from the radar and loop subsystems during those periods when a train was occupying the crossing and detection data was invalid.

The following state diagram (Figure 19) illustrates the comparative analysis process and the resulting video triggers:

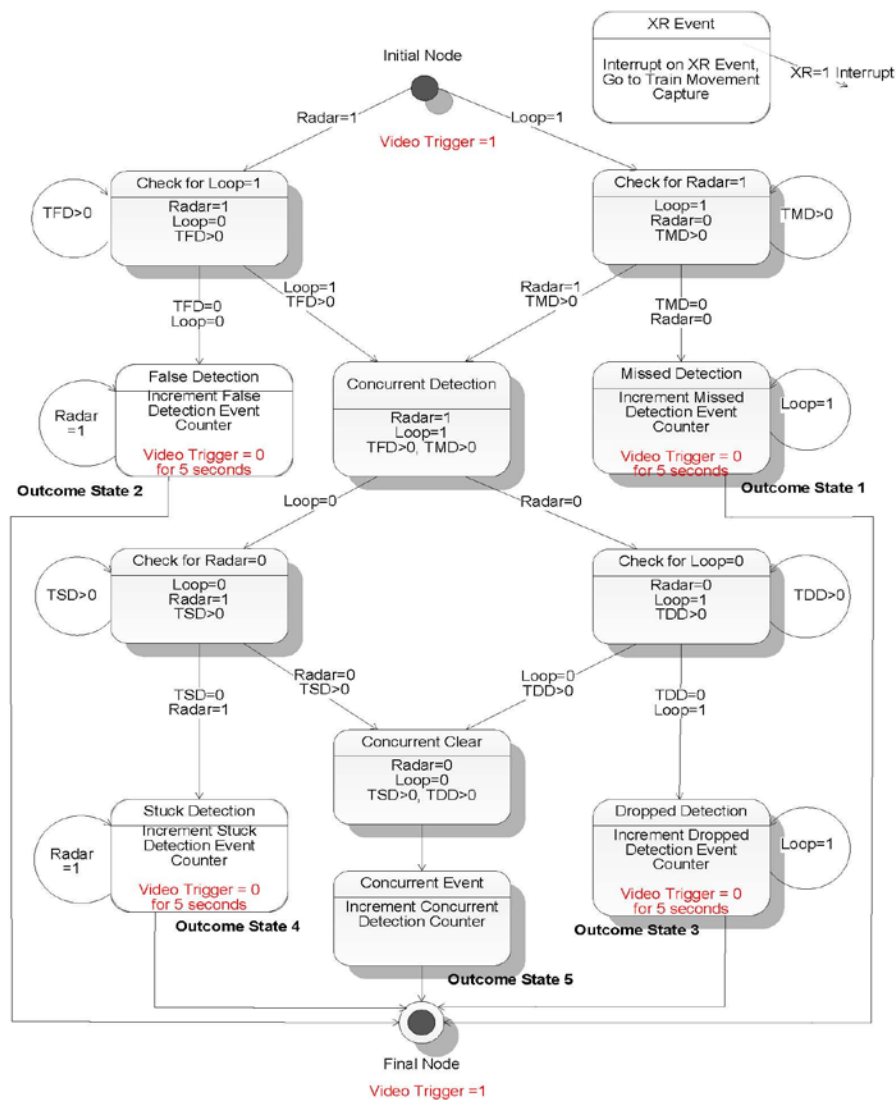


Figure 19. Anomalous Detection Analysis State Machine

Lane-based outputs from the dual radar sensor array and from the eight-loop array were continuously analyzed by the Event Comparator for differences between detection events. Every instance of lane occupancy, whether from single or multiple vehicles, was expected to produce a detection event at the same time and for a similar duration from both detection subsystems—a co-incident detection event. Each of these co-incident events was recorded in the Event Comparator log for periodic download to the host server. If either the radar or the loop detection system signals a detection event and the other system does not, a co-incident event was deemed not to have occurred. In that case, the underlying cause for these potentially anomalous detection events must be discovered. So the Event Comparator was programmed to cause a video clip image capture of the vehicles on the crossing for a period ranging from 4 s before the subject detection event to 6 s after the event. These time windows were adjusted once data collection began in order to center the sequence of images across the event timing.

Captured video clips of potentially anomalous detection events were downloaded to the host server archive for examination, analysis, and permanent storage. The extent to which extreme weather events trigger detection signals was also captured under this test phase and logged initially as anomalous false detection events subject to video clip analysis and verification as described in Section 5.3 and Section 5.4 above.

If the per-lane detection events registered by the radar were not co-incident with those of the loop detection subsystems, then a potentially anomalous detection event was deemed to have occurred and was classified by the event recorder into one of the following four categories:

1. **Missed detection events:** An instance where the radar detection subsystem did not respond to a detection event recognized by the buried inductive loop system.
2. **False detection events:** An instance where the radar detection subsystem registered a detection event that the buried inductive loop system did not.
3. **Stuck detection events:** An instance where the radar detection subsystem and the buried inductive loop system registered detection events but the radar system detection persisted longer than that of the loop system.
4. **Dropped detection events:** An instance where the radar detection subsystem and the buried inductive loop system registered detection events but the radar system detection cleared sooner than that of the loop system.

Downloaded event records were examined for instances of potentially anomalous detection data. Video images associated with these events were analyzed to determine the actual detection events that occurred.

5.6.2 Acceptance Criteria

It is generally acknowledged that the detection of high volumes of vehicles traveling through the crossing island is not an ideal characterization of the intended use case associated with potentially trapped vehicles. However, the continuous collection of detection event data over the course of 3–4 months was intended to illuminate potential detection anomalies and to provide relative measure of detection performance accuracy and repeatability.

5.6.3 Results and Analysis

Event data was collected along with supporting video and image sequence data for the period between January 19 and April 31, 2012. Several interruptions occurred during this period; for example, the loop detection system and/or associated EGMS ‘locked up’, necessitating EGMS power-cycling and board replacement by BNSF personnel. On occasion, the unexpectedly high volume of image data being stored was interrupted and certain event sequences rendered incomplete due to one or more of the following:

- Excessive data being pushed to off-site ftp archive storage
- Periods of time during which event recorder data was being downloaded to the host server, suspending data collection or image capture by the on-site equipment
- A bungalow circuit breaker that periodically tripped due to unknown causes
- Event recorder and video image time stamp drift (NTP time syncs are performed on a daily basis, but periodic unavailability of pooled NTP servers can allow event recorder events and camera images to become uncorrelated)

Factoring out event data that was subsequently unavailable or incomplete, a total of 120,130 complete vehicle detection event sequences was collected—with 95.4 percent confirmed identical, co-incident detection responses from the loop system and the radar system.

The remaining 5,559 potentially anomalous detection events were individually examined to determine the underlying differences between what the loop system detected and what the radar system detected (Table 7).

5.6.3.1 Missed Detection Events

In this most important and critical category, there were no missed detections by either the loop system or the radar system. Given the use of multiple radar sensors and multiple loop sensors, this outcome was not unexpected. Missed detections, were they to occur, would most likely result from the electronics supporting and processing the fundamental detection signals from the radar or loop sensors.

5.6.3.2 False Detection Events

Although minimal, both the loop and the radar systems exhibited instances of false detections, based on factors unique to each system’s basic sensing technology. In a small number of cases, 27 for the radar and 67 for the loop system, false detections occurred with no underlying causal factor visible in the video record.

