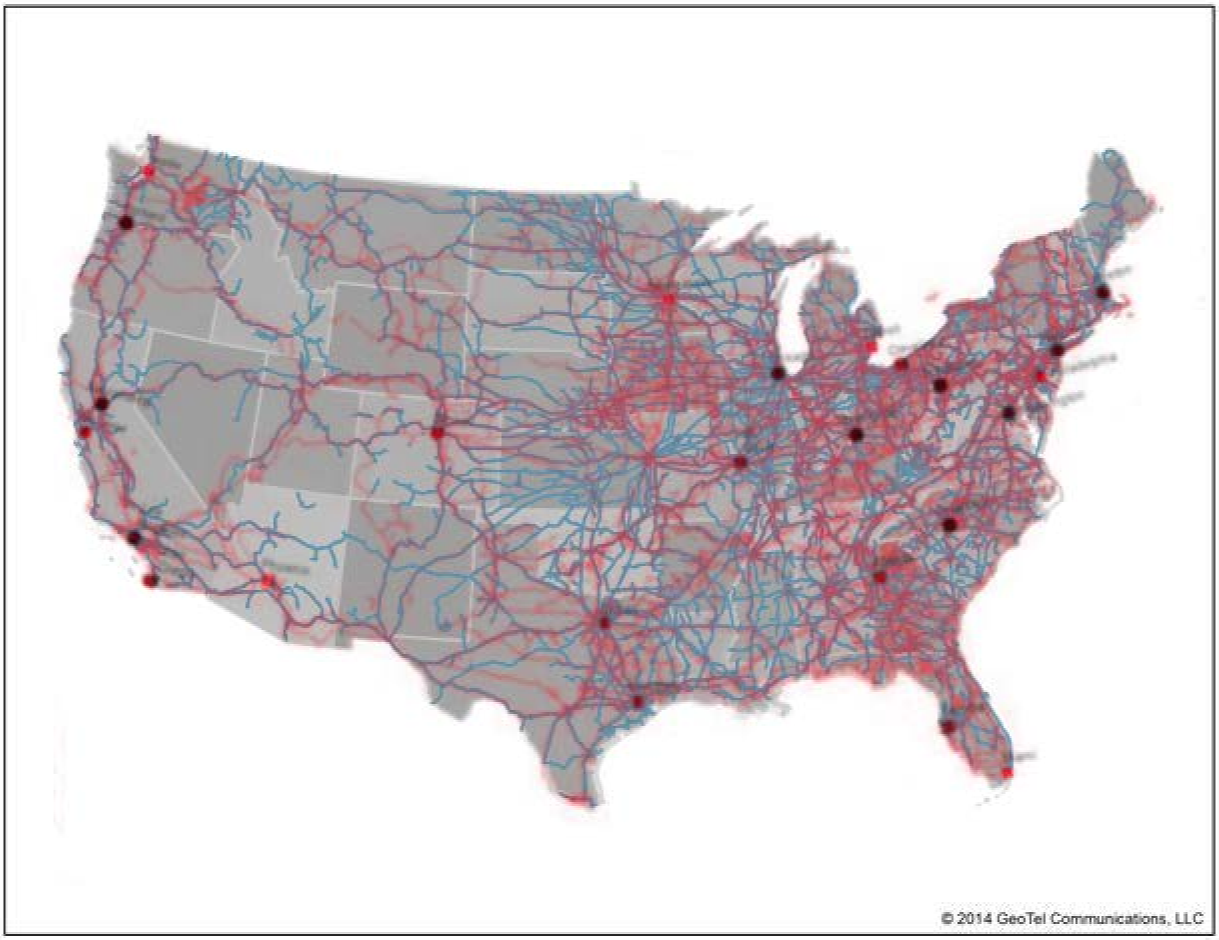
U.S. Department of
Transportation

**Federal Railroad
Administration**

Fiber Optic Availability and Opportunity Analysis for North American Railroads

Office of Research,
Development
and Technology
Washington, DC 20590



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Final Report
July 2018

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13. ABSTRACT (Maximum 200 words) The Federal Railroad Administration (FRA) sponsored an evaluation conducted by Transportation Technology Center, Inc. regarding the opportunity and availability to use Fiber Optic Acoustic Detection (FOAD) in the North American railroad industry. FOAD is an emerging technology with the potential to enhance safety in the railroad industry by continuously monitoring the condition of rail, track and rolling stock. A FOAD system pulses laser light down a fiber optic cable buried near a railroad track and using Rayleigh backscatter, can detect acoustic and seismic signals produced by such events as train movement, rail breaks, wheel impacts, dragging equipment, etc. The objective of this project was to determine the viability and applicability of implementing FOAD technology in the North American railroad environment. The FOAD task force, organized by the Association of American Railroads' (AAR) Railway Electronic Standards Committee (RESC), identified the priority applications for use of FOAD technology to be broken rail detection, train tracking, and monitoring equipment health and track integrity, as well as security and detection of environmental hazards. Additionally, this project identified that there is the potential for cost savings to the railroads, especially if FOAD is used for multiple applications.			
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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

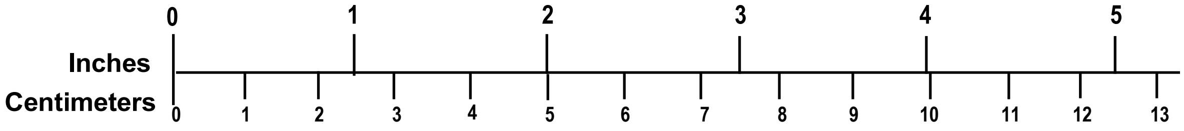
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



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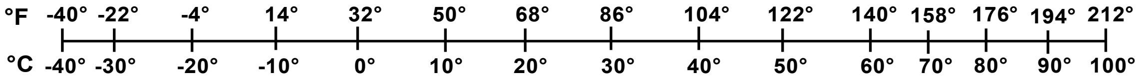

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

The Federal Railroad Administration (FRA) sponsored an evaluation conducted by Transportation Technology Center, Inc. (TTCI) regarding the opportunity and availability to use Fiber Optic Acoustic Detection (FOAD) in the North American railroad industry. The work was performed at the Transportation Technology Center (TTC) from January 15, 2016, through November 14, 2016. The FOAD task force, organized by the Association of American Railroads' (AAR) Railway Electronics Standards Committee (RESC), identified the priority applications for use of FOAD technology to be broken rail detection, train tracking, monitoring equipment health and track integrity, security, and detection of environmental hazards. Additionally, this project identified that there is the potential for cost savings to the railroads, especially if FOAD is used for multiple applications and along regions of track with existing fiber optic cable installed.

