IDEA

Innovations Deserving Exploratory Analysis Programs

High-Speed Rail IDEA Program

Integrated Microwave Range and Velocity Sensors for Railroad Crossing Warnings

Final Report for High-Speed Rail IDEA Project HSR-08

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TRANSPORTATION RESEARCH BOARD
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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD

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Integrated Microwave Range and Velocity Sensors for Railroad Crossing Warnings

IDEA Program Final Report
For the Period April 1997 through April 2000
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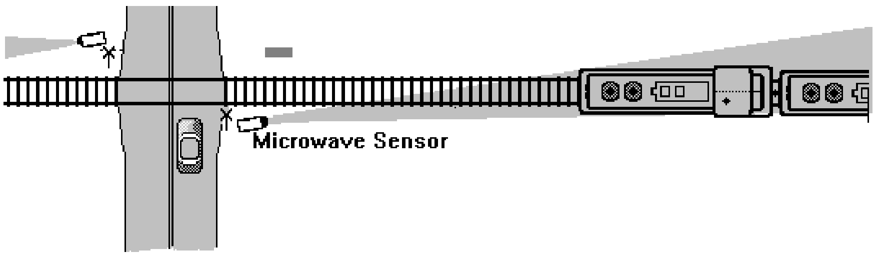
OEI Integrated Microwave Range and Velocity Sensors for Railroad Crossing Warnings

EXECUTIVE SUMMARY

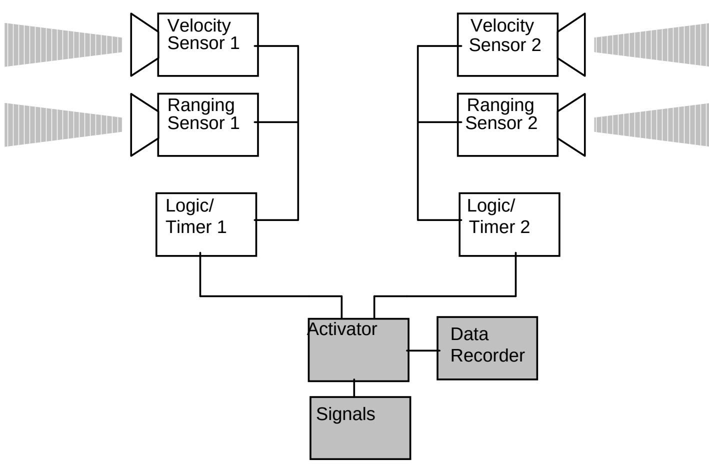
The objective of this project is to assess whether a modular Microwave Warning System has the potential to be a reliable all-weather radar sensing system that can activate grade crossing warning systems when trains are approaching.

The system design is shown below. Microwave sensors, mounted on railroad signal poles at crossings, detect the trains at extended distances. In theory, this distance can be over a mile away in uncluttered environments. In crossings where extended detection distances may be needed (for example, for higher-speed trains) or where there is significant clutter, then remote detectors placed along the right-of-way with an RF link to the crossing might be required. This system was tested at two active grade crossings, one on the Kansas City Southern (KCS) railroad, and one on the Burlington Northern/Santa Fe (BNSF) railroad. A remote unit was constructed during the project for use at one crossing test site, as extended detection distances were found to be needed. Such remote units might be required wherever there are obstructions to the radar signal or where high-speed trains might be expected.



The basic sensor system observes the velocity and range of an approaching train and determines when it will arrive at the crossing. Warning signals at the crossing are timed such that the warning period is constant for a range of train velocities.

In the final design, each microwave warning system consisted of one modular sub-system for each direction. A complete sub-system looked in one direction and consists of a ranging sensor, a velocity-measuring sensor, and a microprocessor. The sub-systems acted independently of each other, although future systems may combine functions. A ranging sensor determined the distance to the approaching train. The velocity sensor then accurately measured the speed of the train, sending this information to the microprocessor that calculated the time when the train would arrive at the crossing and the warning time for gate closure. The design concept is that once the microprocessor has determined that the train is a preset time from the crossing it forces a relay closure that activates the crossing lights and lowers the gates. For tests designed here, event types and the associated times were recorded on an event recorder for analysis. The final system design consisted of components configured as shown in the following figure:



Final System Block Diagram. Shaded blocks denote components added for data collection and remote monitoring.

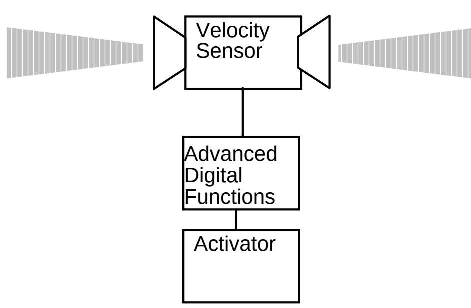
This project included system conception, design, implementation and evaluation. Rather than activate warning devices, a local event recorder that was accessed via remote computer recorded the system performance. Analysis of data demonstrated that whereas the microwave systems were functioning well for normal trains, high-speed fast Amtrak trains traveling up to 88 mph were not being detected sufficiently early to give desired warning times at the crossings. Based on the need for earlier train detection, additional system components were designed and constructed, then evaluated in the field. These include development of digital logic circuits and the associated program to control a remote velocity sensor, develop timing control, and transmit the control information via spread-spectrum link (using Proxim link devices) to the crossing itself. Three different antennas were designed and built, then tested in the field. It was found that helical antenna designs provided adequate range for remote sensors.

