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Analysis of Non-Track-Circuit Highway-Rail Grade Crossing Train Detection Technologies

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13. ABSTRACT (Maximum 200 words) This research investigated the suitability of non-track-circuit-based technologies as a cost-effective means to deploy active warning devices at passive grade crossings. While several promising technologies were identified, some of the findings were unexpected. Mainly, there existed a subset of passive grade crossings that may potentially experience a sharp decrease in risk if these crossings were to be equipped with active warning devices. This finding was based on an analysis of the societal benefits accrued from equipping the crossings with active warning devices relative to the installation and life-cycle costs during the expected lifetime of the equipment. The cost differential between track-circuit-based and non-track-circuit-based systems was minimal and could not be used alone to justify alternative train detection technologies. However, alternative technologies were superior to track-circuit-based systems at locations prone to flooding/snow/ice, leaf buildup on rails, and accrual of rail rust. This finding further suggested that there was a compelling argument for evaluating alternative grade crossing train detection technologies.			
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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

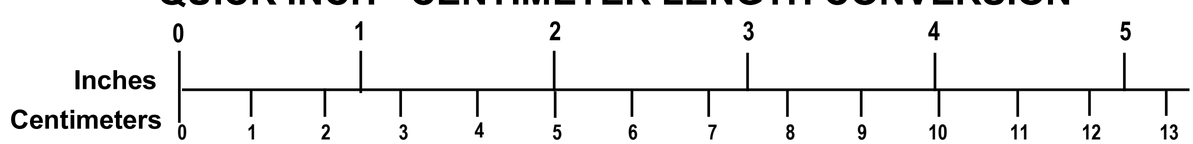
VOLUME (APPROXIMATE)

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 CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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

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Executive Summary

All States prioritize grade crossings in need of improvement by means of a risk ranking system. The most common options are: upgrade to active warning devices, grade separation, or crossing closure. Since funding is a major constraint, the riskiest grade crossings are selected by means of quantitative analysis and expert judgement.

In recent years, a milestone of sorts was reached in the world of highway-rail grade crossing safety. The number of public grade crossings equipped with active warning devices eclipsed the number with passive warning devices. Through March 2015, passive rail crossings accounted for 59,262, or 46 percent, of the total 129,470 public crossings.[1] Passive grade crossings are not equipped with active warning devices due to the low rail and roadway traffic exposure levels found at these crossings. Even so, 30 percent of all grade crossing accidents and 28 percent of all fatalities occur at passive grade crossings. At the time this report was being finalized, a horrific accident occurred at a passive grade crossing in Trinidad, Colorado, resulting in the death of five people in a minivan and the survivor seriously injured (Paul & Munio, 2016).

In response to this challenging environment, the Federal Railroad Administration Office of Research, Development and Technology directed the John A. Volpe National Transportation Systems Center to conduct a technology assessment of low-cost active warning devices for application at passive highway-rail grade crossings. The objective of this research was to present an objective analysis of non-track-circuit highway-rail grade crossing train detection technologies.

Track-circuit-based train detection warning systems are the *de facto* standard for railroads in the U.S. and will remain as such for the foreseeable future. Non-track-circuit-based train detection systems, at a minimum, may offer better performance in locations that are prone to flooding and rail contamination or do not offer adequate access to commercial power. Some of these technologies, such as wheel detectors, are commercially available and in compliance with Federal regulations. While railroads in Europe have been employing wheel detector-based train detection systems for some time, acceptance in the U.S. has been at a much slower pace. Other technologies, such as Fiber Bragg grating, are at a much lower state of maturation and present as potential targets for Federal research and development. Aside from some wheel detector-based systems already in service, these technologies are considered novel. As they are processor-based as well, they are also required to satisfy Federal regulations for processor-based systems.

While researchers identified several promising technologies, some of the findings were unexpected. Mainly, they found a subset of passive grade crossings that may potentially experience a sharp decrease in risk if these crossings were to be equipped with active warning devices. This finding was based on an analysis of the societal benefits accrued from equipping the crossings with active warning devices relative to the installation and life-cycle costs during the expected lifetime of the equipment.

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[1] FRA Office of Safety Analysis (2015). FRA Office of Safety Analysis website. Retrieved March 7, 2015 from https://safetydata.fra.dot.gov/OfficeofSafety/default.aspx.

1. Introduction

Replacing signage at highway-rail grade crossings with active warning devices may provide a significant reduction in accident risk. Track circuit train detection systems have long been established as the preferred means for activating flashing lights, bells, and gates. There are, however, a significant number of site-specific and operational conditions, such as rail surface contamination and poor ballast conditions, for which track circuits are not generally feasible.

This report focuses on identifying potentially cost-effective alternatives, with the ultimate objective of selecting one or two that warrant further investigation. Toward this end, Volpe researchers will conduct a salient characteristics review of the various alternative technologies to determine which can compare favorably with track circuits in terms of performance and life-cycle cost. In conjunction, researchers used grade crossing injury and casualty data from the U.S. Department of Transportation (DOT) Federal Railroad Administration (FRA) safety database to determine the potential for cost-effective train detection solutions to reduce grade crossing accident risk.

Figure 1 shows incident, injury, and casualty trends for public rail crossings from 2005-2014, as published in FRA reports of annual railroad safety statistics. The incident values and the ancillary injury and fatality data in this figure include all reported occurrences at the rail crossings and are not limited to motor vehicles. From 2005-2009, there was an almost linear decrease in the number of incidents. After 2009, the incident data behaved in a similar manner to the injury and fatality data. This broadest measure of public rail crossing safety showed a marked decrease of 25.7 percent, 21.3 percent, and 27.1 percent in incidents, injuries, and fatalities, respectively, from 2005-2014, despite increased rail traffic.

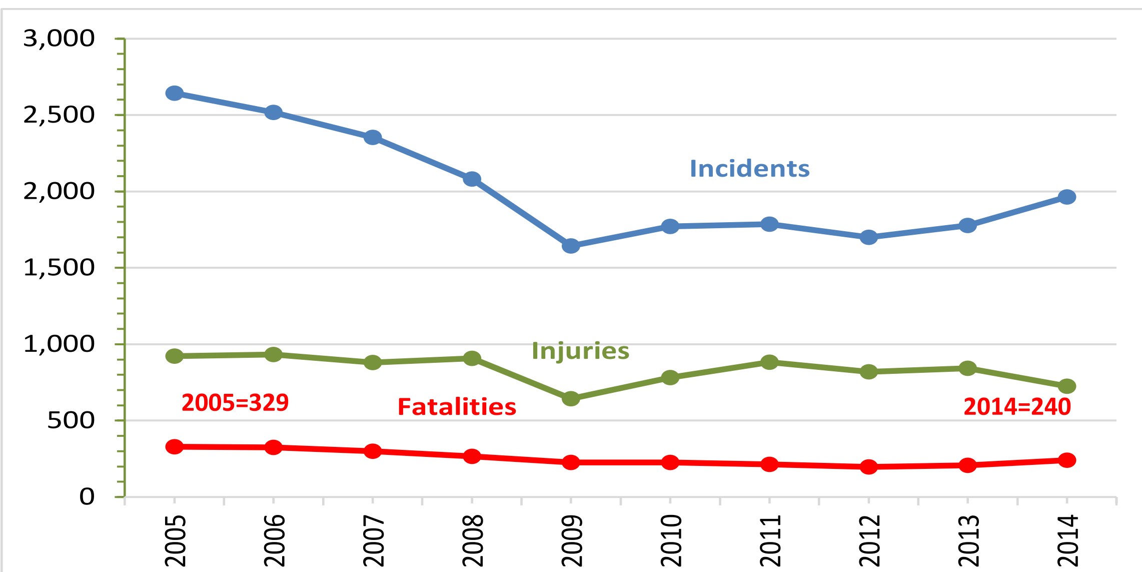

Figure 1. Public Rail Crossing Incident and Casualty Statistics from 2005-2014

This data is for public rail crossings only. Although local and State agencies and railroads submit inventory updates for both public and private rail crossings on a voluntary basis, there is an economic incentive for these organizations to submit public rail crossing inventory updates, because the FRA inventory is used by the Federal government to rank rail crossing risk and provide funding for improvements. Since the majority of risk is confined to public rail crossings, there is little motivation for private entities to submit timely rail crossing data updates. As a result, private rail crossing records in the FRA inventory are, on average, updated less than half as frequently as public rail crossing data records (Peck, Carroll, & Kloeppel, 2010).

1.1 Background

Through March 2015, public passive rail crossings accounted for 59,262 of the total 129,470 public crossings (DOT, FRA, 2015). The warning devices at these rail crossings consist of stop signs, crossbucks, other signs or signals. Some, in fact, have no signs or signals. In 2014, there were 1,964 vehicle collisions with trains at public rail crossings in the U.S., resulting in 240 fatalities and 725 injuries. Of that total, 587 (30 percent) incidents occurred at rail crossings equipped with only passive warning devices, resulting in 67 (28 percent) of the total fatalities and 256 (35 percent) of the total injuries (DOT FRA, 2015). The same research reported that 755 (42 percent) of the 1,810 public rail crossings with multiple accidents were at passive rail crossings. For the 5-year period of 2010-2014, the basis for the analyses contained in this report, 299 (28 percent) of the 1,068 public rail crossings that experienced multiple incidents were passive. Although this represents a significant decrease from the years 1994-2003, when 16,000 (48 percent) of rail crossing accidents occurred at passive crossings (DOT Office of the Inspector General, 2004), additional efforts to reduce these numbers even further are warranted.