FOAD is an emerging technology with the potential to enhance safety in the railroad industry by continuously monitoring the condition of rail, track and rolling stock. A FOAD system pulses laser light down a fiber optic cable buried near a railroad track and, using Rayleigh backscatter, can detect acoustic and seismic signals produced by such events as train movement, rail breaks, wheel impacts, dragging equipment, etc. The objective of this project was to determine the viability and applicability of implementing FOAD technology in the North American railroad environment. To accomplish this objective, TTCI worked with the newly formed FOAD task force, comprised of representatives from all North American Class I railroads, National Railroad Passenger Corporation (Amtrak), AAR, FRA, and several FOAD technology suppliers.

In 2011, CSX Transportation (CSX) initiated FOAD research for use in the U.S. railroad industry by funding a series of proof of concept tests conducted by TTCI. Results of the proof of concept testing were positive, and on the basis of the results, CSX further funded TTCI to develop methodologies for detecting train presence (including front and rear of train and train speed), broken rail detection, flat-wheel detection, and flat-wheel classification. The algorithm development showed promising results, and CSX released their intellectual property rights and published the methodologies to the industry.

To accommodate the development and testing of these algorithms, FRA and CSX have funded the installation of several fiber optic test beds at the TTC. The test beds have since supported various FOAD testing efforts. Other ongoing development projects include BNSF Railway (BNSF) rock fall/slide detection development and a pilot installation for train tracking, train integrity, broken rail, and flat wheel detection from CSX. The strong level of involvement by FOAD suppliers, railroads, and affiliated companies, is indicative of the level of interest in the technology.

As part of this study, TTCI investigated the existing amount of fiber optic cable installed along North American railroads to understand the available FOAD system installation opportunities without installing additional fiber. TTCI solicited the Class I railroads, as well as third party sources, to estimate the amount of fiber optic cable presently installed along the North American rail network. Five railroads responded to the survey. The reported amount of railroad route miles that had existing fiber optic cable installed alongside them ranged from less than 1 percent to 90 percent. Three of these five railroads reported on fiber optic cable coverage for signaled track and two reported coverage on dark territory. The reported amount of signaled track ranged from less than 1 percent to 85 percent and for dark territory, it ranged from 17 percent to 60 percent. The railroad responses indicate that a significant portion of the route mile areas controlled by Class I and Amtrak railroads are in close proximity to existing fiber optic cable, which could greatly reduce implementation costs associated with FOAD.

As interest in this technology has grown, the railroad industry has recognized that FOAD has many potential uses in the railroad environment, and a single FOAD system could potentially perform multiple functions. As a result, an AAR Task Force was formed in 2016 to identify and prioritize the most important applications of FOAD in the rail industry for further research and development.

For this study, the term *cost drivers,* which will also be referred to as *costs,* refers to installation costs, and the yearly ongoing maintenance and inspection costs associated with each system considered in the high-level cost analysis. FOAD suppliers were surveyed for the cost driver information associated with their systems; the North American railroads were surveyed for the cost driver information associated with existing wayside systems used to detect flat wheels, Wheel Impact Load Detectors (WILD), broken rails, and track circuits.

This project performed a high-level analysis of cost drivers and system functionality that compared drivers associated with FOAD technology to drivers associated with current wayside systems used to detect broken rails and flat wheels. The cost analysis also indicates that railroads that use FOAD for more than one application may benefit from potential savings, and those savings would be even greater if existing fiber optic cable can be used for FOAD. The estimated combined installation, maintenance, and inspection costs accumulated over 15 years of FOAD was compared to the estimated combined costs for both WILD systems and track circuits in 1) sections of track in which existing fiber optic cable can be used, and in 2) sections of track in which existing fiber optic cable cannot be used. For sections of track where existing fiber optic cable can be used, the estimated costs will be from 62 percent to 72 percent less with FOAD than the combined costs of WILD and track circuits. For sections of track where existing fiber optic cable cannot be used, the percent difference in costs ranges from 3 percent to 28 percent less costs using FOAD than the combined WILD and track circuit costs.

These percentages are not the result of a detailed cost-benefit analysis, but they are from a high-level cost comparison that is independent of the comparison of functions and features which were performed as part of this project. Currently, FOAD technology cannot fully replace the functionality of other systems, particularly track circuits. For FOAD to supplement or replace existing systems, additional development may be needed, or FOAD may need to be combined with other technologies to provide future functionalities. Alternatively, FOAD may be a viable option to provide various functions along sections of track without existing systems in place (such as wheel impact, broken rail, or rock fall detection). FOAD has the potential for many railroad applications, and the cost benefits improve as the number of functions that a single FOAD system can perform increases.

This analysis shows that FOAD technology may provide railroads with added functionality, increased coverage, and possible cost savings. However, FOAD must undergo additional development before the technology is ready for more widespread implementation by North American railroads.

1. Introduction

Transportation Technology Center, Inc. (TTCI), conducted an evaluation regarding the opportunity and availability to use Fiber Optic Acoustic Detection (FOAD) in the railroad industry. A FOAD task force was created by the Association of American Railroads' (AAR) Railway Electronics Standards Committee (RESC) for the purpose of identifying if there is potential for cost savings to the railroads, especially if FOAD is used for multiple applications, as well as along regions of track with existing fiber optic cable installed.