Data collected from the KCS and BNSF sites were analyzed several times during the course of this project, and circuit and software improvements were made for the BNSF site following these analyses. Trains that stopped sufficiently long that the software "lost" them were omitted. High-speed Amtrak trains were not detected sufficiently close to provide adequate warning times, which led to the development of the remote sensing units. The system did not activate with animals or people walking on the track.

Installed systems were evaluated with respect to their overall reliability, functionality and safety. Summary comments are as follows:

- Some approaching trains were not detected at all, and others were not always detected early enough to permit the desired warning time. These problems were caused by such things as swinging overhead wires and the rounded-nose profile of Amtrak locomotives. These problems can likely be overcome by improvements to the software, and using a tighter beam width and/or a system using remote sensors.
- In the final system, malfunctions were detected by remote monitoring of the event recorder. A capability to detect malfunctions could be developed at low cost in future systems.
- No sensitivity to EMI was discovered during routine monitoring, but no scheduled tests were conducted with railroad equipment. Tests with a local 150 MHz transmitter operating at 25 watts power did not produce any erroneous signals.
- Field tests in moderately severe rains demonstrated that the system performance was satisfactory. The system was not evaluated during hail, sheet rainfall, or high-velocity blowing rain.
- The prototype has the capability to provide 20-30 second advance activation of crossing warning systems for constant-speed trains traveling at moderate speeds. However, additional software and hardware development, testing and evaluation will be required to determine whether this technology can handle such scenarios as: trains that accelerate, decelerate, stop, and reverse; high speed trains with smooth profiles, and under a full range of weather and electromagnetic interference conditions.

As a result of this project two systems designs are recommended for further consideration. These systems would not be expected to replace existing track circuit designs in all cases, but could be useful for rural crossings where it is not cost-effective to install track circuit systems. The first design is the system that has been developed and applied here, with the addition of enhanced safety features such as self-monitoring. The second design that should be considered is a simplified design that would be cost effective yet still provide most basic functions. Based on our results, advanced digital logic may be employed for improved control and better reliability. Self-monitoring and reporting are also possible. The second design that is recommended for development is the following:



One possible future system design would use simplified digital logic, but include self-monitoring functions.

The system evaluated here has possibility for improving safety at crossing sites currently unequipped with crossing signals. It is not operational as a functional replacement for current track-circuit signal controllers.

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1 INTRODUCTION: MICROWAVE SENSOR-BASED WARNING SYSTEM

THE IDEA CONCEPT

The objective of this project is to assess whether a modular Microwave Warning System has the potential to be a reliable all-weather radar sensing system that can activate crossings when a train is approaching.

The system design is shown below. This system was tested at two active grade crossings, one on the Kansas City Southern (KCS) railroad at Furrh Road near Blanchard, Louisiana and the other on the Burlington/Northern/Santa Fe (BNSF) railroad at Knightsen Road near Antioch, California. Microwave sensors, mounted on railroad poles at crossings, may detect trains at distances over a mile away in uncluttered environments. Where extended detection distances are required or where there are overhead wires or other obstructions, then supplementary remote units may be required. A remote unit was constructed for use at the BNSF site, one of two sites chosen for final system implementation.

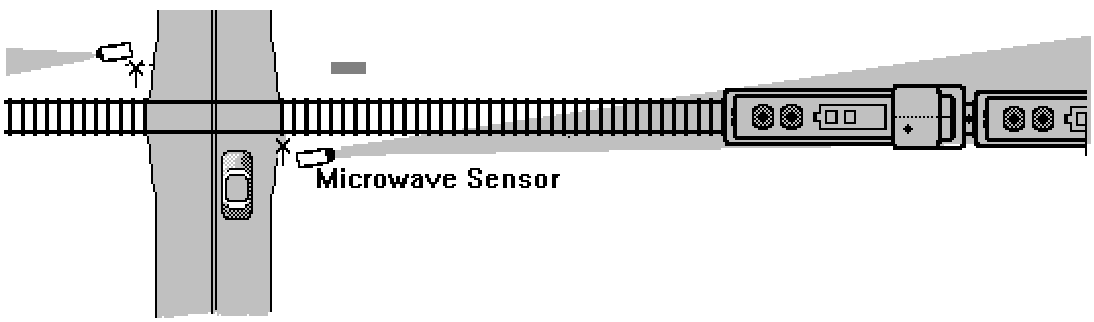

Figure 1. **The basic sensor system observes the velocity and range of an approaching train and determines when it will arrive at the crossing. Warning signals at the crossing are timed such that the warning period is constant irrespective of train speed for constant-speed trains.**

FINAL SYSTEM IMPLEMENTATION

In the final design, each microwave warning system consisted of two modular sub-systems for each direction. A complete sub-system looked in one direction and consisted of a ranging sensor, a velocity-measuring sensor, and a microprocessor. The sub-systems acted independently of each other, although future systems may combine functions. In operation of the final systems at the BNSF site, a ranging sensor determined the distance to the approaching train. The velocity sensor then accurately measured the speed of the train, sending this information to the microprocessor, which calculated the time when the train will arrive at the crossing. Once the microprocessor determined that the train was a preset time from the crossing it forced a relay closure that was recorded on the event recorder. In anticipated operation, this signal would activate the crossing lights and lower the gates.