While significant progress has been achieved in absolute risk reduction, there is still room for improvement. In 2014, the rail crossing incident rate at passive public rail crossings, when normalized for rail and highway traffic exposure, was eight times larger than for active public crossings.[2]

Given the funding constraints of Federal and State rail crossing improvement programs and the multitude of competing rail crossing safety issues, only a small subset of the rail crossings in need of improvement (e.g., lights, lights and gates, traffic signals, channelization, etc.) can be addressed in any given year. With only the riskiest rail crossings being addressed, the likelihood that many lower-exposure, but relatively risky, passive rail crossings will be upgraded is slim.

Low-cost active warning systems have long been pursued, at least since the early 1970s, by the DOT as a means to reduce the risk at passive rail crossings (Hopkins & Hazel, 1971; DOT, 1971). At a 1995 FRA Research Needs Workshop, low-cost alternatives ranked second out of 42 high-priority research needs (Carroll & Helser, 1995). This led to a FRA-sponsored research and test program in 1999 (Reiff et. al., 2003). The 2004 DOT report, *Secretary's Action Plan for Highway-Rail Crossing Safety and Trespass Prevention,* stated that it would "take the lead in development, testing, evaluation, and implementation of low-cost safety improvements or devices for passive crossings." The report also noted that previous efforts to develop such systems had succumbed to reliability and cost concerns.

[2] Exposure at a single crossing is defined as the product of the average daily trains and the annual average daily highway traffic.

1.2 Objectives

Researchers sought to provide an update of the current state of possible alternative warning device technologies for passive public rail crossings and characterize the feasibility of these technologies for revenue service operations.

1.3 Overall Approach

Researchers first established the baseline risk (base case) of the existing FRA public passive rail crossing inventory. They calculated this using a weighted average of the DOT accident prediction formula (APF) and the accident history for the most recent five-year period, 2010-2014. They then compared the base case against the predicted risk for two alternate scenarios: equipping the inventory with flashing lights or with flashing lights and gates. The results of the comparison were used as inputs to a benefit-cost analysis (BCA) model for justification of any future investment in active rail crossing warning technologies.

Researchers performed an evaluation of current and emerging train detection technologies in parallel to the risk analysis. They based the evaluation on design considerations such as safety, cost, performance, maturation, and viability. They proposed an alternate risk assessment approach that evaluated the technology under typical operational conditions (i.e., connected to the railroad infrastructure) rather than *ex situ*.

1.4 Scope

There are approximately 59,000 public passive grade crossings in the U.S. This research explores the potential safety and monetary benefits associated with upgrading passive grade crossings with active warning devices—either flashing lights or flashing lights with gates. In particular, the report determines if a subset of public passive grade crossings responsible for a disproportionate percentage of the risk can be identified. The research also assesses alternate train detection technologies for locations where conventional track-circuit-based train detection is not feasible. Alternate warning device technologies are not addressed.

1.5 Organization of the Report

- Section 2: Literature Review
- Section 3: Benefit-Cost Analysis
- Section 4: Alternative Considerations
- Section 5: Current and Emerging Technologies
- Section 6: Summary
- Section 7: Proposed Migration Path
- Section 8: Conclusion/Recommendations

2. Literature Review

A 1968 report published by the National Academies of Sciences was one the first to identify the development of low-cost warning technologies as a research priority. The authors stated that track circuits were the *de facto* train detection technology for active rail crossing warning systems. While these systems were highly effective in reducing accident risk, they were also costly to install and maintain (Schoppert & Hoyt, 1968). In response, FRA initiated a research program to investigate the feasibility of non-track-circuit-based detection technologies. A 1971 report published under this program by the Transportation Systems Center (TSC) investigated these issues in further detail. The authors found that designing fail-safe components to operate on the closed-loop principle was the primary impediment to the implementation of low-cost warning devices. The report stated that designing components for fail-safe operation was a costly and complex process that precluded many highly reliable and inexpensive non-fail-safe technologies (Hopkins & Hazel, 1971). A report to Congress in 1971 described government publications, such as the Manual of Uniform Traffic Control Devices (MUTCD), as an impediment to the development and fielding of new train detection and warning systems. The report also stated that the introduction of new rail crossing technologies was especially problematic since extensive testing was required to gain acceptance within the railroad industry. Concomitantly, defending the efficacy of unconventional equipment from accident claims was more difficult than with traditional technology (DOT, 1971).

The FRA-funded research program, primarily led by TSC, yielded a significant body of work. Hopkins & Hazel (1971) evaluated the feasibility of several alternative systems. This study included signal activation by microwave communication links and train detection by radar and rail impedance measurement. This was followed by limited testing of microwave telemetry and radar systems (Hopkins, et. al., 1975). A more broad-based study included an evaluation of radar, seismic, infrared, magnetic, rail impedance, and acoustic sensors. The authors found that the rail impedance technique (i.e., employing the rails as a guided transmission line) offered unique advantages, such as:

- Internal compensation for changes in ballast characteristics that affect impedance
- Continuous position and velocity information at arbitrarily chosen increments of distance
- Track-based broken rail detection
- Intrinsically fail-safe operation
- No requirement for grade crossing island detection (Peterson & Boyer, 1977).

The final report in this series evaluated the feasibility of discrete and continuous train detection technologies. Of the multiple discrete technologies evaluated, magnetic sensors held the most promise. Likewise, transmission line measurement bested the other continuous train detection technologies and was recommended for further development (Nylund & Holtermann, 1980). The report also featured evaluation criteria for ranking the technologies.

There was little further progress until 1999, when FRA revisited the prospect of low-cost technology solutions. The research was performed at the Transportation Technology Center (TTC), in Pueblo, Colorado. Five technologies were evaluated for their ability to detect motor vehicles and trains approaching and occupying a rail crossing at TTC:

- Two train presence detection systems—both of which employed vibration and magnetic anomaly sensors.
- Two integrated train and vehicle detection systems—one using inductive loops for train detection and radar for vehicle detection, the other double wheel sensors (axle counters) for train detection and a low-power laser and video imagery for vehicle detection.
- A vehicle detection system that employed passive infrared and ultrasonic detectors.

The results of the testing indicated that some of the detection technologies were sufficiently mature to warrant further evaluation (Reiff et. al, 2003).

In 2004, the Transportation Research Board (TRB) National Cooperative Highway Research Program (NCHRP) awarded a contract to the Texas Transportation Institute (TTI) "to identify and assess low-cost, viable active-warning-system and component designs for highway-rail grade crossings."[3] The authors evaluated 12 low-cost train detection technologies and ranked them using a multi-criteria analysis.

Two low-cost off-railroad right-of-way train detection technologies were selected for further testing and evaluation. The first system was radar-based and the second was based on train horn acoustic signature detection. It was found that both test systems, when "tuned" to successfully detect all trains, generated an unacceptable number of false train detections. TTI also documented the institutional and legal issues regarding the introduction of alternative grade crossing warning systems. In particular, U.S. tort law was found to impede the development and deployment of technological innovations (Roop, Olson, Ruback, Roco & Protopapas, 2007).

More recent research has focused on discrete sensing technologies, such as wheel sensors and magnetometers. A Transport Canada-funded research program resulted in the development of a wheel-sensor-based train detection system that employs spread spectrum radio technology to minimize the cost of transmitting train detection data from the wheel sensors to the grade crossing controller (Southon, 2013).

Brawner & Mueller (2006) demonstrated train detection based on anisotropic magneto-resistive (AMR) sensors. The technology was successfully tested at a rural grade crossing on the Burlington Northern Santa Fe (BNSF) Railway near Emporia, Kansas. However, further research and development was required to integrate the AMR technology within a grade crossing warning system. Ashraf, Baldwin, & Zhou (2010) proposed a solar-powered AMR-based train detection system employing low-power spread spectrum radios for sensor-to-grade-crossing-controller communications. A promising multi-sensor system for roadway worker protection was developed and tested by the University of Nebraska. The system employed piezoelectric accelerometers for train detection, an ultrasonic sensor for proximity detection, an AMR sensor for train classification, and wheel counting for train work zone entrance and departure. For a sample size of 2,000 trains, no missed detections were observed. The false alarm rate was slightly less than 10 percent.

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[3] Retrieved from https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=831

The most research outside of North America has been in Australia. The Victorian Road Authority (VicRoads) performed an evaluation of four train detection technologies (Jordan, 2006):

- A Doppler radar unit
- Two magnetometer systems
- An in-train transmitter
- An induction loop

The induction loop system showed the most promise and was selected for shadow mode testing at a passive grade crossing in Creswick, Victoria. The system demonstrated a false detection rate of 0.02 percent (Parliament of the Commonwealth of Australia, 2009). More recent testing has focused on wheel detector-based train detection systems.

In recent years, much of the grade crossing research has been performed under the auspices of the Cooperative Research Centre (CRC) for Rail Innovation, a consortium of Australian and Canadian government agencies and railroads, and seven Australian research universities. In 2011, CRC initiated the Affordable Level Crossings project. The objective of this project was to investigate the potential of low-cost train detection technologies at low-exposure grade crossings. These technologies were not intended for high-exposure grade crossings or as a replacement for traditional train detection technologies. To this end, a minimum safety criterion for mean time to hazardous event (MTTHE) of 10^6 hours was assumed, significantly lower than the nominal value of 10^9 hours for safety of life railroad systems[4] (Wullems, Baker, Beh, Upton & Wayth, 2013).

Three wheel detector-based train detection systems, two inductive and one AMR, were selected for testing by CRC. The systems are shown in Table 1, below. A comparative 12-month trial was performed, in which the technologies were evaluated in shadow mode at three Australian grade crossings with pre-existing track-circuit-based active warning systems. The crossings, required to be single-track, were selected to ensure each technology would be evaluated to encompass a wide range of conditions, including:

- Passenger and freight rail traffic
- Diesel and electric trainsets
- Varying train speeds
- Single and bi-directional rail traffic
- Varying rail traffic volumes
- Less-than-optimal line-of-sight communication

All three systems were evaluated at each crossing and compared with the performance of the track-circuit systems. The results of the program, completed in 2014, were mostly favorable. However, a large number of axle miscounts were recorded, mostly due to hi-rail vehicles entering the railroad via the grade crossing island (Larue, Wullems & Naweed, 2016).