As described in Section 2.4.2.3, loop detectors that are installed between rails encounter space limitations that limit vertical height detection sensitivity. The compensatory increased gain applied to these interior loops creates a tendency for them to detect vehicles that are technically in the adjacent lane of traffic. The roadway geometry of the test site, a “T” intersection, resulted in many drivers making wide turns into the crossing, often very close to the centerline of the roadway. The radar system was observed to have comparatively tighter detection boundaries and was less frequently triggered by vehicles in an adjacent lane.

Together, these factors resulted in 4,673 adjacent lane detection events by the loop system but not the radar system. Consequently, the event recorder initially classified these events that were detected by the loop system but not by the radar system as missed detections by the radar system.

But since these detections were the result of the loop system detecting a vehicle in an adjacent lane, these events were not actually missed detections. Because a vehicle was present in the crossing during these events, any resultant ascent of the exit gates would not have been a partial activation failure as currently defined by FRA.

Table 7. Comparative Loop versus Radar Test Summaries

Comparative Performance Radar versus Loop Detection January 19, 2012 to April 30, 2012				
Vehicles	120,130			
Coincident Detection Events	114,571		95.4%	
Potentially Anomalous Detection Events	5,559		4.6%	
Potentially Anomalous Detection Event Resolution				
	Radar System		Loop System	
Confirmed Missed Detection Events ¹	0	0.00%	0	0.00%
False Detection - No Vehicles Evident in Either Lane ²	27	0.022%	68	0.057%
Adjacent Lane Vehicle Detection ³	406	0.338%	4,673	3.890%
Loop Detection Persisted After Train Move ⁴	2	0.002%	34	0.028%
Bed Bounce, Phantom Vehicle Detection ⁵	29	0.024%	0	0%
Detections Attributed to Rain or Snow ⁶	14	0.012%	0	0%
Detection Due to Bicycle or Pedestrians ⁷	44	0.037%	4	0.003%
Temporary Stuck Detection Events ⁸	38	0.032%	72	0.060%
Temporary Dropped Detection Events ⁹	76	0.063%	59	0.049%

Notes are detailed in the following subsections.

5.6.4 Notes Regarding Comparative Event Data Results

Note 1. Missed Detection

Initial data identified a number of missed detection possibilities. Further analysis of available video and image sequences associated with the event showed a number of underlying causes that in each case proved to be something other than a missed detection:

- The loop system detected a vehicle close to the centerline in an adjacent lane, resulting in an initial event classification as a missed radar detection in that adjacent lane. These events were reclassified as adjacent lane vehicle detections by the loop system (see Section 5.6.3.2 above).

- The radar system detected a pedestrian or cyclist in a lane, an event to which the loop system could not respond. These events were isolated and re-categorized as detections due to a bicycle or pedestrian.

Note 2. False Detection, No Vehicles Evident in Either Lane

No vehicles were evident in image data within detection event time windows, and there was no visual evidence of other detection causes such as heavy precipitation. Therefore, the underlying cause of these 27 radar system false detections event and 68 loop system false detection events is inconclusive.

Note 3. Adjacent Lane Vehicle Detection

Loop system adjacent lane detection events

The “T” intersection formed by the junction of South Monroe Street and Hinsdale Avenue at the south side of the crossing results in many vehicles performing turns into and out of the crossing, outside of their respective lanes. In addition, because the loop detectors have a “V-shaped” detection cone and because space-constrained interior loops are tuned to near maximum sensitivity, more than 4,600 loop detections were recorded that were the result of vehicles traveling close to the centerline of the crossing. However, it should be noted that these detections were the result of actual vehicles, albeit in another lane, and any subsequent influencing (ascent) of exit gate position would not have been a partial activation failure as currently defined by FRA.

Radar system adjacent lane detection events

In the case of radar-originated false activations, event video data showed that the radar detection zone for lane 1, southbound traffic, extends about 2 ft further than necessary. The wide turns generally executed by drivers at this intersection created an initial jitter effect of a tracked vehicle between lane 1 and 2. That is, a northbound vehicle entering the crossing was first detected by the radar system in the end of the elongated southbound lane detection zone, prior to detection in that lane by the loop system. Consequently, the vehicle was detected in both lanes over the course of 1–2 seconds before the vehicle was fully in the northbound lane (and maintained detection throughout the remainder of its travel through the crossing island).

Increasing the time delay settings in the radar system as described and recommended in Section 5.4.2.1 is recommended to minimize this effect.

Note 4. Loop Detection Persisted More than 5 Seconds after Train Move

For reasons that are not fully understood, on multiple occasions a video image sequence showed a persistent loop presence for a period greater than 5 s while crossing gates were lowered. The fact that no trains were visible in these images suggests that these false loop detections were associated with a train that had just moved through the crossing. In all cases, these persistent detection states cleared as entrance gates were raised and vehicles moved into the crossing island. It is uncertain whether this anomaly was caused by one of the four loops in the affected lane or whether it was the result of the loop system electronics.

Note 5. Radar System Adjacent Lane Vehicle Detection

Described in the foregoing, and unique to the radar detection system, certain large bed trucks were found to create instances of phantom vehicles in the adjacent lanes. Due to their different detection methods, the radar system experienced these adjacent lane vehicle detections but the loop system did not. Whether experienced by the radar detection system or the loop detection system, adjacent lane vehicle detections do not produce a negative safety consequence since there is already a vehicle in the crossing island. However, minimizing this phenomenon in the course of future research is of interest. It is speculated that increasing the time delay parameter of the radar zones to 200–300msec, as suggested in Section 5.4.2.1, would minimize these phantom occurrences. This would require that any short term, intermittent detection event persist for at least this time period before the radar system verified the detection and changed the output accordingly.

Note 6. Radar False Detections Attributed to Rain or Snow

It has been observed that heavy rainfall on non-crowned road surfaces that permit pooling of water and splash turbulence can trigger momentary false vehicle detection events. Tests conducted in the subject evaluation project utilized moderate attenuation settings in the radar sensors to reduce susceptibility to rain-induced false detection events. Although there were only 14 rain-induced false detections during the test period, the loop system did not experience similar false detections owing to its different detection technology. Ongoing research being conducted by the Illinois Center for Transportation focuses additional attention on precipitation effects, utilizing radar settings that include 200 msec ‘delay’ parameters, and requiring that radar signals persist for a minimal period of time before detection and classification decisions are made by the radar sensor. It is thought that these delay settings will further minimize random, stochastic stimulus as a result of surface water rippling and turbidity. More detail may be found above in Section 5.3 and Section 5.4.

Note 7. Radar Detection Due to Bicycle or Pedestrians

Although the radar cross section presented by a human is 15–20 dB less than that of a vehicle³⁰, on occasion, the radar system detected both pedestrians and cyclists. This investigation did not address whether or not reliable and repeatable detection of cyclists would be achievable by the radar system through adjustment of attenuation and delay settings. Furthermore, this investigation did not determine whether the radar system’s ability to detect bicycles or pedestrians is a positive or negative capability with regard to the operation of exit gates in four-quadrant gate warning system installations.

Note 8. Stuck Detection Events

A small number of loop and radar detections appeared to persist beyond the 2-second window that was used to classify Stuck Detections. Whether due to event recorder/video image time synchronization differences or event recorder response times, these detections appear to be timing related—none remained in the ‘Stuck On’ state more than one or two seconds. Therefore, no partial activation failures would have resulted where the exit gate would have remained in the raised position but with no vehicles in the crossing. Future studies that quantify response times in greater detail are recommended.