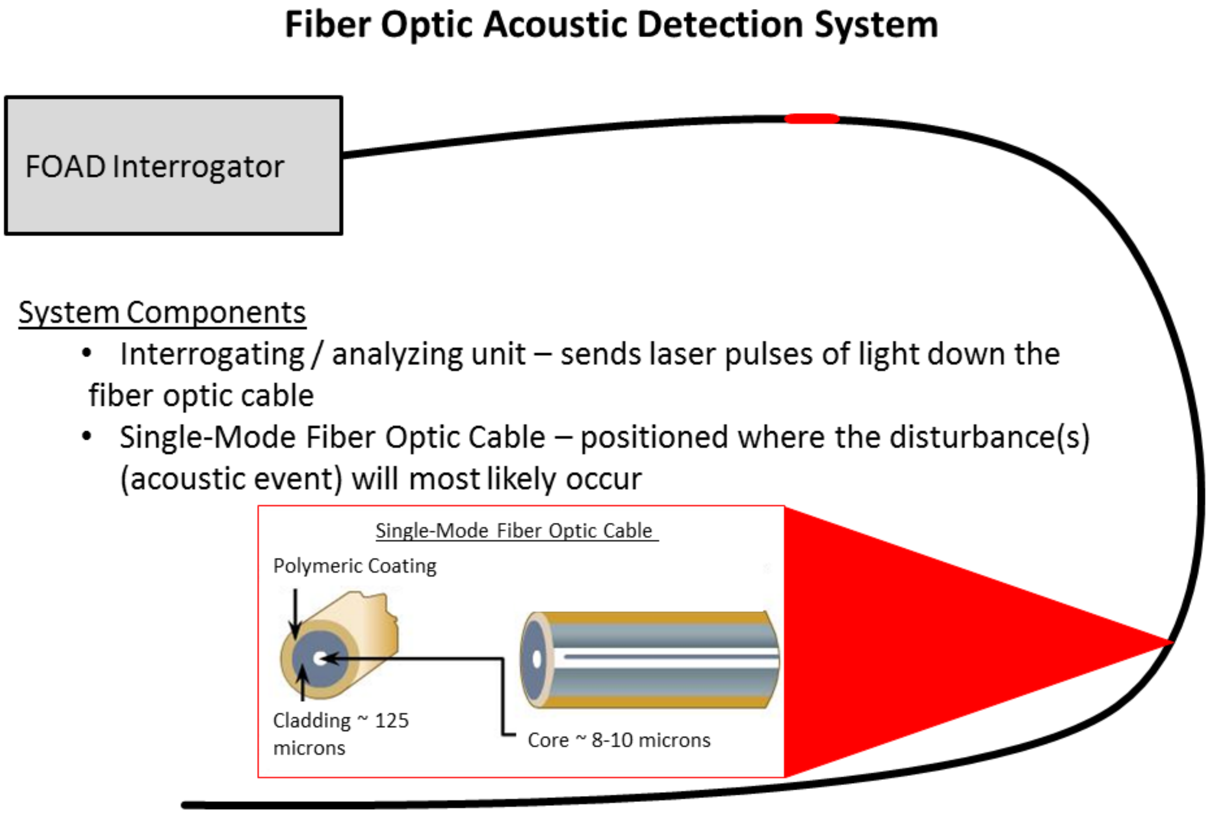
1.1 Background

Throughout the railroad industry, broken rails and broken welds are the single highest cause of train derailments; consequently, efforts to prevent accidents of such high-frequency and high-severity should, and do receive significant and considerable attention (Barkan, C. P.L., Rapik Saat, M., and Xiang, L., 2012). Methodologies to prevent rail breaks or detect rail breaks quickly when they occur, especially when there is potential for safety enhancements and cost savings, are of significant benefit to the railroad industry.

This particular study is intended to evaluate the availability and the opportunity to use an emerging technology known as Fiber Optic Acoustic Detection (FOAD), not only for the timely detection of rail breaks, but also for other potential applications of it in the railroad industry. A single FOAD system could be capable of providing several event detection capabilities that currently require the deployment of multiple systems. In addition to these multi-purpose detection capabilities, a single FOAD system would have the capability of monitoring several miles of track instead of only monitoring a single point or small section, as is the case with most of the rail detection technologies available today. These potential benefits have been recognized by the railroad industry, as well as vendors of the technology, and have resulted in a number of research and development projects meant to further the potential implementation of FOAD in the railroad industry. In fact, this technology has received enough attention by the industry that an Association of American Railroads (AAR) Task Force, the FOAD task force, represented by several AAR member railroads and FOAD vendors, has been formed in an effort to further its development for railroad applications.

FOAD essentially turns a fiber optic cable into a virtual array of distributed sensors that detect strain induced on any section of the fiber by proximate acoustic or seismic events. This is achieved by pulsing light from a laser in the FOAD interrogator unit down the fiber and detecting the light reflected back to the interrogator via Rayleigh scattering from the regions of the fiber that are being strained. In railroad applications, the fiber is typically buried in the ground near the track.

As acoustic waves are emitted on the surface they are transmitted into the ground causing strain on the fiber that is detected by the system. Many events that the railroads are concerned with monitoring along the track produce acoustic signals that may be detected by a FOAD system. These events include, but are not limited to, train movement, broken rails, wheel impacts, dragging equipment, etc. The basic components of a FOAD system are the interrogator and the fiber optic cable. These are shown in Figure 1.



- Interrogating / analyzing unit – sends laser pulses of light down the fiber optic cable
- Single-Mode Fiber Optic Cable – positioned where the disturbance(s) (acoustic event) will most likely occur

Figure 1. FOAD Overview

1.2 Objectives

Due to the rapidly growing interest and research in the application of FOAD technology, the objectives of this report were to determine the viability and applicability of FOAD technology to the North American railroad industry. The project objectives were to:

- Identify potential applications for the use of the technology in railroad applications.
- Estimate to the extent possible the amount of existing fiber optic cable installed along the North American railroad networks, the ownership of the cable, and the approximate quantities of single-mode versus multimode fiber optic cable throughout.
- Estimate a range of installation costs and yearly maintenance costs for a typical fiber optic system for potential applications of FOAD technology, and then compare to the range of typical installation and yearly maintenance costs for existing systems with similar functionality, considering the differences in functions that each technology is designed to perform.

1.3 Overall Approach

TTCI collaborated with the FOAD task force members to develop and prioritize a list of potential applications of FOAD technology of interest to the railroad industry. The TTCI team reviewed relevant literature and gathered information pertinent to the objectives of this project from the railroads, FOAD suppliers, and from fiber optic cable installation companies. The information was then analyzed to provide a comparison of the cost drivers of fiber optic based systems to the cost drivers of non-fiber optic based systems.