[4] An MTTHE of 10^6 hours is equivalent to Safety Integrity Level two (SIL 2), as defined by the European Committee for Electrotechnical Standardization. Similarly, an MTTHE of 10^9 hours is equivalent to SIL 4.

According to Transport for New South Wales (2016) the Australian rail industry pursued type approval for two of the systems.

In a parallel project, a process for developing a generic product safety case for new grade crossing technologies was pursued by a consortium of public, academic, and private sector Australian rail organizations (Wullems & Naweed, 2014).

Table 1. Australian Low-Cost Grade Crossing Technologies
(Wullems et al., 2013)

	Vendor		
Characteristic	Vendor 1	Vendor 2	Vendor 3
Train Detection Technology	Inductive Wheel Sensors	Inductive Wheel Sensors	AMR Wheel Sensors
LCLCWD Component Connectivity	Wireless	Cable	Wireless
Power Supply	Solar	Solar	Solar
Safety Integrity	SIL 4 (MTTHE > 10^8 hours)	SIL 3 (MTTHE > 10^7 hours)	SIL 2 (MTTHE > 10^6 hours)

3. Benefit-Cost Analysis

3.1 Overview

The purpose of the benefit-cost analysis was to determine if further investment in active rail crossing warning systems would be justified. The *base case* of passive warning devices was compared against the two *alternative scenarios* of upgrading to flashing lights and upgrading to flashing lights with gates. For each scenario, the collision risk of the rail crossings was ranked from high to low. Three measures of risk were evaluated: predicted collision reduction from the base case, predicted casualty reduction from the base case, and the 25-year life-cycle inflation-adjusted benefit-cost ratio for the two alternative scenarios.

For the base case (passive public rail crossings), the accident data at public passive rail crossings was analyzed for the 5-year period from 2010-2014. First, FRA accident data was cross-referenced with the most recent version of the DOT National Highway-Rail Grade Crossing Inventory (DOT FRA, 2015). Next, the DOT APF, detailed in Appendix A, was used to estimate the number of predicted accidents for the base case.

At the time the Inventory was accessed, there were 59,262 public passive rail crossings. Table 2 shows the breakdown of these rail crossings by warning device type. Since the FRA Inventory is dynamic in nature, it was expected to show the closest correlation with the 2014 accident data. Accident data from the previous years in the study going back to 2010 were expected to show less of a correlation. Using these criteria, 2,516 accidents for the 5-year study period were retrieved from the FRA accident database. The average annual number of accidents was 503.

Table 2. Distribution of Public Passive grade Crossing by Warning Device Type

Warning Device Type	Number of Crossings
Stop signs	11,032
Crossbucks	45,761
Other signs or signals	274
No signs or signals	2,195
Total	**59,262**

Table 3 shows the collision and casualty data at public passive rail crossings from 2010-2014. The upward trend in collisions and casualties from 2010-2014 is a reflection of the 2014 accident dataset being temporally closer to when the Inventory file was downloaded (March 7, 2015) rather than any change in risk. Many of the passive rail crossings in the earlier years of the dataset, especially 2010, are not present in the 2015 inventory. Accidents attributed to those rail crossings will not be represented in the ensuing analysis. This was an unavoidable aspect of the analysis, since the Inventory is a snapshot-in-time of the composition of the national rail crossing inventory.

The last two columns of Table 3 show the average injury and fatality rates over the 5-year timespan. These values, which remained surprisingly constant between 2010 and 2014, were the basis for all of the risk calculations in remainder of this section.

Table 3. Annual Casualty Data at Public Passive Grade Crossings, 2010-2014

Year	Collisions	Injuries	Fatalities	Injuries Per Collision	Fatalities Per Collision
2010	476	228	49		
2011	486	233	50		
2012	495	237	51		
2013	503	241	51		
2014	556	267	57		
Average	503	241	51	0.4794	0.1021

3.2 Results

In a 2013 paper on Australia, Wullems, Hughes & Nikandros proposed a *minimum exposure* threshold of 24 trains and 100 highway vehicles per day for installing active warning devices at passive grade crossings. These exposure values were employed to "filter" out low-exposure grade crossings that did not pose a high risk and therefore did not require active warning devices. Of the total DOT inventory of 59,262 passive public grade crossings, a subset of 957 crossings meeting the threshold criteria were identified. The filter was used as a first-cut estimate to establish a baseline set of passive grade crossings that may benefit from active warning devices and did not account for differences between U.S. and Australian operating conditions.

Three collision risk-ranking techniques were employed: *minimum exposure threshold*, *DOT APF,* and *5-year accident history*. For each of the techniques, a unique set of 957 grade crossings was generated and ranked from high to low with the *DOT APF*.

The comparative results for the three risk-ranking techniques are found in Appendix B, but only the results of the *DOT APF* ranking technique are presented here. The riskiest 957 grade crossings identified by this technique are shown overlaid on a map of the U.S. in Figure 2. For the scenario of the upgrade to flashing lights, the *DOT APF* predicted a reduction of 109 (48 percent) collisions from the base case of 227 collisions. Similarly, if gates with flashing lights were installed at all 957 crossings, the number of collisions was predicted to decrease from by 198 (87 percent) from the base case of 227 collisions. These values are summarized in Table 4.

Figure 2. The 957 Riskiest Public Passive Grade Crossings with a Minimum Exposure of 24 Trains and 100 Vehicles Daily

Table 4. Risk Reduction Associated with DOT APF for Upgrades to Flashing Lights and Flashing Lights with Gates

Type of Upgrade	Five-Year Averages: Collisions = 227; Injuries = 125; Fatalities = 23 Number of Crossings = 957		
	Annual Collision Reduction	Annual Injury Reduction	Annual Fatality Reduction
Flashing Lights	109.28 (48%)	52.39 (42%)	11.15 (48%)
Gates with Flashing Lights	197.84 (87%)	94.84 (76%)	20.19 (86%)

3.2.1 Casualty Reduction

As with the collision reduction analysis, the DOT APF captured the largest reduction in predicted annual injuries and fatalities for the reduced data set of the 957 rail crossings. For the flashing light upgrade scenario, the numbers of predicted annual injuries and fatalities were reduced by 52 (42 percent) and 11 (48 percent), respectively. The scenario of upgrading the rail crossings to flashing lights with gates yielded a predicted annual decrease of 95 (76 percent) injuries and 20 (86 percent) fatalities. The details may be found in Appendix B.

3.2.2 Predicted Rail Crossing Life-cycle Costs

The collision and casualty reduction results were used as inputs to the benefit-cost analysis. BCA is essentially the method by which the reduction in risk is monetized. For this analysis, the following assumptions were used:

- Rail crossing signaling equipment design life of 25 years (Invensys Rail, 2010)
- A deployment schedule of 10 years with 100 crossings being upgraded annually during the first 9 years and the remaining 57 during the final year.
- Upgrade costs consist of train detection components, warning devices and installation.
- After the first 10 years, only maintenance costs are incurred.

The inputs into the BCA are shown in Table 5. For the upgrade to flashing lights, a unit cost per crossing of $100,000 was employed. The addition of gates to flashing lights was assumed to increase the equipment and labor costs by a factor of two. This probably overstated the additional costs associated with gates, but chosen to provide a significant difference between the two types of warning devices. The present value of the costs were tabulated over the 25-year expected design life of the equipment using an assumed discount rate of 3 percent.

Table 5. Benefit-Cost Analysis Inputs

Upgrade to Flashing Lights	Upgrade to Gates with Flashing Lights
25-year life-cycle	25-year life-cycle
Years 1-9: 100 rail crossings upgraded annually	Years 1-9: 100 rail crossings upgraded annually
Year 10: 57 rail crossings upgraded	Year 10: 57 rail crossings upgraded
Upgrade cost per crossing: $100,000	Upgrade cost per rail crossing: $200,000
Annual maintenance per rail crossing: $5,000*	Annual maintenance per rail crossing: $10,000[5]
Years 11-25: maintenance costs only	Years 11-25: maintenance costs only
3 percent discount rate	3 percent discount rate
Cumulative cost: $147 million	Cumulative cost: $294 million

[5] Includes scheduled and corrective maintenance

Upgrade to Flashing Lights	Upgrade to Gates with Flashing Lights
Value of a statistical life: $9.4 million (DOT, 2015)	Value of a statistical life: $9.4 million

3.2.3 Predicted Benefits from Reduction in Collisions and Casualties

The DOT Office of the Secretary of Transportation (OST-R) publishes guidance on the monetary values of preventing injuries and fatalities associated with highway traffic accidents. The most recent guidance, published in 2015, recommended $9.4 million per fatality (DOT, 2015). The reduction in injury costs was calculated by multiplying the average value of 0.4794 injuries per accident in Table 3 by the average of levels 1-5 in the Abbreviated Injury Scale (AIS) defined by DOT (DOT, 2015). The product was then multiplied by $9.4 million dollars. The reduction in costs associated with lost lives was calculated by multiplying the average value of 0.1021 fatalities per accident in Table 3 by the entire cost of $9.4 million. The expected benefits are accrued incrementally over ten years as the 957 rail crossings are upgraded. From years 11 through 25, the expected benefits remain constant. The present value of the expected benefits over the 25-year expected design life was calculated using a 3 percent discount rate.

Table 6 shows the predicted monetary benefits based on the reduction in risk predicted by the DOT APF for the flashing light and gates with flashing lights upgrade scenarios. The benefit-cost ratio (BCR) of 18.16 for the flashing lights scenario turned out to be slightly higher than for the gates with flashing lights (16.44) scenario.