Additional studies are being conducted by the Illinois Center for Transportation utilizing an event recorder process that can capture individual radar performance and measure the precise duration of radar detection events that persist longer than loop system detection events.

Note 9. Dropped Detection Events

Similarly, a small number of loop and radar detections dropped out prematurely relative to the other detection system and relative to the record established by recorded video image sequences. It was inconclusive as to whether or not these were event recorder time synchronization errors in all observed cases where temporary and detection states were immediately re-established. It is recommended that the ‘extend’ parameter of the radar zones should be increased from their default setting of 0 msec to between 100 msec and 200 msec to minimize these occurrences. This modification would ensure that any radar detection event persisting for this time period would bridge any momentary dropout periods by using the same technique that the loop system relies on to prevent dropout within the crossing as a detected vehicle moves from loop to loop.

Studies are underway at the Illinois Center for Transportation to test an event recorder process that can capture individual radar performance, permitting the precise duration of dropped detection events to be quantified in greater detail.

5.7 Failsafe State Tests

Failsafe tests were conducted to assure that any suspected loss of detection capability would cause the crossing controller equipment, to which the radar system was connected, to assume failsafe states. Potential causes or operational uncertainties that could result in failsafe states are identified below:

- Loss of internal radar heartbeat
- Loss of any of a radar sensor’s sixteen segments
- Loss of partial or total system power
- Loss of communication from a radar sensor

These conditions were created or simulated, as necessary, to observe and confirm failsafe system response.

5.7.1 Loss of Radar Heartbeat (Including HealthCheck Failure, Internal Radar Segment Failure)

5.7.1.1 Procedures and Acceptance Criteria

To simulate the loss of radar heartbeat, the communication circuit was disconnected from one of the sensors. It was expected that the corresponding output channels would revert to their failsafe state. For this test, failsafe output states included:

- The affected radar’s outputs all reverting to their normally-open, ‘vehicle present’ state.
- The affected radar’s ‘HealthCheck OK’ signal changing to its normally-open, inactive state.

5.7.1.2 Results and Analysis

Following disconnection of the radar sensor's data communication connection, the output contact closure circuitry sensed loss of communication from the sensor. This resulted in all outputs reverting to their failsafe, normally-open states in a 10-second time period. In addition, the 'HealthCheck OK' output for the sensor reverted to normally-open. Operating states returned to normal within 30 s of the data line reconnection.

5.7.2 Loss of Power

5.7.2.1 Procedures and Acceptance Criteria

To simulate the loss of radar power, the power supply circuit was disconnected from one of the sensors. The corresponding output channels were examined to confirm that they reverted to their failsafe states as described above in Section 5.7.1.1.

5.7.2.2 Results and Analysis

Following disconnection of power to the radar sensor, the output contact closure circuitry sensed loss of communication from the sensor. This resulted in all outputs reverting to their failsafe, normally-open states within a 10-second time period. In addition, the 'HealthCheck OK' output for the sensor reverted to normally-open. Operating states returned to normal within 30 s of the data line reconnection.

5.7.3 Radar Communication Fault

5.7.3.1 Procedures and Acceptance Criteria

To simulate the loss of effective communication, a noise source comprised of a 12 volt peak-to-peak square wave signal at 1kHz and with a 50 percent duty cycle was capacitively coupled into one of the sensor's RS-485 data communication circuits. This noise signal was injected to disrupt communications between the radar and its associated electronics, and therefore cause the output channels to revert to their failsafe states, as described above in Section 5.7.1.1.

5.7.3.2 Results and Analysis

Substantial degradation of the communication line impeded the sensors ability to deliver heartbeat signals to the output contact closure circuitry. As had occurred with the previous tests, the output contact closure circuitry sensed loss of effective communication from the sensor. This resulted in all outputs reverting to their failsafe, normally-open state within a 10-second time period. In addition, the 'HealthCheck OK' output for the sensor reverted to normally-open. Operating states returned to normal within 30 s of the data line reconnection.

5.8 Blocked Crossing Detection and Classification

An additional, proof-of-concept aspect of the project dealt with the detection of vehicles that may be stopped, stored, or deliberately placed in the crossing island; it also dealt with the

communication of that information via a variety of networks to personnel, facilities, or even locomotives on approach to minimize the possibility of collisions.

Vehicle location tests conducted under Section 5.5 verified the radar system's ability to assert a detection signal only after a vehicle had remained in the crossing for a programmable period of time. Existing features of the Wavetronix SSM radar sensor provide a means to integrate the time of vehicle presence on a zone-by-zone basis. Detection zones programmed into the radar can be overlaid on one another, each configured with different detection time (delay) periods. This capability naturally permits rapid identification of vehicle presence for the purpose of influencing exit gate position, as well as permitting a delayed detection and a separate contact closure for vehicles that have not moved for a longer period of time, for example 90 s.

5.8.1.1 High Centered Vehicle Incident

This 'stuck-vehicle' detection capability became particularly relevant when an event occurred that involved a vehicle that had been inadvertently driven onto the tracks at the crossing, becoming momentarily high-centered on the tracks (Figure 20).

The event took place in late December at 6 p.m. Captured video showed the driver hesitantly entering the crossing from the north and executing a right turn close to the middle of the crossing. Apparently, to the driver, the newly installed preformed panel surface did not appear to be different from the crossing roadway itself. The vehicle was observed driving off the crossing surface and on to the tracks on the west side of the crossing. Several minutes passed before other motorists assisted in removing the vehicle from the track. This dense, triple-track corridor serves commuter trains out of downtown Chicago, one of which passed through the area only 8 min later.



Figure 20. An Auto is High Centered on Track 3 after a Mistaken Right Turn while in the Crossing Island

Because of the large detection footprint presented by the radar system, it was possible to add an additional zone in this area to the west of the crossing roadway—a location where additional loops are not typically installed. This permitted vehicles to be detected in these non-roadway areas. However, due to the radar mounting locations, only the radar on the northbound lane exit gate mast was in a position to monitor this area (see Figure 17).

5.8.1.2 Addition of Communication Provisions

While radar detection of stationary vehicles inside or in extended areas of the crossing island is straightforward, conveying this information to facilities or personnel who can take action is

another matter altogether. Candidate recipients and networks for potential blocked crossing notifications include the following:

- XML document bearing alert, location, and recent static image over any available wired or wireless IP network, including cellular data
- Integration into crossing health status delivered to locomotives on approach and beyond the reach of track circuits, over ITCS, PTC, ACSES, and similar train control systems
- Delivery of a text or multimedia message over cellphone, containing both a recent static image of the potentially obstructed crossing along with a real-time video link that may be accessed from any network device. This method (Figure 21) likely provides the fastest potential means of rapidly disseminating alert and image information to a large set of recipients (even to on-board devices ahead of PTC or ITCS availability), providing each with a real-time link to visual information from the site.