The final system design as constructed and installed consists of components configured as shown in the following figure:

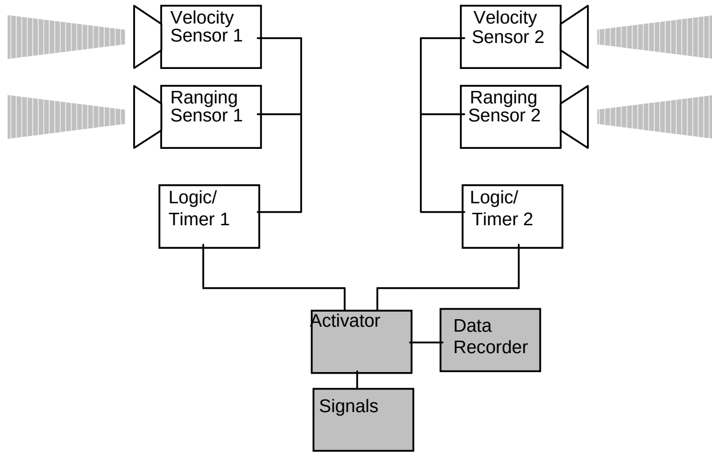

Figure 2. Typical Track Installation Block Diagram. Shaded blocks denote components added for data collection and remote monitoring, plus a hypothetical signal control box.

The six small modules that comprise a system may all be mounted on one of the crossing's signal poles. Each weatherproof steel module is expected to withstand over 10 years of harsh weather.

This project consisted of system conception, design, implementation and evaluation. Rather than activate warning devices, a local event recorder accessible via remote computer recorded the system performance. This data recorder was wired to monitor radar system outputs, radar system power, railroad company (local island) inductive circuits, and railroad system remote inductive circuits. At the KCS site two radar lines, one power supply line, and two inductive circuit lines were monitored. At the BNSF site two radar lines, one power supply line, and four inductive circuit lines were monitored. A change in any one of these lines constituted an "event".

Each passage of a train generated a minimum of three events on arrival and three on departure. Some trains stopped to maneuver or to permit changes of personnel, and these events were challenging to analyze. In these cases both the radar and conventional systems lost the ability to anticipate the time of passage of a train through the crossing and generate an advance warning. Reversing trains generated many events on the recorder. For the analysis shown here, trains producing complex systems of events (more than six correlated events) were not counted or included in the discussion.

DETAILS OF THE FINAL SYSTEM

During the course of this project (April 1997 through April 2000) two bi-directional microwave train-sensing systems were installed and evaluated. These systems were designed to perform operational evaluations of a microwave train sensing system designed to activate gates and other advanced warnings at railroad-highway crossings. The system uses state-of-the-art microwave sensors to remotely sense the presence, position, velocity, and direction of movement of trains in the vicinity of crossings. These velocity and range determining sensors have evolved from technological advancements made during the development of other systems, including automated longitudinal control systems, vessel docking systems, collision warning systems, and traffic flow monitoring systems, and from information developed during the course of this project. Small and light-weight (approximately 4"x 4" x 9" and weighing 4 lb.), the sensors were hoped to provide all the information required to properly activate warnings at crossings, removing the need for direct contact or inductive loop activation circuitry and the costly cabling and wiring requirements. The desired system would be modular in design, flexible, and easy to install and maintain.

The OEI system sensors use either of two basic radar technologies, Doppler processing for velocity, or Frequency Modulated Continuous Wave (FMCW) processing for ranging. The velocity sensors operate at a frequency of 24.125 GHz, have an output power of 5 mw, and are FCC Part 15 approved. The ranging sensors also have an output power of 5 mw and operate in the approved frequency band. Quality velocity and ranging information can be received at target distances of up to one mile in an uncluttered environment. Clutter includes overhead cables, close buildings, and trees.

The narrow beam system, configured for a typical single track railroad-highway crossing, consists of one velocity sensor and one ranging sensor looking down the track for each direction. The velocity sensor and ranging sensor work in unison to verify the presence, position, and velocity of an approaching train. The logic controller uses velocity information from the velocity sensor and range information from the ranging sensor to predict the time the train will enter the crossing and activate the warnings with a pre-defined advance warning time. The train's estimated time of arrival (ETA) at the crossing is updated continuously so the advance warning time will remain constant.

Though they are used in unison to provide the most accurate estimated arrival time (ETA) prediction, either of the velocity or ranging sensors can activate the crossing warnings independently. The velocity sensor uses target signal strength and target velocity to determine the train's ETA at the crossing. Target signal strength correlates directly with target range, thus, the train's position can be determined by monitoring signal strength. It is only a matter of applying velocity to determine the train's ETA at the crossing. The ranging sensor determines the train's ETA by continuously measuring its range and calculating speed through a difference in distance over time calculation. The system's logic unit receives information from both sensors and verifies one against the other to ensure that there is no malfunction.