1.4 Scope

The following describes the scope of work performed to meet the project objectives:

- Collaborated with North American railroads, the AAR, and FOAD suppliers from the FOAD task force to identify and prioritize potential applications of FOAD technology to the rail industry.
- Developed questionnaires to gather information, to the extent possible, from
    - Railroads – for the amount and typical characteristics of existing fiber optic cable installed along the North American rail network, and the cost drivers associated with the installation and yearly maintenance of Wheel Impact Load Detectors (WILD) and track circuits.
    - FOAD suppliers – for the cost drivers associated with the installation and yearly maintenance of a typical FOAD system for railroad use.
    - Fiber optic cable installation companies – to gather cost driver information for installation of fiber optic cable, within a range of soil types, and expected yearly maintenance costs.
- Conducted individual interviews with railroad members and FOAD suppliers of the FOAD task force, to clarify responses and/or more thoroughly complete the questionnaires.
- Generated and gained AAR approval of an outline for the intended method to anonymously report on the confidential cost driver information received from the railroads and the FOAD suppliers.
- Reviewed and analyzed the information gathered from the various FOAD task force members and from relevant literature to provide a high-level comparison of cost drivers for fiber optic based technologies. For this study, the term *cost drivers* which will also be referred to as *costs,* is intended to mean installation costs, and the yearly ongoing maintenance and inspection costs associated with each system considered in the high level cost analysis. The cost comparison was limited to the information available at the time of this study. Since FOAD is an emerging technology in its application to the railroad industry, its performance in revenue service was not well documented. Similarly, the historical costs of FOAD for railroad applications were not available at the time of this study.

- Documented the advantages and limitations for potential fiber optic-based railroad applications and the corresponding, existing non-fiber optic-based systems that perform similar functions.

1.5 Organization of the Report

This report is organized in six major sections:

- Section 1 introduces the importance of the work performed, as well as providing a brief background of FOAD technology with descriptions of the project objectives, overall approach, and scope.
- Section 2 summarizes the current status of research and testing efforts for the application of FOAD in the railroad industry.
- Section 3 discusses the extent and characteristics of existing fiber optic cable along railroad routes in North America.
- Section 4 provides a qualitative comparison of the advantages and disadvantages of existing systems to FOAD, used for the same or similar railroad application.
- Section 5 includes a comparison of the cost drivers of existing systems to the cost drivers of FOAD.
- Section 6 provides the conclusion for this study.

2. Summary of the Current Status of FOAD Technology Used for Railroad Applications

Interest in the application of FOAD in the railroad industry has been developing over the last decade and has given rise to related research and testing activities by FRA, North American railroads, FOAD vendors, and TTCI. In 2011, the value of a fiber optic test bed isolated from the challenges associated with revenue service operations was identified by the rail industry, and ultimately led to the installation of two fiber optic test beds at the Transportation Technology Center (TTC). Consequently, combinations of FOAD suppliers, railroads, and FRA supported or participated in multiple FOAD research and test programs at TTC. Advancements and use of the technology in the railroad industry have also been pursued independent of activities at TTC, in several countries, by railroads and FOAD vendors.

2.1 TTC Test Beds

TTC offers a 52-square mile facility offering many advantages for railroad safety and efficiency testing, and provides the rail industry with a test bed for technology development that is isolated from public exposure and risk. This supports safe track and train testing to be performed on 50 miles of track in a full-scale operating environment under controlled operating conditions that would be impractical to implement for extended periods of time in revenue service.

2.1.1 FAST Operations and HTL Test Bed

Over the past several decades, TTCI and the industry have devoted a great deal of research to understand the technical, safety, and economic issues related to high tonnage freight traffic and heavy axle loads (HAL). Much of this research has been conducted at the Facility for Accelerated Service Testing (FAST) at TTC, which serves as a research and development tool consisting of an operating railroad with mainline track and a HAL train. The facility operates a 110- to 160-million gross tons (MGT) per year durability test bed for railroad track, rail vehicles, and their component parts. An 18,000-ton train, comprising three high horsepower locomotives and 315,000-pound cars are operated over a 2.7-mile mainline quality track, the High Tonnage Loop (HTL), at 40 mph.

Due to the routine controlled operations and track characteristics, the HTL was selected for installation of a fiber optic test bed and deployment of a FOAD system. The installation was jointly funded by TTCI and FRA. The oval-shaped track is comprised of moderate curves and tangent track, with track and bridge components of various composition and design. The track contains two precast concrete bridges and one steel bridge. For approximately one-quarter of the track, the HTL parallels the Railroad Test Track (RTT), with track centerline distances being separated by about 20 feet (ft), thus providing a location for double track testing.

The red dashed line in Figure 2 shows an overview of the fiber optic cable location around the HTL.