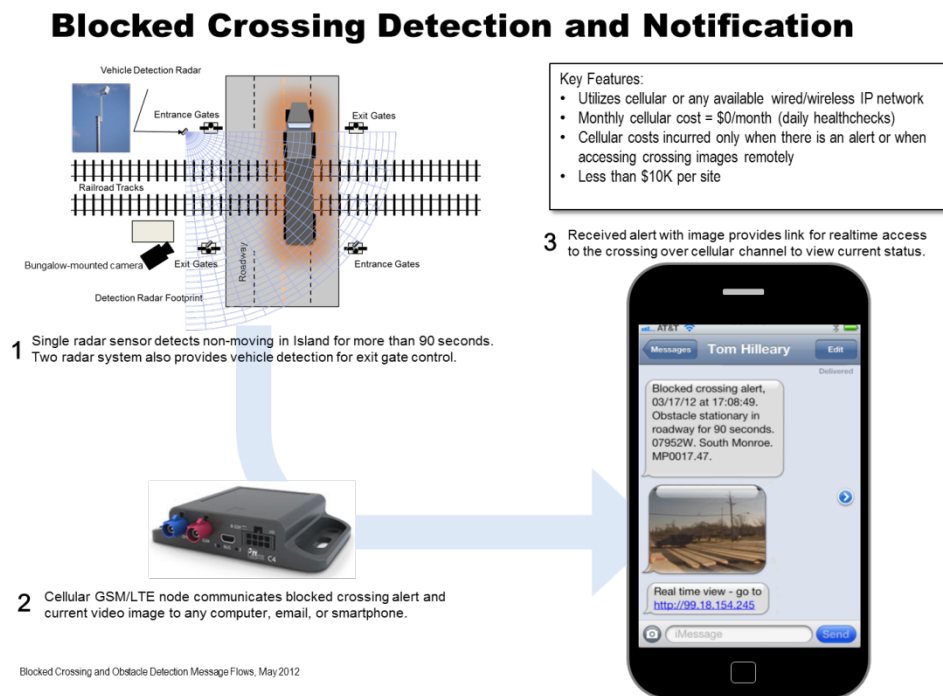


Figure 21. Cellular Dissemination of Blocked Crossing Alerts, with Automated Link to Real-time Visual Information

6. Conclusion

The impetus for this project was a set of railroad industry objectives provided by the State of Illinois and the BNSF railroad pertaining to installation, maintenance, and longevity drawbacks of buried loop detection systems. While buried, embedded inductive loops are the typical choice for vehicle presence detection in crossing applications, their short life, high cost, installation consequences, and lack of desired levels of reliability ultimately engendered a sense of dissatisfaction. Inductive loops have continued to be used because no alternative technology has provided sufficient advantages or net improvements.

Radar advances in traffic intersection control and other ITS applications have matured to the point where they are a viable and frequently utilized alternative to buried detection technologies. Radar devices are rapidly becoming the preferred detection technology choice for the traffic control industry, primarily because of their longer life and ease of installation.

Because of subtle differences between traffic system and railroad applications, operating specifications, and conventions, traffic radars cannot be readily placed into railroad service. However, a unique radar sensor featuring a large detection footprint and numerous other features was successfully adapted for railroad use, with many of its features realizing benefits that were not the original intent of their implementation in the traffic industry. For instance, the ability to isolate multiple radars from one another in traffic intersection applications provided a distinct railroad crossing benefit that permitted two sensors to operate simultaneously in an active redundant configuration—a vital architecture not possible with loop detectors or other popular detection technologies.

Radar system tests and evaluations—of mounting location, vehicle size and location, environmental and meteorological performance, and failsafe scenarios—demonstrated the dual-radar system's potential to perform as well as or better than strategically placed inductive loops in actual railroad crossing installations.

Four months of testing involving more than 120,000 vehicles showed no missed detection events for either the loop system or the dual radar system, not unexpected considering the multiple loops in each lane of traffic and the redundant radar detection mechanism that allowed both radars to monitor all lanes of traffic.

Adjacent lane detections were experienced in both the radar detection system and the loop detection system. However, occurrences in the radar system were approximately 10 percent those of the loop system due to the radar system's more precise detection boundary. Adjacent lane detections by the radar related to multipath reflections were minimal (29 out of 120,130 vehicles or 0.024 percent), but increased delay settings are to be considered in future studies to further minimize these effects.

The radar system showed a propensity for false triggering due to surface accumulation of water during heavy rainfall and wet snow and slush (14 occurrences over a 4-month evaluation period). Attenuation settings in the radar minimized these occurrences, and future research should be focused on optimizing attenuation and integration (delay) settings to further minimize or eliminate these false detections.

At current gain settings radar detection has the ability to detect non-vehicle objects such as bicycles and pedestrians. The railroad industry has not determined whether or how cyclist and pedestrian detection should be utilized in consideration of exit gate control. Should detection of objects other than vehicles be required for four quadrant gate applications, additional research assessing reliability and optimum gain/attenuation settings must be considered.

Radar system life expectancy is greater than that of a loop system based on industry reports reflecting loop experience and calculated MTBF for radar sensors. Average installed loop cost is estimated at \$36,680, 25 percent more than that of the dual radar system cost which is estimated at \$27,500. Estimates included materials, installation labor, underground boring for cable, and in the case of inductive loops, roadway milling and surfacing.

A combination of mean time between failures (MTBF) and mean time to repair (MTTR) showed a slightly higher availability for the radar detection (99.99 percent) system relative to the loop detection system (98.8–99.5 percent). This difference is primarily due to the inductive loop system's markedly higher MTTR, requiring installation in the road surface which typically requires the engagement of independent contractors and favorable temperatures.

In another project phase, using the radar system's inherent ability to sense vehicles that were either moving or stationary, a means was devised to detect and communicate an alert pertaining to vehicles that were stored, disabled, or deliberately placed in the crossing island roadway. Widespread notification of motionless vehicles or other large obstacles was shown to be feasible utilizing any type of wired or wireless network, including PTC and other train control networks. Notification to handheld smartphones, accompanied by an image of the crossing and an Internet link or shortcut that could connect the recipient within 15 s to a real-time visual image of the crossing, permitted the fastest possible dissemination of such an alert. Consistent with the FRA Intelligent Grade Crossing initiative, a full proof-of-concept implementation of this capability would be a worthwhile follow-on project.

Additional topics recommended for further system development and performance evaluation are included in the following section.

7. Recommendations for Future Development and Evaluation

7.1 Future Research

While the radar system was shown to have the potential to be satisfactory and in some cases superior to the loop system, additional research, development, and third-party performance evaluation is warranted and recommended in the following areas:

7.1.1 Effects of Dense Snow and Rain

Data from this project showed no missed detections due to snowfall, snow accumulation, or rainfall. But there were instances of false detections associated with periods of heavy precipitation. In addition, Chicago experienced an abnormally mild winter during the testing that occurred there. It is therefore recommended that future studies examine detection performance under more extreme weather circumstances.

7.1.2 Radar-to-Radar Response Times

The preferred concept required the use of two synchronized radars situated on opposite sides of the crossing to achieve a level of redundancy and vitality not available in loop-based systems. It was noted that radar response time, while satisfactory, differed based on the direction of vehicle approach into a radar's quarter-circle shaped detection footprint.

This project combined the output of each lane's contiguous series of loops as well as detection events from each lane derived from combining outputs from both radars. Quantifying radar response relative to direction of vehicle approach would be beneficial in affirming the need for, and reliance upon, the use of two or more radars.

7.1.3 Optimization of Attenuation and Delay Settings

Adjustment of the radar system 'Delay' and 'Extend' settings have been shown to reduce false detection events due to heavy rain and snow (Section 5.3 and Section 5.4). In addition, it is expected that the use of these settings would minimize the incidence of adjacent lane detection events (Section 5.6.3, note 3). Accordingly, it is recommended that future research be directed at optimization of these settings.

7.1.4 Additional Third-Party Performance Validation

The Wavetronix radar utilized for this project and application has experienced successful use in ITS and traffic intersection vehicle detection applications. However, it is typical and customary that performance be validated and corroborated by multiple evaluation tests and additional third-party research.