2 CROSSING-CONTROL SYSTEMS CONCEPT AND IMPLEMENTATION

COMPONENTS USED IN SYSTEM IMPLEMENTATION

The Crossing Control System is designed to look down one direction of a track at a crossing location. Two systems are required to observe both directions at a typical single-track crossing. The Remote Sensing System is comprised of the following components:

- one velocity sensor;
- one ranging sensor;
- one logic controller;
- one 12 vdc power supply (AC/DC converter); and
- cabling, data recorder and mounting brackets.

The complete system for a single direction may be diagrammed as follows:

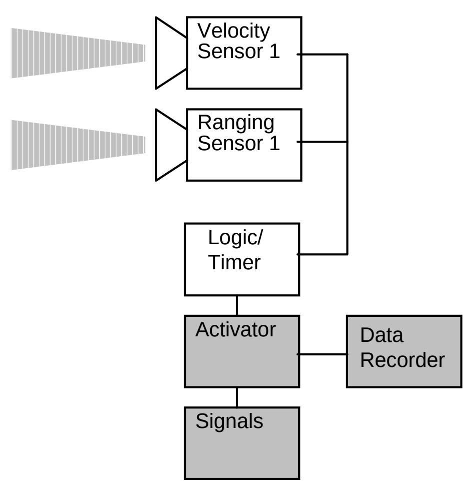

Figure 3. Ranging and Velocity Sensor System Block Diagram. Shaded blocks are components added for data collection and remote monitoring.

The ranging sensor is a Frequency Modulated Continuous Wave (FMCW) radar operating within a frequency range of 24.35 to 24.7 GHz. It has a power output of 0.005 watts, a range under ideal conditions of 1600 meters, and a range resolution of 0.6 meters. Under normal railroad conditions, trees and clutter reduce sensor range.

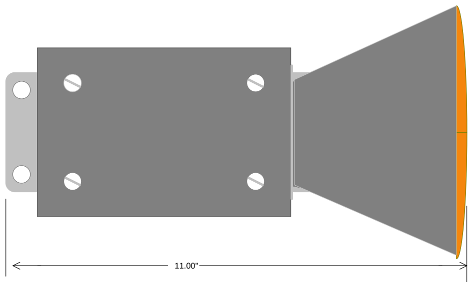

Figure 4. Ranging Sensor external characteristics. The larger horn used on the ranger sensor provides more directionality.

The velocity sensor is a Doppler radar module capable of detecting closing or receding velocities from 0.5 mph up to 150 mph. However, the sensors for this project are electronically limited to 75 mph for better velocity resolution and to match the distance parameters. Operating at 24.125 GHz, it also has a power output of 0.005 watts and a range of 1600 meters.

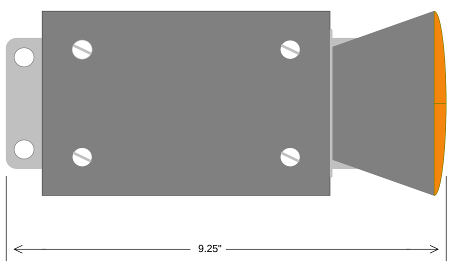

Figure 5. Velocity Sensor external characteristics. Directionality is not so critical with a velocity sensor and a smaller horn may be used, than that required for a ranging sensor.

The System Logic Controller controls the activation of the crossing warnings. The presence or absence of specified signals from both the velocity and ranging sensors provide the basis for warning activation. The following truth table demonstrates the basic logic used in the logic controller:

Condition	Closing	Receding	Signal Detect	Velocity (mph)	Range (feet)	Normal Time-out Activation	Immediate Activation
Train Approaching	Yes	No	Yes	1-70	<2500	Yes	No
Train Receding	No	Yes	Yes	1-70	<2500	No	No
No Train	No	No	No	0	0	No	No

The logic controller included a digital timer which times the activation of the crossing warnings in accordance with a specified advanced warning time. This more stable digital timer replaced an analog timer used for preliminary tests. Though the logic used by the System to control the crossing warnings is somewhat elaborate, integrating the system into the existing warning systems is straightforward. The logic controller feeds voltage to a relay, which, in turn, controls the activation of the crossing warnings. As long as the voltage from the System controller is present, the crossing warnings will not activate. The absence of this voltage causes the relay to drop and the warnings will activate. In this configuration any malfunction of the System results in the activation of the crossing warnings.

3 PROJECT RESULTS: ANALYSIS OF INSTALLED SYSTEMS

Event recorders were installed at the crossings to continuously monitor system performance. It was critical to monitor performance of the microwave sensors in order to evaluate system performance. Data required were gate status determined by software associated with the microwave sensors; railroad remote inductive circuits status; railroad island circuit status; and, for diagnostic purposes, power supply status. The event recorder recorded each change of status, together with the time of occurrence. The electrical interface of OEI equipment with railroad equipment for each system was between the logic/timer boards and the signal activation equipment through a multi-wire cable.

KCS SITE

A complete bi-directional system was installed at the KCS field site. Thus four sensors (two velocity sensors and two ranging sensors) were employed. South-looking and north-looking sub-systems were of different designs. The South-looking design used primarily analogue logic developed for this application. The North-looking system used digital logic, also developed for this project, which promised to permit more flexibility in dealing with complex train traffic patterns.