An interesting unanticipated finding from this analysis was that grade crossings that employed track circuits for train detection would be cost-effective at reducing risk at the 957 grade crossings. The costs associated with the deployment of track-circuit-based active warnings at crossings were in the range of $200,000-$500,000. Assuming that maintenance costs are similar, these systems would provide a BCR significantly greater than one.

Table 6. Benefit-Cost Analysis Associated with DOT APF for Upgrades to Flashing Lights and Flashing Lights with Gates

Five-Year Averages: Collisions = 227; Injuries = 125; Fatalities = 23 Number of Crossings = 957			
Type of Upgrade	Present Value		Benefit-Cost Ratio
	Safety Benefit	Cost	
Flashing Lights	$2,667,629,529	$146,866,832	18.16
Gates with Flashing Lights	$4,829,296,823	$293,733,663	16.44

3.2.4 Discussion

Using the methodology described above yielded a predicted annual reduction of up to 109 collisions if all 957 passive rail crossings in the experimental dataset were equipped with flashing lights and 198 collisions if they were upgraded with gates and flashing lights. This improvement was quite significant and based on the premise that installing flashing lights (or gates with flashing lights) at a passive rail crossing provides a 70 percent (83 percent for gates with flashing lights) reduction in the unnormalized predicted accidents of the base case, as described in Appendix A. The effectiveness values of 0.7 and 0.83 used for this calculation have not been updated in 30 years. Therefore, it was not clear if they were an underestimate or overestimate of the current effectiveness.

Other studies have employed the DOT-modified APF to estimate the predicted risk reduction in terms of fatalities per year. This model was not used for several reasons. First, the severity component of the model was based on rail crossing accident data from 1975-1995. The primary inputs into the model were: 1) the probabilities of a train striking a vehicle and a vehicle striking a train, 2) the mixture of automobile and commercial vehicle traffic at rail crossings, 3) the distribution of passenger and freight rail traffic, and 4) train speed. The model assumed a vehicle mixture of 73 percent automobiles, 19 percent trucks, and 8 percent truck trailers. The current mixture was unknown to researchers, making it impossible to update the severity component.

Second, as the authors of the model state, the risk component of the model did not include an adjustment factor for actual experience similar to the formula and warning device constants employed in the DOT APF. Although the model was sufficient for ranking the risk among rail crossings for the allocation of improvement funds, it was not appropriate for comparing actual and predicted risk or comparing risk before and after rail crossing improvements.

4. Considerations

4.1 Safety and Reliability

For any alternative to a track-circuit-based system to be considered viable by the railroad industry, there are two principal hurdles to be cleared: performance and cost. The fail-safe performance of any alternative to a track-circuit-based system will be required to demonstrably equal to or exceed that of a track-circuit-based system. Track circuits are classified as safety-critical, a term meaning that the correct performance the equipment is critical to the safety of personnel and/or equipment.

Some systems are proven fail-safe by means of a safety assurance concept called *intrinsic* fail-safety. These systems, composed of discrete electrical circuits and mechanical components, are sufficiently simple in design such that all unsafe failure modes can be identified and removed by means of a verifiable process, such as a failure modes and effects analysis (FMEA). Should a critical failure occur, these systems will always fail to a known safe state (Positive Train Control Systems, 2010). Some examples from the railroad industry are relay-based train detection circuits and mechanical interlockings.

Safety-critical systems that employ microprocessor-based hardware and software applications comprise a second category. Since these systems are extremely complex, it is not possible to demonstrate that they are intrinsically fail-safe. However, it can be shown that they are statistically fail-safe.

To this end, the railroad industry has adopted a more flexible definition of fail-safe that encompasses both intrinsically and non-intrinsically fail-safe systems, as provided below:

A design philosophy applied to safety critical systems such that the result of hardware failure or the effect of software error shall either prohibit the system from assuming or maintaining an unsafe state, or shall cause the system to assume a state known to be safe.[6]

The safety of processor-based safety-critical systems is measured in terms of MTTHE. International Electrotechnical Commission (IEC) 61508, Standard for Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems, defines MTTHE in terms of safety integrity levels (SILs). The most stringent, SIL 4, corresponds to an MTTHE of 10^9 hours or greater, and is the fail-safe equivalent for processor-based systems (IEC, 2014).

According to McKeown (2008), track circuits, axle counters, and grade crossing predictors are intrinsically fail-safe train detection technologies. That is, the probability of an undetected failure (e.g., missed train detection) is essentially zero. These components, along with control system components, are accepted as fail-safe.

Highway-rail grade crossing systems, as a whole, are not fail-safe. The majority of components, including power supplies, lights, and bells are designed for redundancy and risk mitigation (McKeown, 2008; Wullems, 2012). This is acceptable as long as no failure of any of these components can result in an unsafe condition. However, long-term commercial power failures can lead to the depletion of back-up battery systems. At an active grade crossing equipped with

[6] Institute of Electronic and Electrical Engineers. Standard for Verification of Vital Functions in Processor Based Systems Used in Rail Control. IEEE-1483-2000. March 30, 2000.

only flashing lights, a “not safe” condition exists in the absence of electrical power. Roadway vehicle users would not receive any indication that a train is approaching or that the flashing lights have failed. Typically, the back-up battery system is sized to operate for a length of time that encompasses the range of most commercial power failures. To mitigate any further hazards, sensors are installed to detect commercial power failures and transmit alarms to railroad maintenance personnel.

Since a grade crossing system is part of the larger railroad signaling and control system, a better method to evaluate its fail-safe attributes is under real-world operating conditions. For track circuits, external factors, such as rail condition, are critical to ensure proper fail-safe operation of train detection components. Significant build-up of rust, sand, salt, and debris, as well as unbalanced ballast, can compromise the fail-safe operation of train detection components. These are the most common causes of missed train detection, and as a result warning devices are not being activated; these are known as wrong-side failures (McKeown, 2008).

In North America, the benchmark for fail-safety is a MTTHE greater than 10^9 hours, or 100,000 years. This is comparable to the European standard of 10^8-10^9 hours offered by SIL 4 certification (IEC, 2014). As stated earlier, although train detection components are classified as fail-safe, train detection systems and, by extension, grade crossing warning systems are not fail-safe.

However, there is evidence to suggest that the actual MTTHE is on the order of 6.7×10^7 hours, as described below. This implies that not *all* causes of failure have been identified when stipulating that track circuits have a MTTHE of 10^9 hours. Wullems (2012), found the MTTHE of track-circuit-based train detection systems to be 6.38×10^6 hours. This is equivalent to SIL 2, and significantly more than the 10^9 hours benchmark used for fail-safe systems. Likewise, data from the U.K. suggests a MTTHE of 3.33×10^7 hours, which is also SIL 2 (Heibel & Chatterjee, 2010).

Real-world FRA data is in line with the Australian values. FRA require U.S. railroads to submit a report any time a grade crossing activation failure occurs. These reports are maintained in an activation failure database that FRA makes publicly available. An analysis of the activation failure data for the 5-year period 2010-2014 at the approximately 67,000 public active grade crossings in the U.S. is presented in Table 7. The first column shows that a total of 1,952, or an average annual 390.4 activation failures occurred. Assuming that a grade crossing system is “on” continuously (8,760 hours per year), MTTHE could be estimated. For the 2010-2014 dataset, an MTTHE of 1.5×10^6 hours per grade crossing was estimated, which turned out to be quite close to Wullems’ result. Since different methodologies were employed to arrive at these values, further analysis is necessary to determine the relationship between the two results.

By cross-referencing the activation failures with FRA grade crossing accident data, 10 activation failures were found to have an association with an actual grade crossing collision.

The breakdown of activation failures by FRA failure cause is located in Appendix C.

Table 8 shows the results of an analysis of the expected failure metrics if an MTTHE per crossing of 10^9 hours is assumed. As seen in the first column, the expected annual number of failures per crossing from 2010-2014 was 0.587. This was lower than the FRA data by a factor of almost 10^3.

Table 7. Grade Crossing Activation Failure Data, 2010-2014

Observed Activation Failures				
Total and (Average) Annual Failures 2010-2014	**Average Hourly Failures 2010-2014**	**Average Hourly Failures per Crossing 2010-2014**	**MTTHE per Crossing (Hours)**	**MTTHE per Crossing (Years)**
1,952 (390.4)	4.46E-02	6.35E-07	1.58E+06	180

Table 8. Expected Grade Crossing Activation Failure Rates, 2010-2014, Based on MTTHE per Crossing of 10^9 hours

Expected Activation Failures				
Total and (Expected) Annual Failures 2010-2014	**Expected Hourly Failures 2010-2014**	**Expected Hourly Failures per Crossing* 2010-2014**	**MTTHE per Crossing (Hours)**	**MTTHE per Crossing (Years)**
2.94 (6.15E-01)	7.02E-05	1.00E-09	1.00E+09	114,155

*The expected hazardous failure rate of 10^{-9} per hour is based on CENELEC 61508 SIL 4 and is considered equivalent to fail-safe.

4.2 Cost

Petit (2002) pointed out the difficulty in attempting to define typical values for the various cost categories associated with installing track-circuit-based train detection systems. Petit calculated average costs for each cost category and then related each as a percentage of the total project cost. The analysis of Roop et al. (2007) found close agreement with Petit.

Table 9 shows the initial system costs for the installation of track-circuits for non-redundant and redundant train detection configurations. These values are based on the cost allocation scheme used by Petit, assuming the installed cost of a typical rural track-circuit-based system is in the order of $200,000. A relatively small amount, approximately 12 percent, is attributed to the train detection subsystem category. The most significant cost driver for track-circuit-based systems is the cost of installation, which ranges from 23 percent to 43 percent of the project total.