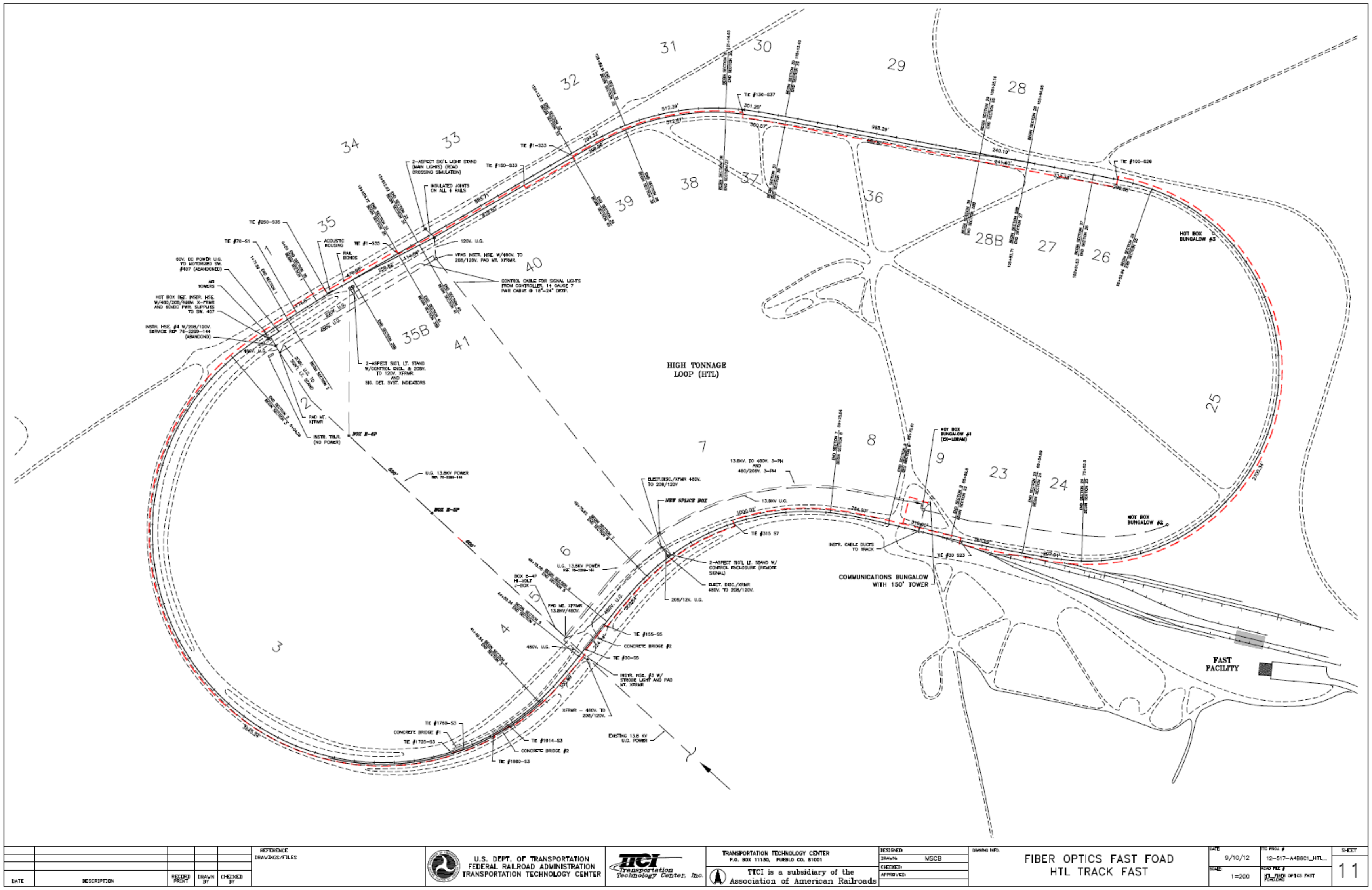


Figure 2. Overview of Fiber Optic Cable Location at the HTL

An overview of the HTL fiber optic cable installation is described by the following:

- The main sensing fiber is Superior Essex Series W7001KU101 Fiber-to-the-Premises (FTTP) cable. It is loose tube, single jacket cable with 12 single-mode fibers in an FTTP profile. Figure 3 shows a diagram of the cable.

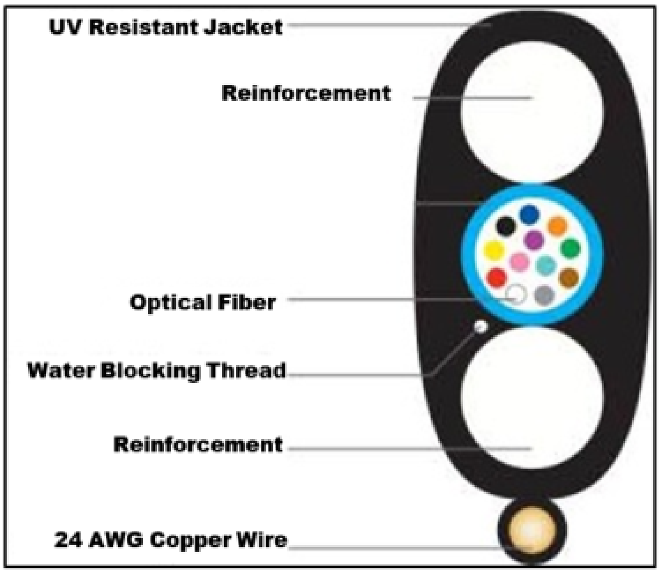


Figure 3. Superior Essex FTTP

- The fiber installation was performed as close as practical to the method of fiber installation along live track in revenue service to best represent typical installation scenarios. Single-mode fiber was buried an average of 36-in deep typically paralleling the track, and 15 ft. from centerline of track. In certain locations, the fiber was buried at depths of 18-in and 42-in.
- The cable was buried using both direct burial and directional boring techniques. A small section of the fiber was buried in conduit, and the fiber is attached to two of the three bridges in rigid metal conduit, see Figure 4.

Figure 4. HTL Bridge with Fiber Optic Conduit

- Thirteen splice vaults were installed in predetermined locations around the perimeter of the HTL to allow for easy manipulation of the fiber optic cable in future tests.
- The fiber is installed starting and ending at the FAST communications bungalow (located near HTL Section 9, see Figure 2) to allow for multiplying fiber lengths should a fiber length of more than 3 miles be required. The bungalow provides a suitable location for a FOAD system, as it offers a controlled environment and adequate space for working and monitoring testing activities.
- All fiber optic burial cable installed in open ditch was surveyed using high accuracy Global Positioning System (GPS). This survey serves as a reference both to depth and location to track.
- For approximately one-quarter of the track, the HTL runs parallel to the RTT with track centerline distances being separated by about 20 feet. By installing the fiber under and on the outside of the RTT in a portion of this test section, the cable configuration provides the capability to collect data for single track testing (by excluding RTT traffic during test runs) and offers the potential for acquiring data for double track testing.

2.1.2 RTT Test Bed

TTCI, in conjunction with FRA and CSX, also constructed a fiber optic test bed on the RTT at TTC. The RTT is a 13.5-mile, Class 9 track, with speed capabilities of up to 165 mph and the ability to support electrified testing with a 25 kilovolt overhead catenary system. The RTT was chosen as a prime fiber optic test bed for several reasons:

- The capability to test both light rail and heavy freight trains of either diesel or electric propulsion.
- Signaled track, with a total of 12 signal blocks that are electrically isolated from each other with the use of insulated track joints. Having a fiber optic test bed near signaled track provides the opportunity for analysis of track joints using FOAD technology.
- Two high-speed road crossings located near the core area of the track. These road crossings in close proximity to a fiber optic test bed provide a means of testing and developing FOAD technology for crossing monitoring and activation. One of the RTT crossings is shown in Figure 5.