Figure 6. The above photograph shows the system installation at the KCS site with the south looking sensors installed.

Of interest at this site is the close forest cover that rises above the railroad. This posed a special challenge in aiming the sensor units down the tracks, and served as a challenge to the velocity-sensors because the trees can respond to winds. However, no instances of false gate closing signals due to local winds were identified in the data for this site.

Of the two systems installed at this site, the North-looking (digital) system did not function well. The sensors are now functioning well, but there still seems to be a difficulty with the software for that direction. The South-looking sensor, although of analogue design developed early in the project, yielded useful data, and these data were analyzed to demonstrate the limitations of a purely analogue system. Data were recorded and analyzed for the period 1/22/00-2/11/00. In this interval, 92 trains were selected for analysis. Trains exhibiting complex behavior (stops, slowing, reversals etc.) were not included. The decision of whether to include the trains or not was based on site sensor data recorded by the event recorder.

In Figure 7 the frequency distribution of warning times is shown in comparison with the least squares fit to a normal distribution for 92 northbound trains. The warning times are distributed around a mean value of 46 seconds +/- 28 seconds. The data are distributed in a regular manner with the exception of points lying beyond a warning time of 80 seconds. These times exceed the ability of the software to track slow-moving trains, plus some trains presumed to decelerate and stop near the junction. Omitting values greater than 80 seconds leaves 82 trains for which the software was assumed to be capable of tracking. The mean value was 39 seconds +/- 21 s.

The curve is truncated at 0 because of the obvious lack of warning times less than zero (although this could occur if the trains accelerate and the software does not update velocity measurements). The curve was truncated for times greater than 80s for this plot because it appeared that other mechanisms might be causing some variability. The Kolmogorov Smirnov d=0.061 implying that one may not reject the hypothesis that the data are normally distributed. The tentative assumption of a log-normal distribution gives a K-S value of 0.153, $p<0.05$, suggesting that one may not reject the possibility that these data may be log-normally distributed. They are closer to normal (Gaussian) than to log-normal in distribution. Thus, of the 82 trains for which the software was assumed capable of tracking, 23% of the measured values were below 20 seconds, while 62% of the values lay above 30 seconds.

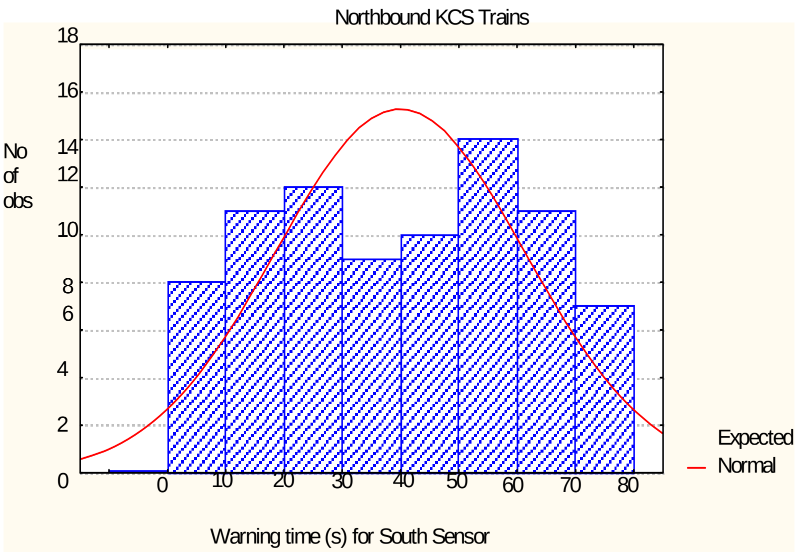

Figure 7. Frequency distribution of warning times are shown in comparison to a fitted Gaussian distribution for Northbound trains at the KCS site (Furrh Road, Louisiana). 23% of the measured values fell below 20 s, while 62% of the values lay above 30 s.

Field testing at the KCS field site during the design phase of this project demonstrated that the velocity sensors were somewhat vulnerable to blowing rain. Intermittent velocity readings of as much as 5 mph in heavy blowing rains were seen when a train was not present. (As expected, this symptom would disappear once the sensor locked onto a significant target such as a train.) In response to this vulnerability, a major design change was implemented to the sensor circuitry. Tests of the improved sensor design indicated that the sensor will no longer trigger on blowing rain, yet its sensitivity to train presence and movement is undiminished.

BNSF SITE

An advanced digital logic system was developed and installed at the BNSF site. The site was in operation for a period of approximately two years, during which time several modifications were made. Final data were collected for analysis during the period January 13 through February 2000. Digital logic timing was employed, and was set to provide a nominal 12 second delay. Data collected were voluminous. The data set of over 500 KB in length contained records for 502 trains, of which 284 were Eastbound. Each train generated approximately 6 lines of records stored in an event recorder and downloaded remotely for analysis.

Figure 8 shows the rank-ordered data for Eastbound trains fitted to a Gaussian distribution. The digital logic associated with the sensor is detecting and calculating warning times correctly for approximately 180 of the trains, as evidenced by the clustering of the data around a target value of 12 s. This value was chosen to evaluate the software at a site where the radar (because of ground clutter) could not see far enough in the distance to permit calculation of greater warning times for faster trains.