Table 9. Track Circuit Initial System Costs

	Element	Non-Redundant Train Detection	Redundant Train Detection
1	Engineering, site survey, design, documentation, testing, etc.	$26,000	$26,000

	Element	Non-Redundant Train Detection	Redundant Train Detection
2	Shelter, equipment racks/enclosures, and wiring	$22,250	$22,250
3	Batteries and battery charger	$6,000	$6,000
4	Grounding and bonding	$8,200	$8,200
5	Gates, flashing lights, and bells	$29,600	$29,600
6	Crossing controller/event recorder	$8,800	$8,800
7	Surge suppressors, power conditioning devices, breaker panels, etc.	$3,000	$3,000
8	Utility power drop and interface to battery system	$9,200	$9,200
9	Freight	$6,600	$6,600
10	Train detection	$13,400	23,700
11	Installation of train detection system	$40,000	$40,000
12	Installation of shelter, crossing controller, warning devices, etc.	$26,750	$26,750
	Initial cost	**$199,800**	**$210,100**

Although cost effective alternatives to track circuits have long been sought, alternatives to track circuits will not gain acceptance unless either installation and/or the maintenance costs are significantly less. The challenge has been identifying a technological approach that equals the track circuit in performance, dependability, and cost. A relatively small cost advantage is not likely to be a persuasive factor to the railroad industry. On the other hand, there may be a compelling case for targeting alternative train detection technologies at sites where track-circuits are not generally feasible.

Alternative technologies may provide additional performance features, such as continuous system validation and remote maintenance monitoring. Once dependability has been demonstrated, the reduced scheduled maintenance costs may provide the necessary financial incentive for the railroads to adopt alternative train detection technologies.

Given that installation is the primary cost driver, three possible configurations for installing train-detection sensors are considered: train detection exclusively at the crossing, train detection at the approaches and at the crossing, and continuous train detection. Budgetary estimates for the configurations are shown in Table 10. The estimated comparative 25-year life-cycle costs for these configurations compared to that of a track-circuit-based system are shown in Table 11. The values provided in both tables reflect "basic" systems—no added redundant elements.

The budgetary estimates in Table 10 are representative of costs obtained from "discussions" with system developers and online research conducted by the authors. The first configuration allows for the requisite sensors and signal processing equipment to be installed in the vicinity of the crossing. The second requires sensors to be installed at both approaches and on both sides of the crossing island. This necessitates power sources at three locations and a means[7] for communicating with the approach sensors that are as much as 2,500 feet from the crossing. The third is an optical fiber that provides continuous train detection throughout a zone defined by both approaches. The optical fiber provides the dual functionality of communication media and sensing element. All system components requiring power are installed in the vicinity of the crossing.

Table 10. Alternative Train Detection Technologies Budgetary Estimates for Initial System Costs

		Train Detection Exclusively at the Crossing[8]	Train Detection at the Approaches and at the Crossing[9]	Continuous Train Detection[10]
1	Engineering, site survey, design, documentation, testing, etc.	$26,000	$26,000	$26,000[11]
2	Shelter, equipment racks/enclosures, and wiring	$22,250	$22,250	$22,250
3	Batteries and battery charger	$1,500	$4,500	$3,000
4	Grounding and bonding	$8,200	$8,200	$8,200
5	Gates, flashing lights, and bells	$29,600	$29,600	$29,600
6	Crossing controller/event recorder[12]	-	-	-
7	Surge suppressors, power conditioning devices, breaker panels, etc.	$3,000	$3,000	$3,000
8	Utility power drop and interface to battery system	$9,200	$9,200	$9,200

[7] Transceivers to drive 2,500 feet of copper/optical fiber cable or wireless links.

[8] Both signal processing and train detection occurs at the crossing (rail acoustics). Power is required only at the crossing.

[9] Signal processing and train detection occurs at both approaches and at the crossing (wheel counters, inductive loops, and magnetometers). Power required at three locations. Solar/battery power sources and wireless or land line communication links required for accessing sensors at the approaches.

[10] Train detection occurs at both approaches and at the crossing; however signal processing only occurs at the crossing (optical fiber based sensing). Power is required only at the crossing.

[11] Does not include non-recurring engineering cost of product adaptation.

[12] The cost of the crossing controller event recorder is incorporated into the train detection system.

		Train Detection Exclusively at the Crossing[8]	Train Detection at the Approaches and at the Crossing[9]	Continuous Train Detection[10]
9	Freight	$6,600	$6,600	$6,600
10	Train detection system	$50,000	$23,500	$35,000
11	Installation of train detection system	$5,000	$28,000[13]	$30,000[14]
12	Installation of shelter, crossing controller, warning devices, etc.	$26,750	$26,750	$26,750
	Initial cost	**$188,100**	**$187,600**	**$199,600**

The estimates in Table 11 include assumptions for training and configuration management that were based on supporting multiple installations. The costs associated with corrective maintenance, which was based on the number and mean time between failures (MTBF) of the system components, can be substantial. Systems requiring wireless communication links to access the approaches as well as systems requiring as many as eight sensor units are particularly burdened.

Examples of failures not specifically associated with intrinsic reliability, but nonetheless requiring unscheduled maintenance to restore service, include:

- Resetting inbound and outbound counting units not in agreement
- Adjustment of voltage thresholds
- An extended period of cloudy days for solar panel based systems
- An extended outage of utility power for battery backed systems
- A communication link degraded by intermittent radio-frequency interference

The availability of any one system component is ultimately a function of the operational environment and the potential impact of external factors. Also, the distinction between intrinsic and operational reliability is crucial when comparing alternative technologies and approaches. Fail-safe operation can be maintained if the mission availability of all sensors is continually verified by the computing platform and "the relay" is continually energized.

An extensive literature search did not yield published MTBF data for the sensors used by the alternative systems reviewed in this report. In the absence of published reliability data, the authors assumed a representative reliability value of 100,000 hours for the discrete sensing elements of the alternative systems. This value was previously employed by Nylund and Holtermann in 1980 as the MTBF for a single DC track circuit element. Appendix D provides

[13] Based on wireless links and solar/battery power sources at the approaches

[14] Includes installation of 5,000 feet of optical cable via direct earth burial

the calculated MTBF values of the systems referred to in Table 11, thereby highlighting the impact that the number of system components has on system MTBF.

While system redundancy will increase system availability, the additional required components will produce a greater demand for corrective maintenance. Since no redundancy scheme can ensure fail-safe operation, the scheme that is eventually selected should be based on a comprehensive benefit-cost analysis. That analysis should reflect the potential operational impacts from the increased frequency and duration of crossing closures associated with lower reliability to determine if increased complexity and cost is warranted. An inherently reliable non-redundant system designed to be fail-safe will generally be the most cost-effective solution. Alternatively, more frequent preventive maintenance can optimize system availability by minimizing the potential demand for corrective maintenance. Its cost also should be weighed against the benefit that it yields.

Table 11. Life-Cycle Costs in Constant Dollars as Calculated by the Volpe Center

Cost Element	Metric	Track Circuit	Train Detection Exclusively at the Crossing	Train Detection at the Approaches and at the Crossing	Continuous Train Detection
Software licensing	25 years @ $500/year	N/A	$12,500	$12,500	$12,500
Battery replacement	8-year battery life	$13,500	$2,500	$7,500	$2,500
Spares	10% of the electronics & relays cost	$1,500	$5,000	$2,500	$2,500
Scheduled maintenance[15]	See footnote	$215,000	$215,000[16]	$215,000[13]	$215,000[13]
Corrective maintenance	12 hours per event @ $85/Hour, 11 events	$11,220			
Corrective maintenance	8 hours per event @ $85/Hour, 13 events		$8,840		
Corrective maintenance	8 hours per event @ $85/hour, 42 -50 events			$28,560-$34,000	
Corrective maintenance	8 hours per event @ $85/hour, 12 events				$8,160
Equipment & materials	$500 per event	$5,500	$6,500	$21,000-$25,000	$6,000
Training	4 hours per year @ $85/hour, 25 years	$8,500	$8,500	$8,500	$8,500
Configuration management allocation		$500	$500	$500	$500
Life-cycle costs		**$255,220**	**$255,220**	**$296,060-$305,500**	**$255,660**

[15] Scheduled maintenance values for labor hours, materials, and vehicles from Canadian Transportation Agency report *Guide to Railway Charges for Crossing Maintenance and Construction 2014*. The scheduled maintenance cost associated with track circuits is the dominant life-cycle cost factor.

[16] The maintenance schedule is dictated by the existing CFR. That schedule is based on track circuit performance potentially changing over a relatively short period of time due to a variety of possible causes. If the CFR were to accept that the performance of the alternatives is more consistent over time, and would include remote maintenance monitoring, the need for, and cost associated with, scheduled maintenance could be minimized. Furthermore, remote maintenance monitoring (performance trend analysis) would provide the necessary data to address many impending failures during *scheduled* preventive maintenance activities, thus minimizing emergency restoration services.

5. Current and Emerging Alternative Technologies

This analysis focuses on proven and emerging technologies that show *realistic* promise with respect to performance and cost. Optical systems which rely on lenses subject to environmental contamination are considered to have a disqualifying limitation, given that it is not possible to know, *a priori,* that the lenses have, or have not, been contaminated.

The presence of rail vehicles on a parallel track or siding within the desired detection zone will possibly be an impediment to dependable performance for non-track-specific systems such as radar and wayside-installed AMR sensors.

Table 12 summarizes salient aspects of alternative technologies compared to track-circuit-based train detection.

Table 12. Differences between Track Circuit and Alternative Train Detection Technologies
(Aguilera Fernández, 2014)

	Track Circuits	Alternative Technologies
Energy Supply	Main power (including trenching)	Solar power (solar panels and batteries)
Connectivity	Trenching for cable runs	Wireless communication
Train Detection	Track circuits; requires installation of insulated joints	No track work required.
Maintenance Requirements	Traditional grade crossings require frequent on-site inspections.	Remote monitoring minimizes on-site maintenance.