7.2 Future Development

Also noted in the course of this project were development areas thought to be beneficial to radar system use in railroad crossing applications:

7.2.1 Dual Radar Configuration Tool

The Wavetronix radar utilized for this application was initially designed to detect vehicles approaching a traffic intersection. As such, the radar's configuration application permitted and facilitated the establishment of lanes and detection zones for a single radar. The railroad crossing application utilizes multiple radars, each detecting vehicles in identical lanes and detection zones, and requiring that installers individually coordinate the setup of the radars. A means of setting up a single set of lanes and detection zones and configuring the associated radars simultaneously would be a benefit to the installation process

8. References

1. Highway-Rail Grade Crossing Guidelines for High Speed Passenger Rail. Version 1.0. U.S. DOT Federal Railroad Administration, Office of railroad Safety. November 2009.
2. Illinois High-Speed Rail Four-Quadrant Gate Reliability Assessment. Final Report. U.S. Department of Transportation, Federal Railroad Administration, DOT/FRA/ORD-09/19, October 2009.
3. Medina, J.C., Benekohal, R.F., Chitturi, M. Evaluation of Video Detection Systems. Illinois Center for Transportation Transportation. Reports No. FHWA-ICT-09-039, FHWA-ICT-09-046, FHWA-ICT-09-047, FHWA-ICT-08-024. 2008, 2009.
4. Medina, J.C., Benekohal, R.F., Hajbabaie, A. Evaluation of Sensys Wireless Detection System. Illinois Center for Transportation, Reports No. FHWA-ICT-09-059, FHWA-ICT-11-081, FHWA-ICT-11-083. 2009, 2001.
5. Jami K. Erickson. 1996. Undergraduate Transportation Engineering Fellows. Vehicle Detection at Highway-Rail Intersections. Retrieved January 2012 from <http://iricen.gov.in/IRICEN1/documents/Shared/KUM642/VEHICLE%20DETECTION%20AT%20LEVEL%20CROSSING.pdf>
6. Mollenhauer, Reiner. April 17, 2007. Level Crossing Obstacle Detection System. 2007 IET Seminar on Reducing Risk at the Road Rail Interface.
7. Middleton, D. Parker, R., October 2002. Vehicle Detector Evaluation, Texas Transportation Institute, Report No. FHWA/TX-03/2119-1.
8. ATMS14-Advanced Railroad Grade Crossing (Market Package, National ITS Architecture V6.1).
9. AREMA C&S Manual, 2012 Edition.
10. Alternative Rail Intruder and Obstacle Detection Systems. October 2009. Research Results RR-08-10. US Department of Transportation, Federal Railroad Administration
11. Section 8C.06 Four-Quadrant Gate Systems, Dec 2009, Manual on Uniform Traffic Control Devices (MUTCD) is approved by the Federal Highway Administrator as the National Standard in accordance with Title 23 U.S. Code, Sections 109(d), 114(a), 217, 315, and 402(a), 23 CFR 655, and 49 CFR 1.48(b)(8), 1.48(b)(33), and 1.48(c)(2).
12. U.S. DOT Federal Railroad Administration's Third Research Needs Workshop on Highway- Rail Grade Crossing Safety and Trespass Prevention: Volume I–Summary of Results.
13. Alternative Rail Intruder and Obstacle Detection Systems. 2007. Research Results RR07-21. U.S. Department of Transportation, Federal Railroad Administration.
14. Coleman, F. and M. Chitturi (2002). Four-Quadrant Gate Safety Analysis. Champaign-Urbana, IL: University of Illinois.
15. Federal Register/Vol. 76, No. 43/Friday, March 4, 2011/Proposed Rules.

16. Kotzenmacher, Jerry and Minge, Eric D., P.E. (2005) Evaluation of Portable Non-Intrusive Traffic Detection System. Minnesota Department of Transportation, Research Services Section.
17. Trains Magazine, Vol. 71, No.8, Kalmbach Publishing, August 2011.
18. Carroll, A., Gage, S., Gordon, J., Reiff, R., January 13-17, 2002, Evaluation of Alternative Detection Technologies for Trains and Highway Vehicles at Highway/Rail Intersections, Federal Railroad Administration (FRA), 81st Annual Meeting of the Transportation Research Board.
19. Watson, W., September 10-13, 2000. Highway Grade Crossing 4 Quad Gates. Proceedings of the AREMA 2000 Annual Conferences.
20. Middleton, D., Longmire, R., Turner, S., October 2007. State of the Art Evaluation of Traffic Detection and Monitoring Systems. Texas Transportation Institute, Prepared for Arizona Department of Transportation.
21. Jennings, L.S., 2009. Compilation of State Laws and Regulations Affecting Highway-Rail Grade Crossings, 5th Edition. US Department of Transportation, Federal Railroad Administration
22. SRF Consulting Group, Inc.. Ramp Queue Detection. Minnesota DOT ITS Innovative Ideas Program Final Report. January 2009.
http://www.dot.state.mn.us/guidestar/2006_2010/rqd/RQD_FinalReport.pdf
23. Minge, Erik. SRF Consulting Group, Inc. Evaluation of Non-Intrusive Technologies for Traffic Detection. September 2010. Minnesota Department of Transportation Research Services. Final Report #2010-36. <http://www.lrrb.org/pdf/201036.pdf>
24. Yu, Xin. Evaluation of Non-Intrusive Sensors for Vehicle Classification on Freeways. University of Hawaii at Manoa, Department of Civil and Environmental Engineering. Submitted to the Second International Symposium on Freeway and Tollway Operations, Honolulu Hawaii, June 21-24, 2009
25. Woodham, Lamar S. SmartSensor Matrix Model WX-SS-225 Approval Certificate, PEB2250. Alabama Department of Transportation, October 4, 2010.
26. Wilson, Mark C. Certificate of Conformance-Traffic Control Device, #66013653209011. Florida Department of Transportation, December 8, 2010.
27. Tomlinson, Douglas. Non-Provisional Certificate of Approval for the Sale of Traffic Signals or Other Power-Operated Traffic Regulatory Devices, #WAV002P, Commonwealth of Pennsylvania Department of Transportation, June 13, 2012.
28. Yeray, Jason M. Wavetronix Matrix Approval letter, Ohio Department of Transportation, August 23, 2011.
29. FHWA-HRT-06-139. Traffic Detection handbook: Third Edition – Volume II, Appendix M. Extent and Causes of Inductive-Loop Failures. October 2006.
30. N. Yamada, Radar Cross Section for Pedestrian in 76 GHz Band, Toyota Central Research & Development Labs, 2004. http://www.tytlabs.co.jp/english/review/rev394epdf/e394_046yamada.pdf