Figure 5. Crossing on RTT

- Approximately 2.7 miles of track length is paralleled by the Transit Test Track (TTT), allowing for the study using FOAD technology to determine track occupancy and train position in multiple-track locations.

The RTT fiber optic cable installation is described by the following:

- The fiber optic cable used was the same 12-core, single-mode, FTTP cable used for the HTL test bed, and currently spans 6.8 miles of the 13.5-mile track.
- The existing RTT test bed cable was direct buried 36 in deep and typically within 15 ft. to 25 ft. of the centerline of the RTT, lending itself to high levels of spatial resolution via the FOAD system.
- A 1.3-mile section the fiber was installed in an above-ground recycled plastic trough through the core section of the RTT. The purpose for the trough section of fiber is to evaluate this installation method as used with a FOAD system, and to not disturb other buried utilities along this length of the RTT.

- The fiber optic cable is installed with flexibility of the test bed in mind. There are several risers along the 6.8-mile route, which allow for flexibility in position of the FOAD interrogator unit.

2.2 FOAD Development Projects at TTCI

Since 2011, TTCI has been involved in several projects relating to research and development of FOAD for railroad-specific applications. Due to its facilities and, in particular, the fiber optic test beds established by TTCI, FRA, and CSX, TTC has been the center of research, testing, and development of this technology for the North American railroad industry.

2.2.1 FRA-Funded Research and Development

From 2012 through 2014, FRA funded feasibility studies at TTC in an effort to assess the capabilities of FOAD for the railroad industry (Holcomb, M., and Mauger, W. D., 2013) (Holcomb, M., and Sheehan, R., 2015). These were multifaceted projects with the following objectives:

- Install fiber optic test beds on the HTL and a portion of the RTT at TTC
- Install fiber optic related test equipment and data acquisition systems for acquiring acoustic/seismic data from the track during train operations at FAST
- Store and manage the data for potential subsequent processing and analysis
- Monitor train movement during FAST operations and document broken rails (on average, two to three broken rails per week) on the HTL
- Process and analyze the broken rail data
- Provide data to vendors interested in using it for developing rail break detection algorithms
- Install GPS receivers and related equipment on the head and tail end of test trains for each of the tests, and then store and manage the data for potential subsequent processing and analysis
- Monitor simulated roll-out events using two separate FOAD systems
- Process and analyze GPS and FOAD train location data to determine the accuracy of FOAD in determining train location and velocity
- Process roll-out data to determine if FOAD is capable of detecting siding rollouts.
- Process and analyze data generated by Multiple Track Occupancy (MTO) to determine the feasibility of using FOAD as a means of determining track occupancy in multiple-track territories and switching yards

As a result of these FRA-funded projects, much was learned about FOAD and its potential application to the railroad industry. Establishing fiber optic test beds at TTC has been valuable to follow-on research and development of the technology.

In 2016, FRA began a trial to determine the current state of broken rail detection among participating FOAD suppliers, Fotech and OptaSense®. This trial is being conducted at TTC on the HTL during FAST operations. FAST operations typically produce two to three broken rails per week on the HTL, providing an excellent opportunity to conduct an evaluation of this kind.

2.2.2 CSX and Fotech Solutions

In 2011, CSX funded proof of concept testing at TTC with Fotech Solutions and its FOAD system. The primary focus of this testing was to evaluate the system's capability to detect and track wheel impacts. The results of this testing were positive and warranted follow-on testing.

After the establishment of the fiber optic test beds on the RTT and HTL, CSX, Fotech Solutions, and TTCI began a project in 2014 to develop a railroad specific FOAD system. Proof of concept testing was conducted at the TTC fiber optic test beds, and it was determined that it is viable for FOAD to perform train tracking, but it has not yet been confirmed if it can do this in a fail-safe manner. It has also been determined that it is viable for FOAD to detect certain defects such as broken rails and wheel impacts at a range of up to 24.9 miles (40 kilometers) from the sensor. Proof of concept algorithms for train tracking, broken rail detection, and wheel impact detection were developed by TTCI and integrated with the system by Fotech. All data collection and subsequent testing was performed at TTC. In order to meet requirements set forth by CSX, Fotech developed a system that is capable of monitoring 49.7 miles of track in the harsh railroad environment. This project was completed in 2016. CSX now intends to begin a pilot program on its network, comparing the performance of FOAD to its current systems.

2.2.3 OptaSense®

In 2015, OptaSense® began developing a railroad-specific FOAD system and installed some of its systems on the HTL at TTC. Taking advantage of the fiber optic test bed on the HTL allowed OptaSense® to gather valuable data from FAST operations. This data has been used by OptaSense® in its development of train tracking and broken rail detection capabilities.

2.3 BNSF and OptaSense® Efforts

In addition to the various collaborative efforts that have taken place at TTC among the FRA, TTCI, CSX, Fotech, and/or OptaSense®, the use of FOAD technology for railroad applications is being explored by other railroads and FOAD suppliers. Joint efforts carried out by BNSF and OptaSense® to investigate the use of FOAD technology for detection of rock falls along railroads is discussed in a 2013 AREMA article titled "Fiber Optic Sensing for Detecting Rock Falls on Rail Rights of Way." In 2010, a 30-ton rock fell onto a section of track in the Wind River Canyon, causing the locomotive and three cars to derail. This led BNSF to consider installation of a rock fall detection system in an area of the canyon particularly prone to rock falls (Akkerman, J., and Prahl, F., 2013).

In 2010, BNSF and OptaSense® teamed up to discuss and assess the potential for the OptaSense® FOAD system to be used in this capacity. After evaluating the advantages and limitations, both cost-related and functional, of using a FOAD system versus a slide fence for rock fall detection, BNSF elected to have a FOAD detection system installed to monitor a 21.6-mile section of track in the Wind River Canyon (Akkerman, J., and Prahl, F., 2013).

Information shared by OptaSense®, aside from the rock fall detection jointly investigated by BNSF and OptaSense®, highlight OptaSense's involvement in exploring the application of FOAD technology in the rail industry with other railroads from several other countries.