The paragraphs that follow provide a concise discussion of the physics and salient advantages/disadvantages of various approaches to train detection: wheel/axle detectors; inductive loop sensors; AMR magnetometers; acoustic sensors based on the rail as a transmission medium; radar; optical-based fiber Bragg grating technology; Intelligent Transportation System Connected Vehicle technology; and Positive Train Control (PTC).

5.1 Wheel Detectors

A wheel detector assembly senses the significant change in reluctance between its transmitting and receiving coils when a rail-wheel flange "bridges" the gap between the transmitting and receiving coils. Wheel detector assembly pairs are installed at the opposing approaches and on both sides of the grade crossing using designed-for-the-purpose mounting brackets. The detector assembly pairs are installed on opposing rails and longitudinally offset by wheel-set axle separation. The detectors are interfaced to counting units that in turn communicate with a logic unit at the grade crossing. The logic unit counts wheels "in" and wheels "out" to determine train position with respect to the train detection system configuration.

The logic unit controls the grade crossing warning devices. An interruption in either the power or the communication links between the logic unit and remote detectors may result in a wheel miscount. A wheel miscount requires a presumption of an occupied, or soon to be occupied, grade crossing until the logic unit can be reset.

The dynamic range that provides optimum detection of locomotives and rail cars may limit the ability of a wheel detector to detect the smaller diameter wheels of a hi-rail vehicle.

5.2 Inductive Loops

An inductive-loop detector circuit resonates at a frequency based on the intrinsic inductance of a given loop. A rail-bound vehicle, while passing over, or stopped on, a loop creates a magnetic circuit. The inductance of the magnetic circuit is decreased by the presence of a rail-bound vehicle. The "unique" variations in the signal induced by rail-bound vehicles are characterized by a loop-signal processing unit.

Loop detectors are installed between the rails at the opposing approaches and within the grade crossing island. The detectors communicate with a logic unit at the crossing that controls the warning devices.

5.3 Anisotropic Magneto-Resistive Magnetometer

An AMR magnetometer produces a signal relative to the earth's magnetic field within its effective detection range. A ferromagnetic object entering or within the detection range "distorts" the ambient magnetic field sensed by the magnetometer and the signal it produces. The processing unit of the system characterizes the "unique" variations in the signal produced by rail-bound vehicles.

Magnetometers are installed within the railroad right-of-way at the opposing approaches and at the grade crossing. The magnetometers at the opposing approaches communicate with a logic unit at the grade crossing that controls the grade crossing warning devices.

A notable advantage of the AMR technology is the ability to sense both motionless trains and trains in motion, irrespective of direction, that are within detection range. A site-specific limitation of a magnetometer is its operation in the "near-presence" of high-voltage transmission lines that produce a varying magnetic field as a function of power demand. These devices also require a means to compensate for diurnal temperature changes.

While auto-calibration for temperature may be generally feasible for the approach sensor, an island sensor would require an independent means to establish that the crossing is not currently being occupied by roadway vehicles.

5.4 Acoustic

The rail functions as a waveguide/transmission medium for the acoustic vibrations produced by rail-bound vehicles in motion.

The processing element of the system characterizes the "unique" acoustic-signature vibrations produced by various rail-bound vehicles to determine rail-bound vehicle type and position. The logic unit provides the signals for controlling grade crossing warning devices. Acoustic-sensor assembly pairs are installed on both sides of the grade crossing.

The nature of the signal and its transmission medium, the rail, require that the sensor be bonded to the rail. Air gaps in the transmission medium result in an unacceptable amount of acoustic energy being reflected versus transmitted. Accordingly, continuously welded rail (CWR) is required throughout the detection zone.

The notable advantage of acoustic detection technology is that there is no requirement for equipment/detectors, or a power source, at the opposing approaches.

5.5 Radar

The radar principle is to transmit a pulse and analyze its return to determine "target" range and possibly target speed. It is, in theory, a viable candidate for detecting a train entering the approach zone. The cost to implement a sufficiently reliable system will ultimately be the decisive factor in determining its acceptability as an alternative to track circuits. Being able to locate the system exclusively at the crossing would be a significant advantage. A separate system would be needed for the crossing island.

The significant disadvantage is that *dependable* detection at the nominal 2,000-foot approach point is *not achievable* at this time for commercially available systems suitable for traffic monitoring applications. The notable advantage is that there is not a requirement for equipment/detectors, or to provide power, at the opposing approaches.

5.6 Bragg Grating

Fiber Bragg gratings (FBGs) are designed to reflect a specific wavelength of light in fiber-optic cables. An FBG is created by etching an optical waveguide with a sequence of circumferential lines of a specified periodicity to produce a "grating." The periodicity of the grating determines the wavelength of light that will be reflected. External stressors will distort the grating; the distortion, effectively, changes the separation/periodicity of the circumferential lines and the wavelength of light that will be reflected.

The signal processing element, an interrogator, analyzes the stressed-induced change in the wavelength of the reflected signal that results from the distortion caused by the loading of rail-bound vehicles.

Optical fiber is buried at a prescribed depth alongside the track within the right-of-way from the grade crossing to both opposing approaches. Interrogators at the grade crossing process the signals to detect the presence and position of rail-bound vehicles. The logic unit component of the interrogator controls the grade crossing warning devices.

Other fiber solutions rely simply on analyzing the rail-bound-vehicle-induced perturbations of a transmitted pulse of light. The notable advantage of this technology is that no requirement exists for equipment/detectors or electrical power at the opposing approaches.

Analysis and testing is required to determine an optimum burial depth of the optical fiber/FBG. The optimum burial depth is likely to be affected by site-specific soil mechanics over a wide range of temperature and hydrological conditions.

FBGs, either "etched" into a continuous length of fiber or discrete sensors interconnected by optical fiber, is an example of a sensor technology currently being used for other applications that possibly can be adapted for cost-effective use in grade crossing train detection.

5.7 Connected Vehicle

Intelligent Transportation Systems (ITS) technology, employing the Vehicle-to-Infrastructure (V2I) platform whereby a train would communicate its speed and position to a roadside-based subsystem to activate/deactivate grade crossing warning devices, provides yet another possible solution.

Given that the maximum speed of the track for the crossings being considered is not a factor and assuming that line-of-sight is not an issue, the 1,000-meter range of a Dedicated Short Range Communications (DSRC) transmitter could provide the statutory minimum of 20 seconds advance warning. Moreover, it could also provide a constant warning time. The principal obstacle is that Connected Vehicle technology imposes requirements on the railroads not currently required under law.

5.8 Positive Train Control

PTC will eventually provide a low cost solution for crossings located on PTC-equipped territory. At present, PTC is only mandated by Congress on passenger rail corridors and freight corridors meeting annual gross tonnage and hazardous materials requirements (Signal and Train Control Systems, 2015).

A PTC-communication-compliant crossing controller, wirelessly interfaced to a PTC-equipped train, would provide an optimum level of advanced warning and would not be limited by train speed to activate/deactivate crossing warning devices. The Fixing America's Surface Transportation (FAST) Act, enacted in December 2015, directs DOT to study the possible effectiveness of PTC and related technologies on reducing collisions at highway-rail grade crossings.

6. Summary

Table 13 summarizes features, characteristics, and limitations. A detailed listing of the more promising technologies is included in Appendix E.

Ideally, the number of candidate system/sensor types will be limited to one or two, given the costs associated with supporting multiple systems, such as:

- Engineering and configuration management
- Logistics and documentation
- Training and related materials
- Testing and test equipment related costs
- Performance and reliability testing[17]

The one-size-fits-all type of system approach (i.e., designing for "all possible" site conditions) may unnecessarily increase system complexity—with a corresponding adverse impact on system reliability. A preferred solution would be for the sensor-data-processing component to provide/include interfaces for two or more types of train detectors. A hybrid system, which features two or more train detection technologies, offers some potential, but requires a highly reliable/dependable design in order to overcome the additional costs associated with supporting more than one technology. It is also preferred that the train detection components be commercially available, given that established products have "known" performance and reliability values. Adaptation of a product designed for a similar application, depending upon the extent of the adaptation, may be acceptable.

[17] Establishing the performance and reliability of a system in its typical operating environment is time consuming, with corresponding costs, particularly so when the number of daily operations is limited.

Table 13. Train Detection Technology Comparative Matrix

Characteristic	Train Detection Technology								
	Track Circuit	Acoustic*	Wheel/Axle Counter*	Radar	Inductive Loop*	AMR Magnetometer	Optical Fiber/FBG*	PTC*	Connected Vehicle
Continuous train detection	Yes	No	No	No	No	No	Yes	Yes	Yes
Susceptibility to EMI** environment	Yes	No	No	No	Yes	Yes	No	N/A	N/A
Susceptibility to contamination from environment	Yes	No	Minimally	No	Minimally	No	No	No	No
Revenue vehicle required for testing	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Power required at the approaches	Yes	No	Yes	No	Yes	Yes	No	No	No
Sensors required at the approaches	No	No	Yes	No	Yes	Yes	No	No	No
Requires CWR	No	Yes	No	No	No	No	No	No	No
Limited train detection range	Yes	Yes	No	Yes	No	No	No	No	Yes

* More promising technology. Refer to Appendix E for details.

**Electromagnetic Interference

7. Proposed Migration Path

Prior to proceeding with additional research in this area, the findings of the risk analysis in this report should be shared with the railroad industry to gauge their interest in addressing the 957 high-risk grade crossings cited herein. Given sufficient interest, the next step would be to determine the percentage of the 957 grade crossings for which track-circuit-based systems have been deemed generally "not feasible."