9. Acronyms, Abbreviations, and Definitions

ADTC	Average Daily Traffic Count	Average number of vehicles passing through an intersection of crossing per day
ACSES	Advanced Civil Speed Enforcement System	A positive train control cab signaling system developed by PHW and Alstom
CW	Continuous Wave (Modulation)	Single frequency radar emissions
EGMS	Exit Gate Management System	A crossing warning system controller that raises and lowers exit gates in four-quadrant gate installations (manufactured by Invensys Rail North America)
EGOM - Dynamic	Exit Gate Operating Mode – Dynamic	Exit gate behavior in four- quadrant gate systems wherein exit gates descend only if it is verified that the crossing island (or a particular lane) is free of vehicles that may otherwise be trapped
EGOM - Timed	Exit Gate Operating Mode – Timed	Exit gate behavior in four-quadrant gate systems wherein exit gates descend a fixed time after activation of the crossing warning system
FMCW	Frequency Modulated Continuous Wave	Swept frequency radar emissions
GUI	Graphical User interface	A type of user interface that allows users to interact with electronic devices using images rather than text commands
HSR	High-Speed Rail	Type of passenger rail transport that operates significantly faster than traditional rail traffic. In the United States, the U.S. DOT defines it as “sustained speeds of more than 125 mph,” although the Federal Railroad Administration defines HSR as 110 mph
ICC	Illinois Commerce Commission	Regulatory authority in Illinois for highway and rail traffic
IODS	Intruder and Obstacle Detection Systems	General class of detection system for vehicles or other objects within a protected boundary
IR	Island Relay	A relay that signals train occupancy on a crossing island
ITCS	Integrated Train Control System	Incremental Train Control System developed by General Electric Transportation
ITS	Intelligent Transport System	Advanced applications which, without embodying intelligence as such, aim to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer, more coordinated, and ‘smarter’ use of transport networks
MTBF	Mean Time Between Failures	The predicted elapsed time between inherent failures of a system during operation.
MTCD	Minimum Track Clearance Distance Zone	The trapezoidal crossing area (Island) in which vehicle detection is to be accomplished
Non-Embedded		A vehicle or obstacle detection system or technology not buried in the pavement or roadway
SSM	SmartSensor Matrix	Wavetronix radar featuring sixteen discreet radars in a single sensor
SSM	Supplemental Safety Measure	Additional safety improvements when implementing four-quadrant gate systems.
PTC	Positive Train Control	Wireless railroad infrastructure wherein trains receive information location and where it is allowed to safely travel. Equipment on board the train then enforces this, preventing unsafe movement
XR	Crossing Relay	A relay that initiates activation of a crossing warning system, generally upon detection of a train on approach

Appendix A. Four-Quadrant Gates in Illinois

Illinois guidelines for implementation of four-quadrant gate crossing warning systems, which include radar detection systems initially operating in a back-up role.

Rail Safety Section | Transportation Bureau Illinois Commerce Commission

Release v1.0

Four Quadrant Gates in Illinois



History of Four Quadrant Gates in Illinois

While the earliest use of an active four quadrant gate system in the United States was 1952, the State of Illinois' modern experience with four quadrant gate systems began in 2001. During this time, the Rail Safety Section of the Illinois Commerce Commission (ICC) worked with the Illinois Department of Transportation (IDOT) and the Union Pacific Railroad Company (UP) to install four quadrant gate systems at 69 public highway-rail grade crossing locations; each system was equipped with vehicle presence detection. In most cases, the crossings were located in smaller towns or rural areas with a single track layout. The "Exit Gate Management System" (EGMS) developed by Railroad Controls Limited (RCL), and special inductance pre-formed presence detection loops developed by Reno AE, were utilized to provide vehicle detection and exit gate control equipment offering adaptability to varying conditions. Extensive design and testing was conducted by RCL, UP, and the ICC to insure a reliable system. As further confirmation of the performance, The Volpe National Transportation Systems Center (VOLPE), a part of the U.S. Department of Transportation's Research and Innovative Technology Administration, conducted an independent "Reliability Assessment Study." The study showed that "the four quadrant gate and vehicle detection equipment had a minimal direct impact on the frequency and duration of grade crossing malfunctions."

In 2003, the ICC partnered with CSX Transportation, IDOT, and the City of Chicago to complete a demonstration project with the installation of four quadrant gates systems at 10 double-track public highway-rail grade crossings located in an urban area. This project further demonstrated the solid performance and low maintenance needs associated with EGMS and in-pavement vehicle detection.

Currently, the ICC is partnering with the BNSF Railway and the Village of Hinsdale on a demonstration project to install a four quadrant gate system at a triple-track public highway-rail crossing that has more than 140 trains per day. While the EGMS and loop detection have performed very well, with this train volume, a critical commuter rail schedule, and an urban environment with the potential for highway traffic queuing, a back-up vehicle detection system is being pursued.

Many items remain consistent with what was originally developed in 2001. However, as new locations, applications, and requirements are identified, the ICC's Rail Safety Section is committed to revisiting the operating criteria and typical design to continue to allow for safe installations. The following information includes the latest requirements of the ICC's Rail Safety Section for the installation of four quadrant gates systems at public highway-rail grade crossings in the State of Illinois.



Contents

History in Illinois	1
Criteria	2
Special Considerations	3
Four Quadrant Gate Checklist	4
Plan - Primary Detection	5
Plan - Skewed Crossing	6
Plan - Back-up Detection	7

For more information, please contact:

Michael E. Stead
Rail Safety Program Administrator
(217) 557-1285
mstead@icc.illinois.gov

John Blair
(217) 785-8421
jblair@icc.illinois.gov

Stan Milewski
(815) 463-8387
srmilewski@icc.illinois.gov

Dan Powers
(847) 516-0733
dpowers@icc.illinois.gov

Brian Vercruyse
(312) 636-7760
bvercrv@icc.illinois.gov

March 2010

Four Quadrant Gate Criteria



Four quadrant gate systems should consist of front lights and back lights, as well as bells on each signal mast. Crossing activation shall result in all lights activating simultaneously. The system shall also include a drive mechanism and fully retro-reflectorized red and white striped gate arms with lights, which in the down position, extend individually across the approaching and exit lanes of highway traffic. Gate arm design, colors, and lighting requirements should be in accordance with the standards contained in Section 8 of the Manual on Uniform Traffic Control Devices (MUTCD).

All four quadrant gate systems shall be equipped with vehicle detection capabilities to prevent vehicles from becoming trapped between the entrance and exit gates. The vehicle detection system should consist of pre-formed inductive loops with self-test capabilities, located under the surface of the roadway and adjacent to the crossing surface(s) as shown on the attached typical layouts. To reduce the detection area, the entrance and exit gates should generally be installed parallel to the tracks. All four quadrant gate systems should also be equipped with remote monitoring and alarm capabilities.

Dynamic Mode with Vehicle Detection (Inductive Detection Loops & Ability to Utilize Back-up Detection

1. The gate arms for the entrance lanes of traffic shall start their downward motion not less than 3 seconds after the flashing-light signals start to operate.
2. Exit gates shall be designed to fail in "up" position.
3. All four quadrant gate systems shall be designed to utilize vertical and horizontal gate contacts.
4. All systems shall have the capability to apply a programmable vehicle detector call delay on all detectors when all gates are horizontal; as a programmable feature, all systems shall have the ability to ignore an individual detector once all gates are horizontal.
5. All systems shall have the capability to extend vehicle calls.
6. All systems shall be designed such that each individual detector loop will only raise its associated exit gate. And, after a programmable timer expires, the opposite exit gate should also rise.
7. Normally, vehicle detection shall be disabled when the train enters the island circuit and exit gates should lower, or remain lowered.
8. In the event there is a stopped train near the island circuit (crossing not active), the system shall delay the exit gates, through the use of a programmable timer, if a vehicle call is present and the train proceeds into the island circuit.
9. All systems shall be designed such that if the entrance gate does not reach its horizontal position within a programmable time, the associated exit gates should raise.
10. All gate arms shall remain down as long as the train occupies the highway-rail crossing.
11. When the train clears the crossing, and no other train is detected, exit and entrance gates shall ascend to their upright position in not more than 12 seconds, following which the flashing lights and the lights on the gate arms should cease operation.
12. With no trains present within the approach circuits, if an exit gate is not vertical the entrance gates shall lower to horizontal.
13. Exit gates shall descend after entrance gates move off vertical contact unless a vehicle is detected within the crossing zone. All systems shall also provide a programmable timer to provide additional exit gate delay time, as necessary.
14. When required, the four quadrant gate system shall have the capability for a back-up detection system. The back-up detection shall have self-test capabilities. With the presence of a failed detector loop, all remaining healthy detector loops should remain active, and the system shall be manually cutover to the back-up detection. The system shall also have the ability to automatically utilize the back-up vehicle detection in lieu of the failed detector. The failed detector shall result in an alarm. In addition, the system shall have the option, as user programmed, to apply a gate delay to the exit gates in the event of a detector failure, even if gate delay is not utilized during normal operation when all primary detectors are functioning.