To analyze performance of the system in the region where trains were detected sufficiently early to permit software to function as intended, the higher values were truncated. Values of warning times less than 10 s were due to fast trains and these were omitted. The remaining values for 124 Eastbound trains were analyzed. Data were reduced to derive warning times for each train, and analyzed to provide mean value (11.9 s) and standard deviation (0.9 s). For these data, 74% of observations were within +/- 1 second while 94% were within +/- 2 seconds of the mean value. The results are shown in Figure 8, where the data are fitted to a Gaussian distribution.

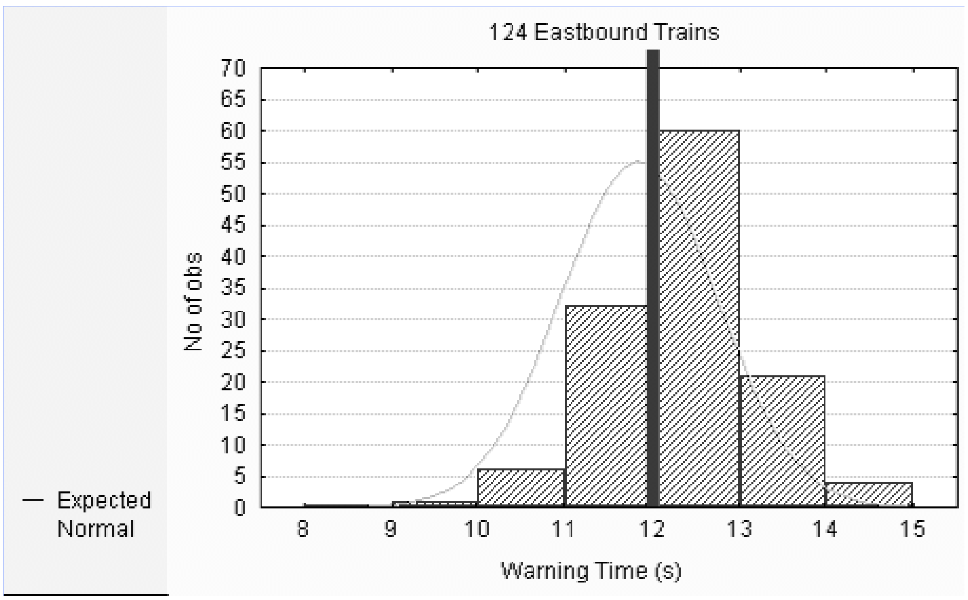

Figure 8. Distribution of warning times for 124 Eastbound trains at the BNSF site, Knightsen Road, California. The data cluster strongly around the design value of 12 s, shown here by the black vertical line.

Figure 8 demonstrates that the digital logic was maintaining a warning time as designed for 12 seconds for roughly one-half of the trains (rank order 6 through 145). Very slow trains, trains stopping near the crossing itself, and Amtrak trains had movement patterns which exceeded the ability of the two-sensor system to follow. Thus for Amtrak trains, the warnings were short, while for slow trains, the warning times were longer than intended, due to software problems. The usual warning time design value is 25 seconds. The software was not designed to continue to update position and speed data, and thus did not work well for slow trains.

A second challenge found at this site is that there is a lot of reflective clutter in the form of overhead wires and buildings. Early testing demonstrated that there was inadequate detection range for 25 s warning times. Thus a choice was made to evaluate the equipment by choosing a shorter time (12 seconds). These data demonstrate that the system logic performs as designed, but that the sensor detection distance is on the order of 0.5 miles in an environment such as this.

Another problem occurs with the Amtrak trains. Sometimes they are missed. The original system design was not designed to detect fast, low cross-section trains. The Amtrak trains were not detected early enough for the system to function properly. As discussed previously, solutions may be found for this difficulty by using remote detectors and modifications to the software.

A second digital sub-system, this for monitoring Westbound traffic, was also installed at the BNSF site. Figure 9 shows the frequency distribution of values for Westbound traffic. In the same manner as for the Eastbound traffic, all event data records were examined for the period January 13- February 11, 2000. Very slow trains and trains that stopped inside the crossing area were omitted. This left records for 236 Westbound trains. As seen above for the digital system, the warning times cluster around the 10-18 s warning time, but there is considerably more complexity in the Westbound traffic flow.