Once those grade crossings have been identified and deemed of sufficiently high risk to warrant action, one or more of the alternative systems discussed in Section 5 should be selected for one or more demonstration projects. Toward this end, the first step would be to determine if existing systems (e.g., magnetic or rail acoustic) in general use in other countries provide a solution acceptable to the railroads.

Another possibility would be to determine if a technology such as FBGs can be cost effectively adapted to grade crossing train detection. Adapting FBG technology would require further analyses to determine if the number of potential grade crossings for which track circuits are not feasible would justify the investment associated with the non-recurring engineering and testing associated costs.

Whichever technology or technologies are selected for further development and testing will no doubt employ microprocessors to control safety-critical functions. FRA regulatory guidance regarding the introduction of processor-based grade crossing technologies is codified in Grade Crossing Safety (2015). Subpart 234.275 of the regulation states that any processor-based grade crossing system placed in service after June 6, 2005 that contains new or novel technology is required to comply with FRA regulations governing processor-based PTC systems (Signal and Train Control Systems, 2015). It is essential that any new grade crossing system be designed to comply with these regulations.

Empirical data from multiple countries suggests that the MTTHE of track-circuit-based train detection systems is on the order of 10^6-10^7 hours. This is significantly lower than the 10^9 hours that the railroad industry employs for processor-based train detection systems. The railroad industry does not publicly release the probability of unsafe track circuit failures in terms of hours or usage. The significance of these results would be immensely improved if they could be corroborated by signaling specialists within the industry. If the frequency of unsafe track circuit failures is indeed less than 10^9 hours, then a value more reflective of real-world data should be considered as the benchmark for safety.

As noted in this report, track-circuit-based train detection technology is not suitable on low train frequency rail lines or in locations where ballast contamination is problematic. Wheel detection technology is currently commercially viable, and therefore does not require a government research investment. FBG technology is very well-suited for low exposure grade crossings but requires a research, test, and evaluation investment before being ready for commercial deployment. If the technology can be proven to operate as reliably and safely as track-circuit-based systems, then there is a possibility for broader applications than grade crossing train detection.

While the CFR covers the introduction of processor-based grade crossing train detection technologies, to date, there is only limited experience in introducing new technologies. The regulations provide highly prescriptive inspection and maintenance requirements specific to track-circuit-based train detection systems. Alternative technologies are broadly addressed in the CFR on the basis of performance requirements. Currently, a railroad must demonstrate that an alternative technology “will not result in risk that exceeds the previous condition” (i.e. track circuits) as stated in 49 CFR 236.909 or complies with the requirements stipulated in 49 CFR 236.1015. In either case, railroads are required to submit inspection and maintenance procedures that are specific to the technology being implemented.

The above subparts were written to address the congressionally mandated implementation of PTC systems. Alternative grade crossing train detection systems, which would be introduced on a voluntary basis, would nonetheless be subjected to the same rigorous requirements. This would require a significant investment by the railroad and railroad suppliers to ensure compliance.

8. Conclusion/Recommendations

This report provides the data and analysis to support the assertion that significant benefit can be accrued by providing active warning devices at a subset of the approximately 59,000 public passive grade crossings in the US. The 957 grade crossings analyzed in this report were identified by means of a simple filter that employed minimum thresholds for train and highway traffic exposure. The filter was employed to demonstrate the feasibility of such an undertaking, and the results should not be interpreted as conclusive or an endorsement of a particular approach.

The results do show that there exists the potential to significantly reduce the loss of life and economic consequences from grade crossing accidents at public passive grade crossings. Also, there is an economic argument for investing in active grade crossing systems at a subset of the current passive grade crossing inventory, independent of the train detection paradigm. Typically, each State DOT identifies the riskiest grade crossings under its jurisdiction and targets them for improvement with Federal and State highway improvement funding. This is performed on an annual basis and is quite successful in risk reduction at the State level. While many States employ the DOT APF to identify risky grade crossings, there is no national consensus as to how this process should be implemented.

The cost differential between track-circuit-based and alternative-train-detection-based systems is minimal and cannot be used alone to justify alternative train detection technologies. However, alternative technologies are superior to track-circuit-based systems at locations prone to flooding/snow/ice, leaf buildup on rails, and accrual of rail rust. This finding further suggests that there is a compelling argument for evaluating alternative grade crossing train detection technologies.

As a first step, the findings of this report should be shared with the FRA Grade Crossing Safety Task Force. The efficacy of many of the results in this report, such as the hourly grade crossing activation failure rate, is predicated on forms voluntarily submitted by U.S. railroads to FRA. The railroad industry, which maintains much more accurate system performance data than is submitted to FRA, is most qualified to confirm these findings and clear the way for acceptance of non-track-circuit-based train detection technologies. In parallel, further investigation of alternative technologies, both empirical and analytical, is needed to prove that these technologies satisfy Federal safety regulations. To this end, a Federal research and demonstration program could be implemented to provide guidance and funding to facilitate the introduction and acceptance of alternative grade crossing train detection technologies.

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Appendix A. DOT Accident Prediction Formula

The DOT accident prediction formula (APF), in actuality a set of three equations, is used to predict the expected number of incidents at a grade crossing based on its physical and operational properties stored in the DOT/FRA Highway-Rail Grade Crossing Inventory database. The three equations are the basic APF calculated from the FRA crossing inventory, a weighted average of the basic APF and accident history (generalized APF), and the generalized APF multiplied by a normalizing constant representing the predicted annual accidents for a specific type of warning scheme (e.g., passive, flashing lights, or gates). This is the final APF.

The basic APF, which is not normalized for accident history or warning device type, is expressed as follows:

$$a = K \text{ x } EI \text{ x } DT \text{ x } MS \text{ x } MT \text{ x } HP \text{ x } HL \quad (1)$$

where:

a = unnormalized initial accident prediction, in accidents per year at the crossing

K = formula constant

EI = factor for exposure index based on product of highway and train traffic

DT = factor for number of through trains per day during daylight

MS = factor for maximum timetable speed

MT = factor for number of main tracks

HP = factors for highway paved

MS = maximum railroad timetable speed

HL = number of highway lanes

The non-normalized accident prediction output of the basic formula and the accident history (typically five years) are used as inputs to the generalized APF in equation (2). The output of this formula and the warning device normalizing constants are used as input to the final APF in equation (3).

$$B = \frac{T_o}{T_o+T}(a) + \frac{T}{T_o+T}\left(\frac{N}{T}\right) \quad \text{generalized APF} \quad (2)$$

$$A = B \times Normalizing\ Constant \quad \text{final APF} \quad (3)$$

Table A-1 shows the normalizing constants for the three types of warning devices.

Table A-1. APF Normalizing Constants from 2014[1]

Warning Devices Groups	Normalizing Constant
Passive	0.5086
Flashing Lights	0.3106
Gates	0.4846

[1] Retrieved from https://gradedec.fra.dot.gov/.

If a rail crossing has been improved within the past 5 years, the accident prediction methodology is different. Research shows that during the first 5 years following an upgrade to active warning devices, the final APF underestimates the reduction in accidents. A more appropriate approach is to estimate the reduction in accidents on the base case scenario resulting from the installation of the improved warning devices. This reduction is the product of the base case unnormalized APF and an effectiveness value between zero and one.

The effectiveness values published by FRA are shown in Table A-2, below. These values were calculated by comparing accident rates at grade crossings, between 1975 and 1980, prior to and following the installation of improved warning devices. Just as the values of the APF normalizing constants have changed over time, there is the possibility that the effectiveness values have changed as well, especially given the number of years since they were first calculated.

Alternate cases 1 and 2 are represented by the *passive to flashing lights* and the *passive to lights and gates* rows, respectively. All calculations involving effectiveness used the standard values of 0.7 and 0.83 in the last column. Consider a rail crossing that is improved from passive warning devices (*base case*) to flashing lights (*alternate case 1*). The reduction in accidents from the base case to flashing lights is 70 percent.

Table A-2. Effectiveness Values for Various Combinations of Warning Device Upgrade and Train Frequency

Effectiveness Values[1]					
	Total trains per day				
	10 or less		More than 10		
Improvement Action	Single Track	Multiple Track	Single Track	Multiple Track	Standard Value
Passive to Flashing Lights	0.75	0.65	0.61	0.57	0.70
Passive to Lights and Gates	0.9	0.86	0.8	0.78	0.83
Flashing Lights to Gates	0.89	0.65	0.69	0.63	0.69

[1] Farr, E. H. (1987). Rail-Highway Crossing Resource Allocation Procedure: User's Guide (No. DOT-TSC-FRA-87-1).

Appendix B. Comparative Analysis of Different Risk Ranking Techniques

Using the *minimum exposure* threshold technique, the 957 grade crossings identified in the report employed the minimum exposure values of daily train and highway vehicle traffic described in Section 3.2. This set of 957 rail crossings was ranked in terms of risk from high to low using the DOT APF. With the second technique, DOT APF, the entire public passive rail crossing inventory was ranked by risk in descending order. The 957 rail crossings with the highest risk were selected for comparison against the 957 identified with the minimum exposure level technique. Using the 5-year accident history technique, the 957 passive rail crossings with the highest number of accidents from 2010-2014 were selected for comparison against the two other two datasets.

Table B-1. Comparison of Predicted Collision Reductions for Flashing Lights Upgrade under Various Ranking Scenarios

Flashing Lights Upgrade				
Number of Crossings	Ranking Scenario	Average Collisions 2010-2014	Predicted Annual Collision Reduction (Number)	(%)
957	Minimum Exposure	28	24.81	89%
957	DOT APF	227	109.28	48%
957	5-Year Accident History	253	104.28	41%
All	DOT APF	503	383.21	76%

Table B-2. Comparison of Predicted Collision Reductions for Gates with Flashing Lights Upgrade under Various Ranking Scenarios.