Four Quadrant Gate Special Considerations

All four quadrant gates systems shall address the type of rail operations present, maintenance protocol, pedestrian utilization, interface with other railroad equipment and other special considerations.

High Speed Rail Corridors

On High Speed Rail Corridors where passenger train will operate at speeds between 80 mph and 110 mph, all four quadrant gate systems shall be equipped with a presence detection system that is interfaced with the Positive Train Control System (PTC), per the Federal Railroad Administration's "Highway-Rail Crossing Guidelines for High-Speed Passenger Rail" published November 2009. Commands to reduce train speed to restricted speed (20 mph) shall be transmitted to passenger trains through the PTC system when any of the following conditions are not met:

1. Confirmation the warning system health is ok.
2. Confirmation the Exit Gate Management System (EGMS) health is ok.
3. Confirmation that all crossing gates are in a fully-lowered position and no vehicles are detected by the presence/intrusion detection system.

The PTC system command shall be made in time for passenger trains to reduce speed to restricted speed (i.e. approximately 20 mph) or stop before reaching the crossing. Freight train operations in the corridor will not be governed by this information.

Pedestrians

As part of the necessary Diagnostic Review, pedestrian warning devices and/or other treatments shall be reviewed. A separate pedestrian gate is necessary for the exit side of the crossing.

Detector Loop Layout

Prior to ordering the detector loops, a field layout should be completed with the ICC and Railroad to finalize dimensions, lead-in, and home-run cable lengths. The current induction loop utilized is Reno A&E PLC for Railway Applications, and the exit gate control is completed by the "Exit Gate Management System" now owned by Invensys Rail (fka Safetran).

ICC Rail Safety Section - Four Quadrant Gate Checklist

Railroad: _____

Highway Crossing: _____ AAR/DOT #: _____ Milepost: _____

GENERAL

- ☐ 1. Front & Back Lights on Each Roadway Signal Mast; bells required for each Roadway Mast
- ☐ 2. Pedestrian treatments as determined by Diagnostic Review _____

- ☐ 3. Gate Design, Colors and Lighting Requirements per MUTCD and AREMA
- ☐ 4. Gates Designed for Parallel Placement. If not, explain: _____

- ☐ 5. ICC Four Quadrant Gate Criteria Compliant
- ☐ 6. Loop Dimensions Verified in Field with ICC Engineer Prior to Ordering
- ☐ 7. Four Quadrant Gate System Including Detection, Interfaced with Positive Train Control System

DYNAMIC MODE

Primary Detection

- ☐ Inductive Detector Loops
- ☐ Exit Gate Control
- ☐ Detection Failure with Alarm