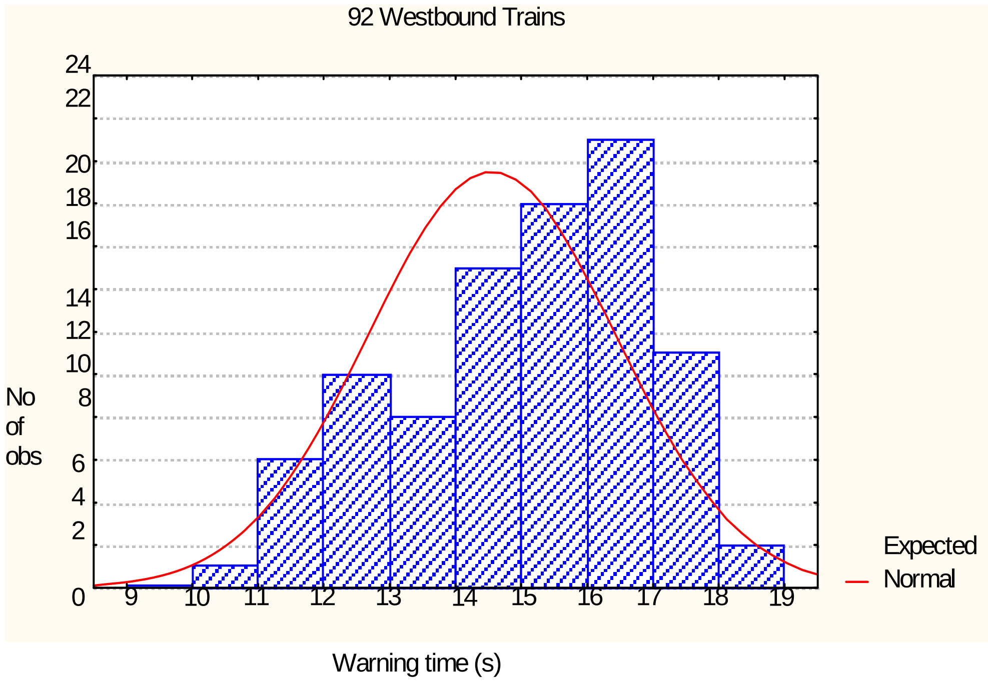

Figure 9. Frequency distribution of warning times for 92 Westbound trains at the BNSF site. This distribution shows an initial region of fast trains, which arrive with short warning intervals; an intermediate region with much more accurate software computation of warning times; and finally, a long-warning time region computed for slow trains

Data were selected for the portion of the curve where the software appeared to be functioning properly. For the 92 trains where the warning time was between 10 and 18 s, the mean value was 14.6 s and the S. D. was 1.9 s. These data were fitted to a Gaussian curve and plotted in Figure 9. There was considerable scatter in these points when compared to the values for the Eastbound trains. Partially because of the inability of the software to properly handle slow/stopped trains and partially because of the complex traffic pattern at this site, only 27% of the Westbound trains arrived within +/-2 seconds of the target warning time of 12 seconds.

The Eastbound sensor system demonstrates that consistent warning times can be achieved over a range of conditions. One must ensure that there is adequate warning time to detect and track the faster Amtrak trains. Furthermore, software must be designed to repeatedly update train position and speed in order to correctly predict arrival time at the crossing. Data for the Eastbound and Westbound sites have different frequency distributions, partially resulting from different train activity patterns and partly from the occurrence of different types of reflective ground clutter. The performance of the Westbound system suffered from the inability of the software to accommodate the clutter caused by overhead wires.

DESIGN AND TESTING OF REMOTE SENSORS AND COMPONENTS

Examination of status records from the BNSF site demonstrated that whereas most trains were detected sufficiently early to provide the desired control of the crossing signal, this was not always true for the Amtrak trains. The problem with the Amtrak trains is twofold: First, the frontal profile of these trains does not provide as strong a reflected signal as conventional, more planar engines. Second, the higher speed of the Amtrak train requires more distant detection in order to achieve the required 25 s warning time before arrival of the train in the crossing. Possible solutions to these problems included the following ideas:

- Employ reflectors or transponders on the faster train engines;
- Develop a redesigned RADAR system to provide better signal detection;
- Use a stronger RADAR signal could be used (undesirable from the standpoint of potential human exposure); and

- Deploy remote RADAR units along the track, away from the crossing, to extend the effective monitoring range at the crossings.

It was decided to configure two remote velocity sensors to the east and west along the tracks at distances of 1000m from the crossing. Two remote sensors could be used, one in each direction. These remote sensors can communicate with the local (crossing) system via spread-spectrum radio links. Three Proxim Link units were purchased and matched to either RADAR sensor boards configured to provide a variable velocity signal or to a computer that monitored status of the sensor boards using the radio link. Initial tests indicate that (1) the Proxim units are interfaced correctly to the RADAR boards and to the computer; (2) the PIC microprocessor on the RADAR board is communicating correctly with the Proxim unit and (3) we are achieving reliable transmission of 9600 baud ASCII signals over the wireless links.

It was found that noticeable loss of synchronization between the spread-spectrum transceivers was evident for distances beyond 120 meters, using ¼ wavelength antennas supplied by Proxim, Inc. Proxim communication engineers did not offer antennas that were expected to give sufficiently improved performance. This finding is important because of the need to communicate reliably over paths of about 1 km. The maximum distance expected for these experiments is the 1.2km distance (measured in October) for the west approach at the BNSF site. For the railroad application, some of the reflectors that might cause signal fading are the moving trains themselves.

A decision was made to evaluate several types of antennas to determine the reason for poor communications. A search was made for antennas that would offer reliable communications between remote radar units and the crossing area. This is thought to require a gain of 11 dBi or greater, over the ¼ wavelength antenna. Furthermore, there is no assurance that normal (linear polarization) antennas are suitable in this case, since reflections from the ground and trains adjacent to the signal path may cause signal loss due to destructive interference between signals from different paths.