Flashing Lights and Gates Upgrade				
Number of Crossings	Ranking Scenario	Average Collisions 2010-2014	Predicted Annual Collision Reduction (Number)	(%)
957	Minimum Exposure	28	26.19	94%
957	DOT APF	227	197.84	87%
957	5-Year Accident History	253	168.81	67%
All	DOT APF	503	410.80	82%

Table B-3. Comparison of Predicted Casualty Reductions for Flashing Lights Upgrade under Various Ranking Scenarios

Effectiveness Value = 0.70							
Number of Crossings	Ranking Scenario	Average Injuries 2010-2014	Predicted Annual Injury Reduction (Number)	(%)	Average Fatalities 2010-2014	Predicted Annual Fatality Reduction (Number)	(%)
957	Minimum Exposure	14	11.89	86%	4.4	2.53	57%
957	DOT APF	125	52.39	42%	23	11.15	48%
957	5-Year Accident History	138	49.99	36%	26	10.64	41%
All	DOT APF	255	183.71	72%	51	39.11	77%

Table B-4. Comparison of Predicted Casualty Reductions for Gates with Flashing Lights Upgrade under Various Ranking Scenarios.

Effectiveness Value = 0.83							
Number of Crossings	Ranking Scenario	Average Injuries 2010-2014	Predicted Annual Injury Reduction (Number)	(%)	Average Fatalities 2010-2014	Predicted Annual Fatality Reduction (Number)	(%)
957	Minimum Exposure	14	12.55	91%	4	2.67	61%
957	DOT APF	125	94.84	76%	23	20.19	86%
957	5-Year Accident History	138	80.93	59%	26	17.23	66%
All	DOT APF	255	196.93	77%	51	41.93	82%

Appendix C. Grade Crossing Activation Failures by Failure Cause

Table C-1. Grade Crossing Activation Failures by Failure Cause from 2010-2014[1]

FRA Cause Code	Failure Cause	Failures	Average Annual Failures 2010-2014	Average Hourly Failures 2010-2014	Average Hourly Failures per Crossing 2010-2014	MTTHE per Crossing (Hours)	MTTHE per Crossing (Years)
01	Sand, Rust, or Other Deposit On Rail	195	39	4.45E-03	6.34E-08	1.58E+07	1,800
02	Failure of Relay	259	51.8	5.91E-03	8.42E-08	1.19E+07	1,355
03	Crosses, Grounds, Foreign Current, or Open Circuits	187	37.4	4.27E-03	6.08E-08	1.64E+07	1,877
04	Apparatus Broken, Defective, or Out of Adjustment	98	19.6	2.24E-03	3.19E-08	3.14E+07	3,582
05	Lightning/Power Surge	180	36	4.11E-03	5.85E-08	1.71E+07	1,950
06	Vandalism	87	17.4	1.99E-03	2.83E-08	3.53E+07	4,035
07	Errors in Connections or Adjustments	30	6	6.85E-04	9.76E-09	1.03E+08	11,701
08	Design Error	27	5.4	6.16E-04	8.78E-09	1.14E+08	13,001
09	Directional Lockout of Stick Circuit or Interlocking Relay	21	4.2	4.79E-04	6.83E-09	1.46E+08	16,716
10	Commercial Power Failure	166	33.2	3.79E-03	5.40E-08	1.85E+07	2,115
11	Railroad Power Failure (Primary Battery or RR Power Lines)	121	24.2	2.76E-03	3.93E-08	2.54E+07	2,901
12	Failure of Electronic Device	146	29.2	3.33E-03	4.75E-08	2.11E+07	2,404
13	Interference	264	52.8	6.03E-03	8.59E-08	1.16E+07	1,330
14	Other, Miscellaneous	171	34.2	3.90E-03	5.56E-08	1.80E+07	2,053

[1] Retrieved from http://safetydata.fra.dot.gov/OfficeofSafety/publicsite/affp/AfBrowse.aspx.

Appendix D. MTBF Calculations

Table D-1. MTBF Calculations for Various Train Detection Systems[1]

Train Detection Component	Track Circuit		Wheel/Axle Counters		Rail Acoustic		Magnetometer		Optical Fiber Bragg Grating	
	MTBF	UNITS/ SYSTEM	MTBF	UNITS/ SYSTEM	MTBF	UNITS/ SYSTEM	MTBF	UNITS/ SYSTEM	MTBF	UNITS/ SYSTEM
Computing Platform	150,000	1	150,000	1	150,000	1	150,000	1	150,000	1
Wireless Transceivers	100,000	0	100,000	3		0	100,000	3		0
Interrogator	35,000	0		0		0		0	35,000	1
Sensors	100,000	3	100,000	8	100,000	4	100,000	3	250,000	1
Power	80,000	1	80,000	3	80,000	1	80,000	3	80,000	1
System	20,500		4,250		17,000		5,250		18,000	
Failures per 25 years	11	5	50	15	13	6	42	10	12	4

[1] Representative values selected by Volpe for the purpose of cost comparison.

Appendix E. Alternative Technology Comparison Matrix

Table E-1. Comparison of Track Circuit Technology with Acoustic, Inductive, Optical, and PTC Alternatives

Technology	Track Circuit	Acoustic	Wheel/Axle Counter	Inductive Loop	Optical Fiber/FBG	Positive Train Control
Works in all territories (dark, signaled, PTC)	Yes	Yes	Yes	Yes	Yes	No
Compliance with existing FRA regulations	Yes	Possibly	Yes	No	No	Expected
Proven technology for revenue service train detection	Extensive	Yes	Extensive	No	No	Yes
Probability of a failure to detect a train	Low[1]	Low	Low[2]	Low[3]	Low	Low
Probability of a false detect	Low[4]	Low	Low	Moderate	Low	Low
Fail safe design (mean time to hazardous event $\geq 10^9$ hours)	Yes	Possibly	Yes	No	No	Yes
Stopped train within approach zone detection	Yes	No	No	Conditional – based on loop dimensions	Yes	Yes

[1] *In-situ* conditions may adversely influence detection performance.

[2] Functionally dependent on the means of wayside communication.

[3] See [4].

[4] See [1].

Technology	Track Circuit	Acoustic	Wheel/Axle Counter	Inductive Loop	Optical Fiber/FBG	Positive Train Control
Continuous detection	Yes	Yes	No	No	Yes	Yes
Broken rail detection	Yes	Yes	No	No	Possible	No
Detects *all* rail-bound vehicles, e.g., hi-rail vehicles	Yes	Possibly	No	Yes	Yes	No
Fixed warning times	Yes[1]	No	Yes	No	Yes	Yes
EMI susceptibility	Yes	No	No	Yes	No	No
Sensitivity to power fluctuations	Yes	No	No	No	No	No
Susceptibility to top of rail contaminants: sand, salt residue, rust, grease, leaves, water, etc.	Yes	No	No	No	No	No
Sensitivity to ballast and/or tie resistance to earth ground	Yes	No	No	No	No	No
Sensitivity to train axle resistance	Yes	No	No	No	No	No
Detection distance limited[2]	Yes	No	No	No	No	No
Limitations due to site-specific environmental conditions, e.g., areas subject to frequent flooding, adjacent high voltage distribution lines	Yes	No	No	Yes	No	No
Insulated joints required	Yes	Possibly	No	No	No	No

[1] Via an auxiliary system.

[2] With respect to a practical limit for activating protective devices at a grade crossing.

Technology	Track Circuit	Acoustic	Wheel/Axle Counter	Inductive Loop	Optical Fiber/FBG	Positive Train Control
CWR required	No	Yes	No	No	No	No
Communication and/or power required at approach zone threshold	Yes	No	Yes	Yes	No	No
Power consumption	High	Low	Low	Low	Low	Low
Communication medium	Rail	Rail	Landlines Or Wireless	Landlines Or Wireless	Optical Fiber	Rf Link
Easy to install	No	Yes	Yes For Wireless	No	No	Yes
Easy to modify point of train detection	No	Yes	Moderate For Wireless	No	Moderate	Yes
Corrective maintenance frequency	Moderate	Low	Low	Moderate	Low	Low
Easy to repair or replace train detection element	N/A	Yes	Yes	No	No	N/A
Mean Time To Restore (MTTR) service	Moderate	Low	Low	Moderate	Low	Low
Reset required following power interruption	No	No	Yes	No	No	No
Built-in Self-Test	N/A	No	Yes	Yes	Yes	Yes
Easy to verify operation after maintenance	Yes	No[5]	No[1]	No[5]	No[5]	Yes

[1] Requires revenue type rail-bound vehicle.

Abbreviations and Acronyms

Abbreviation or Acronym	Name
AADT	Average Annual Daily Traffic
AIS	Abbreviated Injury Scale
AMR	Anisotropic Magneto-Resistive
APF	Accident Prediction Formula
BCA	Benefit-Cost Analysis
BCR	Benefit-Cost Ratio
BNSF	Burlington Northern Santa Fe
CFR	Code of Federal Regulations
CRC	Cooperative Research Centre
CWR	Continuously Welded Rail
DSRC	Dedicated Short Range Communications
EMI	Electro-Magnetic Interference
FMEA	Failure Modes and Effects Analysis
FRA	Federal Railroad Administration
ITS	Intelligent Transportation Systems
MTBF	Mean Time Between Failures
MTTHE	Mean Time To Hazardous Event
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
OST-R	Office of the Secretary of Transportation
PTC	Positive Train Control
RD&T	Research, Development, and Technology
TRB	Transportation Research Board
TSC	Transportation Systems Center
TTC	Transportation Technology Center
TTI	Texas Transportation Institute
US	United States

Abbreviation or Acronym	Name
DOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
VicRoads	Victorian Road Authority
Volpe Center	John A. Volpe National Transportation Systems