Repair Protocol

☐ *Back-up Detection*

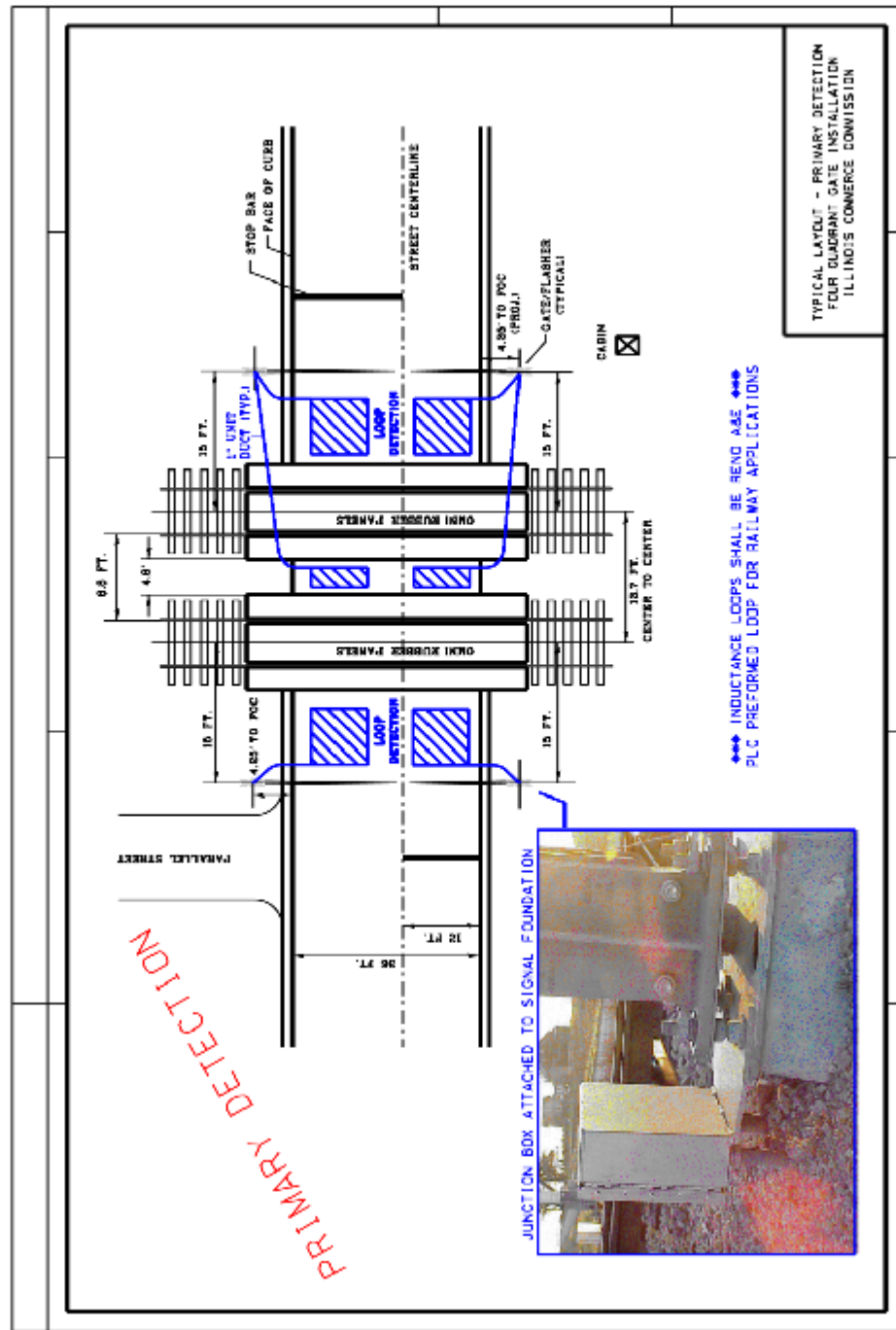
Train Operations

- ☐ Turn-On Inspection

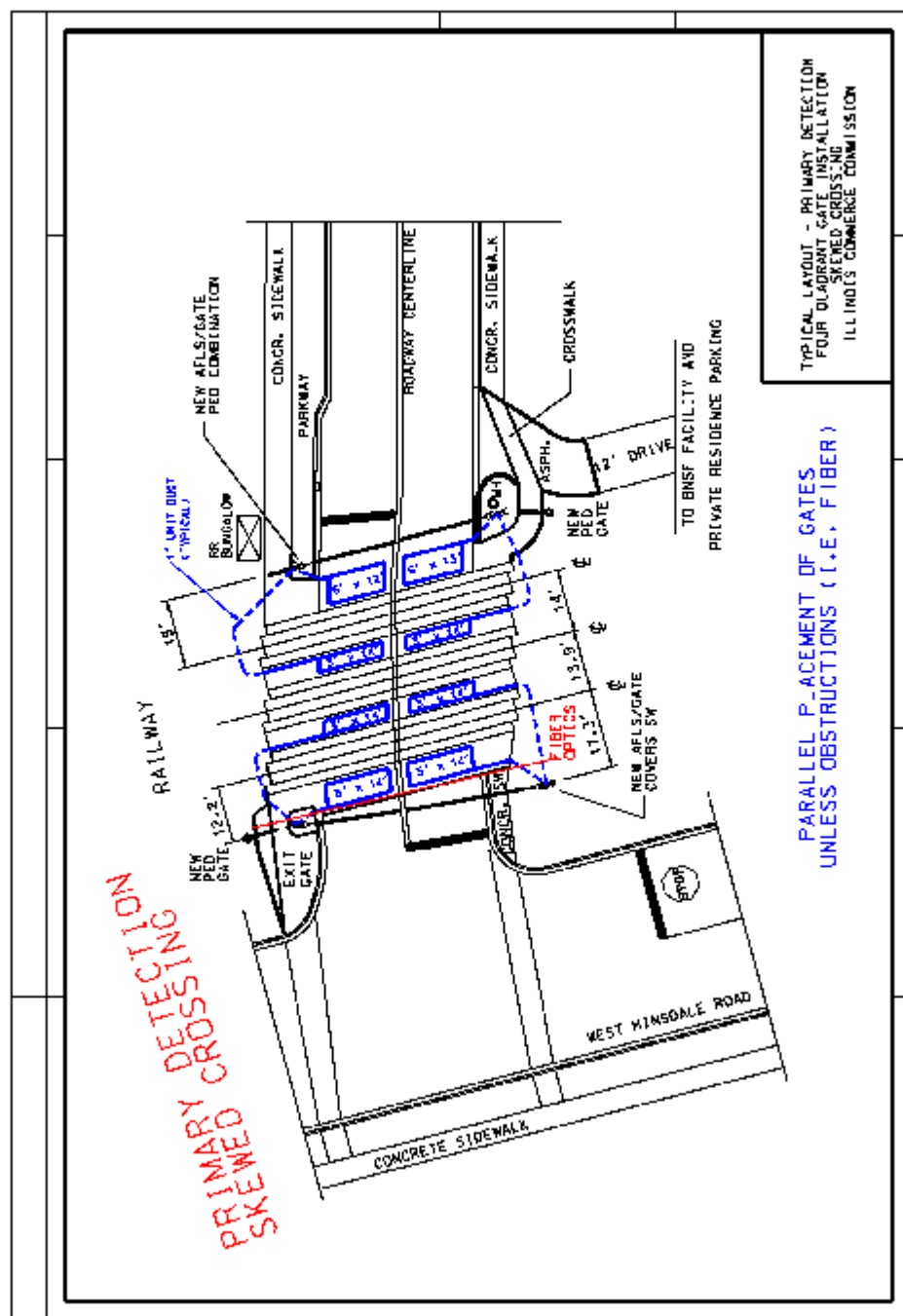


March 2010

Four Quadrant Gate 90 Degree Layout

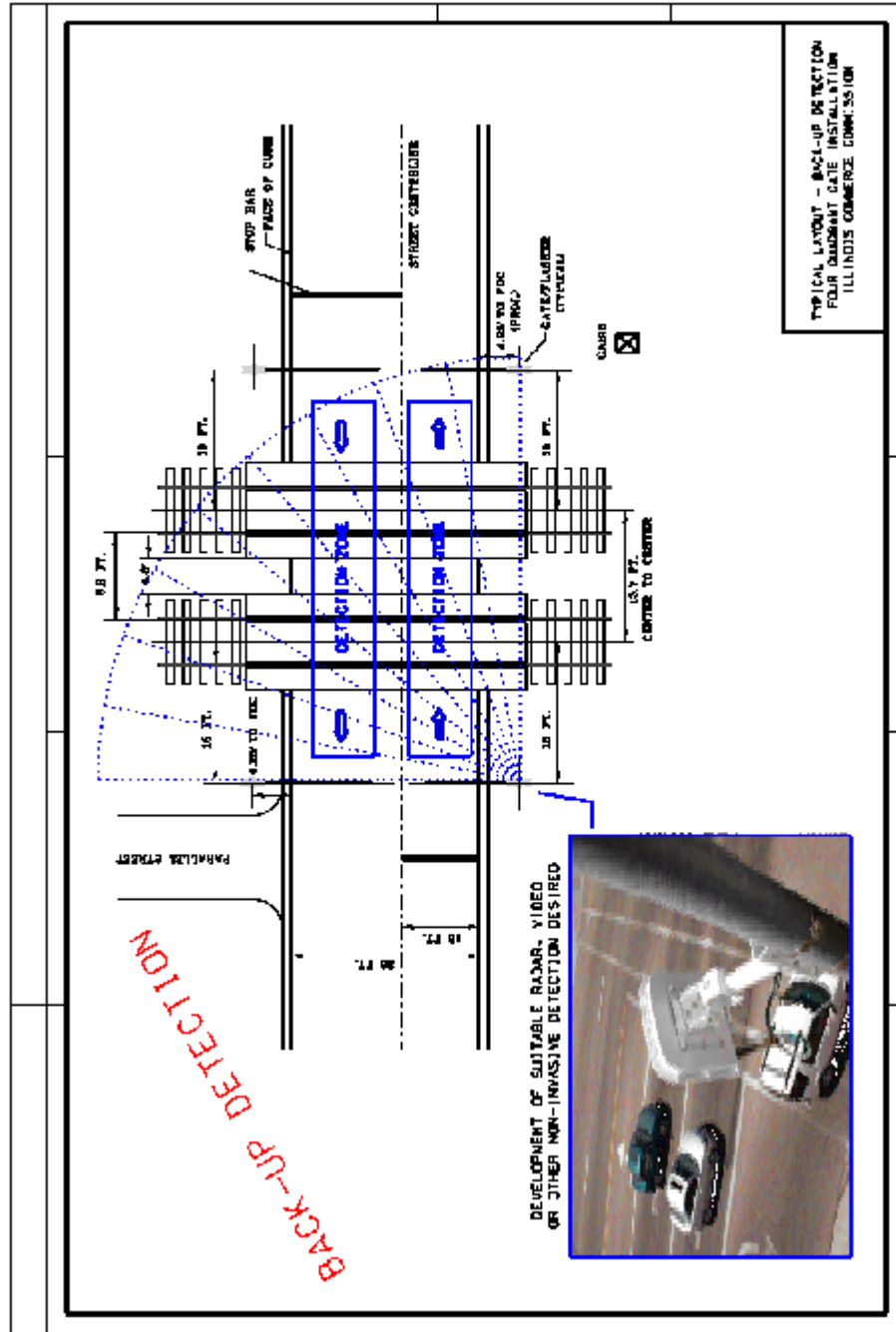


March 2010



March 2010

Four Quadrant Gate Back-up Detection



March 2010