Three antennas were constructed for field evaluation. These were a 2.4 GHz Quagi antenna; a 2.4 GHz Helical antenna with stub matching; and a 3-Element Helical antenna. These antennas were tested at a site chosen for similarity to railroad sites of interest. This test was conducted in complex surroundings with multiple signal reflection paths. For each test, two Proxim links were used and were monitored for synchronization. One link was at a fixed site with the antenna being evaluated. The second link was inside a car, which was driven along the field test site road that was 1.5 km long. Except for the last test where 2 helical antennas were used, the (reference) Proxim link in the car was equipped with a ¼ wavelength antenna.

Good synchronization between Proxim links at this uncluttered field site using ¼ wave antennas was achieved at up to 0.6 km.

A significant improvement in data transmission was found when the two helical antennas were used with the Proxim links. Good synchronization was found up to 1.2 km, which should be sufficient for the railroad application. It should be noted that the test site does not have large reflectors, such as trains, so one must still be careful to ensure that synchronization can be maintained at the railroad site.

It was apparent from the above tests that significant improvements in results can ensue from the use of circular polarization. There is less sensitivity to interference problems from reflections than with linear polarization.

A remote velocity sensor unit was programmed constructed for use at the BNSF site. The unit was tested and performed satisfactorily in laboratory and field tests in January, but was not installed at the Knightsen facility because of difficulties in coordinating activities with the BNSF site.

4 CONCLUSIONS AND DISCUSSION

The system evaluated here has potential for improving safety at crossing sites currently unequipped with crossing signals. It is not operational as a functional replacement for current track-circuit signal controllers.

Installed systems were evaluated with respect to their overall reliability, functionality and safety. Summary comments are as follows:

- Some approaching trains were not detected at all, and others were not always detected early enough to permit the desired warning time. These problems were caused by such things as swinging overhead wires, buildings, and the rounded-nose profile of Amtrak locomotives. These problems can likely be overcome by improvements to the software, and using a tighter beam width and/or a system using remote sensors.
- The prototype has the capability to provide 20-30 second advance activation of crossing warning systems for constant-speed trains traveling at moderate speeds. However, software modifications will be required to

provide such constant warning times for trains that accelerate, decelerate, or stop after they are initially detected.

- In the final system, malfunctions were detected by remote monitoring of the event recorder. A capability to detect malfunctions could be developed at low cost in future systems.
- No sensitivity to EMI was discovered during routine monitoring, but no scheduled tests were conducted with railroad equipment. Tests with a local 150 MHz transmitter operating at 25 watts power did not produce any erroneous signals.
- Field tests in moderately severe rains demonstrated that the system performance was satisfactory. The system was not evaluated during hail, sheet rainfall, or high-velocity blowing rain.

The current microwave warning system detects and predicts the arrival of trains under a limited scope of operational conditions. Tests conducted to date show these systems have the potential to provide adequate crossing warning activation for through trains travelling at relatively constant speeds. In addition, the system does not activate with animals or people walking on the track. However, additional software and hardware development, testing and evaluation will be required to determine whether this technology can handle such scenarios as: trains that accelerate, decelerate, stop, and reverse; high speed trains with smooth profiles, and under a full range of weather and electromagnetic interference conditions.

The system can likely be expanded to cover such scenarios as the following:

- detecting vehicles, pedestrians or other obstacles inside the crossing;
- linking of functions between the 2 sub-systems;
- detecting traffic waiting at or near the crossing;
- detecting speeding vehicles that are approaching the crossing too fast to stop (additional sensors required); and
- solar powered systems.

Other options that would require more extensive modifications are the following:

- information transfer from the microwave warning system to the train, and vice-versa;
- information transfer from the sensors to traffic, such as school buses, emergency vehicles;
- measuring length of traffic backed-up at the crossing;
- relay of digital information from emergency vehicles to trains;
- wireless system-to-system data linking; and
- controlling traffic lights at complex crossings.

If warning tolerances in the order of 10 to 20 seconds are allowed, a simple system using only 4 watts can be installed at any remote straight track location. For most locations in the United States, a single solar panel and battery could continuously power the system.

5 RECOMMENDATIONS

As a result of this project two systems designs are recommended for further consideration. The first design is the system that has been developed and applied here, with the addition of enhanced safety features such as self-monitoring. The second design that should be considered is a simplified design that would be highly cost-effective yet still provides most basic functions. Based on our results, advanced digital logic may be employed for improved control and better reliability. Self-monitoring and reporting are also possible.

The second design recommended for future development is the following:

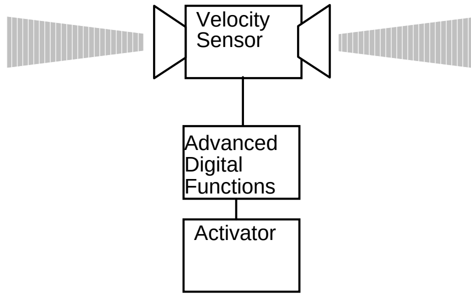

Figure 10. Simplified sensor system block diagram recommended for future implementation. This system would incorporate several advantages including physical simplicity (low parts count and reduced number of sub-modules), advanced digital logic, fault checking and automatic function monitoring.