OptaSense® has deployed systems monitoring approximately 1,100 miles of rail lines in several different countries, including the Deutsche Bahn in Germany, ÖBB Railjet in Austria, high-speed European lines, underground metro lines, and lines in Africa, Saudi Arabia, Japan, and Australia. OptaSense® currently offers FOAD systems that can provide:

- Infrastructure security
- Monitoring of locations for unauthorized activity, including cable and metal theft
- Rock fall detection
- Train tracking

OptaSense® can currently network several interrogation units and processing units to support centralized monitoring and reporting along fiber optic cable potentially spanning several hundred miles. Research and development efforts are underway at OptaSense® to use the technology for (Vivek, C., Bradley, P., and Rosenberger, M., 2016):

- Structural health monitoring
- Track condition monitoring
- Rail break detection
- Flat wheel detection (Ciorra, J., and Hill, D., 2016)

In the April 2014 edition of "The Rail Engineer," OptaSense® described the recently announced, collaboration between themselves and Deutsche Bahn. Under the collaboration, 25 different test scenarios were planned in an effort to evaluate the potential for FOAD technology to replace many conventional trackside sensors, and consequently reduce costs associated with trackside monitoring (Kessell, C., 2014).

2.4 Frauscher Sensor Technology USA, Inc.

Established in 1987, the Austrian-based company, Frauscher Sensor Technology USA Inc. (Frauscher), has been a leading supplier in the world market for inductive sensors, such as axle counters and wheel sensors. In March 2016, Frauscher presented on the status of its research and development efforts regarding FOAD in the rail industry at TTCI (Vivek, C., Bradley, P., and Rosenberger, M., 2016). From 2012 to 2014, Frauscher researched new sensors and technologies, and identified FOAD technology as a system with significant potential for application and benefit to the rail industry. Deployment of Frauscher Tracking Solutions (FTS) pilot systems commenced in 2015 and by the end of 2016 the company will have over 20 FTS pilot and contract systems installed in various locations around the world. The function of each system varies per installation, but includes rock fall detection, train tracking, train speed, rail break detection, flat wheel detection, or some combination of these functions. With the intent to enhance the system's detection capabilities and accuracy, the FTS system combines the existing Frauscher axle counting sensor with a FOAD system. Frauscher has focused its research of development around the following three categories which the FTS technology is well suited, and will likely provide lasting benefits and enhancements to the railway industry:

- Train tracking – train detection, time table analysis, tunnel traffic management, single line protection, and level crossing protection

- Asset condition monitoring – rail break, flat wheels, catenary flash overs, infrastructure, point machines, generators, and track defects
- Security – people, animals, rock fall, landslides, worker protection, and copper theft (Vivek, C., Bradley, P., and Rosenberger, M., 2016)

These efforts reflect a growing interest among railways and FOAD suppliers from various locations around the world, as the potential applications and benefits of this technology to the rail industry are better understood.

3. The Current Status of North American Fiber Optic Cable Installations

The North American railroad routes have provided advantages to telecommunication companies due to the installation of long-haul, fiber optic cable. With the emergence of FOAD in the rail industry, this may, in turn, be beneficial to the railroads. With the main two components of FOAD being the interrogator and the fiber optic cable, understanding the extent and characteristics of existing fiber optic cable installed along the railroad rights-of-way is of interest, because the fiber could be leveraged for use with a FOAD interrogator and result in reduced implementation costs of FOAD along the railroad lines.

3.1 U.S. Class I Railroad Routes

Class I railroads make up over 94,264 miles of the U.S. track network (Association of American Railroads, 2015). There are seven Class I railroads that operate in the United States: BNSF, Canadian National Railway (CN) (with Grand Trunk Corporation), Canadian Pacific Railway (CP) (with Soo Line Corporation), CSX, Kansas City Southern Railway (KCS), Norfolk Southern Corporation (NS), and Union Pacific Railroad (UP). As of 2014, a U.S. railroad is considered to be Class I if its yearly revenue is $475.75 million or more (Association of American Railroads, 2015). Amtrak is also a major rail operator, while the company does not own a substantial amount of track, it does operate on over 21,356 miles throughout the United States (Association of American Railroads, 2015).

The U.S. track routes of the Class I railroads span a large area of the United States with greater density on the eastern half of the country, as seen in Figure 6. BNSF and UP routes cover the western region of the country; CP and KCS routes are primarily in the Midwest and central region; and CN, CSX, and NS cover the central and eastern states. Most of the track is installed on property owned by one of the North American Class I railroads. Due to these narrow lots of property designed as the distribution arteries of North America, they have uses beyond moving freight along the rails. One important example of this is the railroad right-of-way being used for installations of long-haul, single-mode fiber optic cable. This type of fiber optic cable, unused or "dark," can be harnessed for use with a FOAD system.

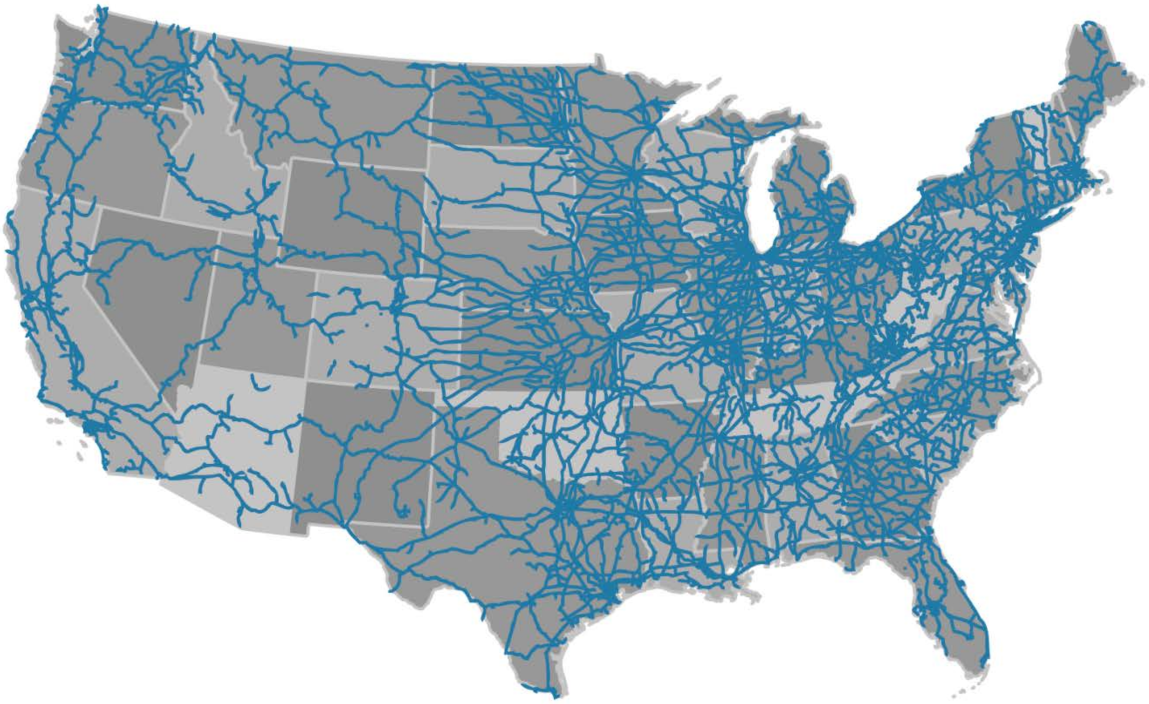


Figure 6. Class I Railroad Track U.S. Map (140,000-Mile Private Rail Network Delivers for America's Economy) (FreightRailWorks, 2010)

3.2 Installed Fiber Optic Cable

The expansive U.S. fiber optic network footprint, shown in Figure 7, represents the fiber optic connections between the top 25 most fiber-dense cities in America (Forrest, C., 2014). Many different companies, mainly telecommunication corporations, have ownership of these cables, mainly telecommunication corporations. Companies pursuing fiber optic installation projects across the United States recognized the challenges associated with city and state regulations and ownership policies. The vast and already-established railway network was identified as a potential means for avoiding some of the installation challenges, so they sought permission from the railroads to lay fiber along the track system (Barford, P., Durairajan, R., Sommers, J., and Willinger, W., 2015). In some instances, railroads began to proactively license their land out as fiber-install ready, with NS having 19,946 miles of fiber-ready land (Norfolk Southern Corporation, 2018).

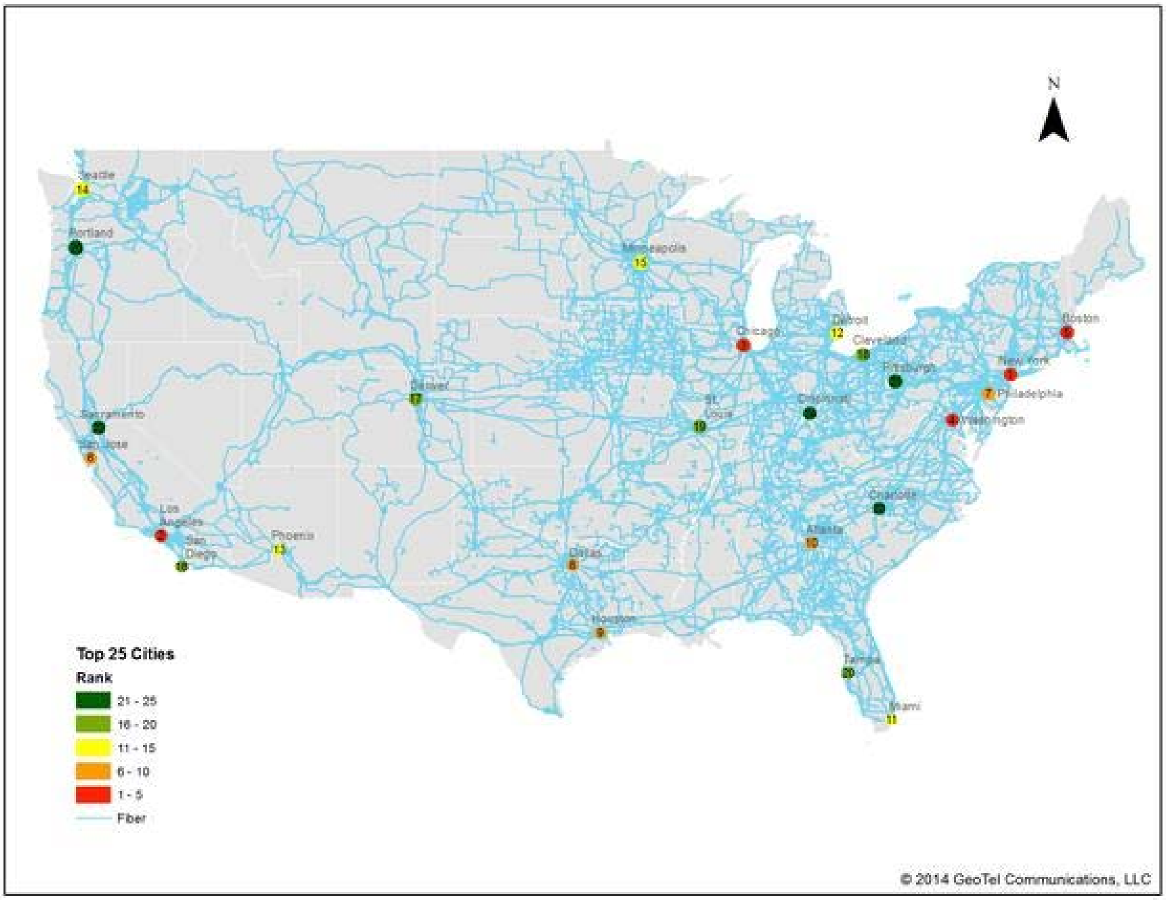


Figure 7. The Top 25 Fiber-Connected Cities in the United States (Forrest, C., 2014) (Used with Permission from GeoTel Communications, LLC)

3.3 Estimated Amount of Fiber Optic Cable Installed Along the U.S. Rail Network

Figure 8 shows the result of overlaying the Class I railroad map, Figure 6, and the existing fiber optic network map, Figure 7. When comparing the rail network to that of fiber, they appear similar, as every major city labeled on the fiber map appears to be a hub for rail and fiber alike. As examples, Salt Lake City, UT, Albany, NY, and Birmingham, AL, are all easily identified as locations of convergence for both railroad and fiber routes. These cities are indicated with yellow circles on Figure 8.

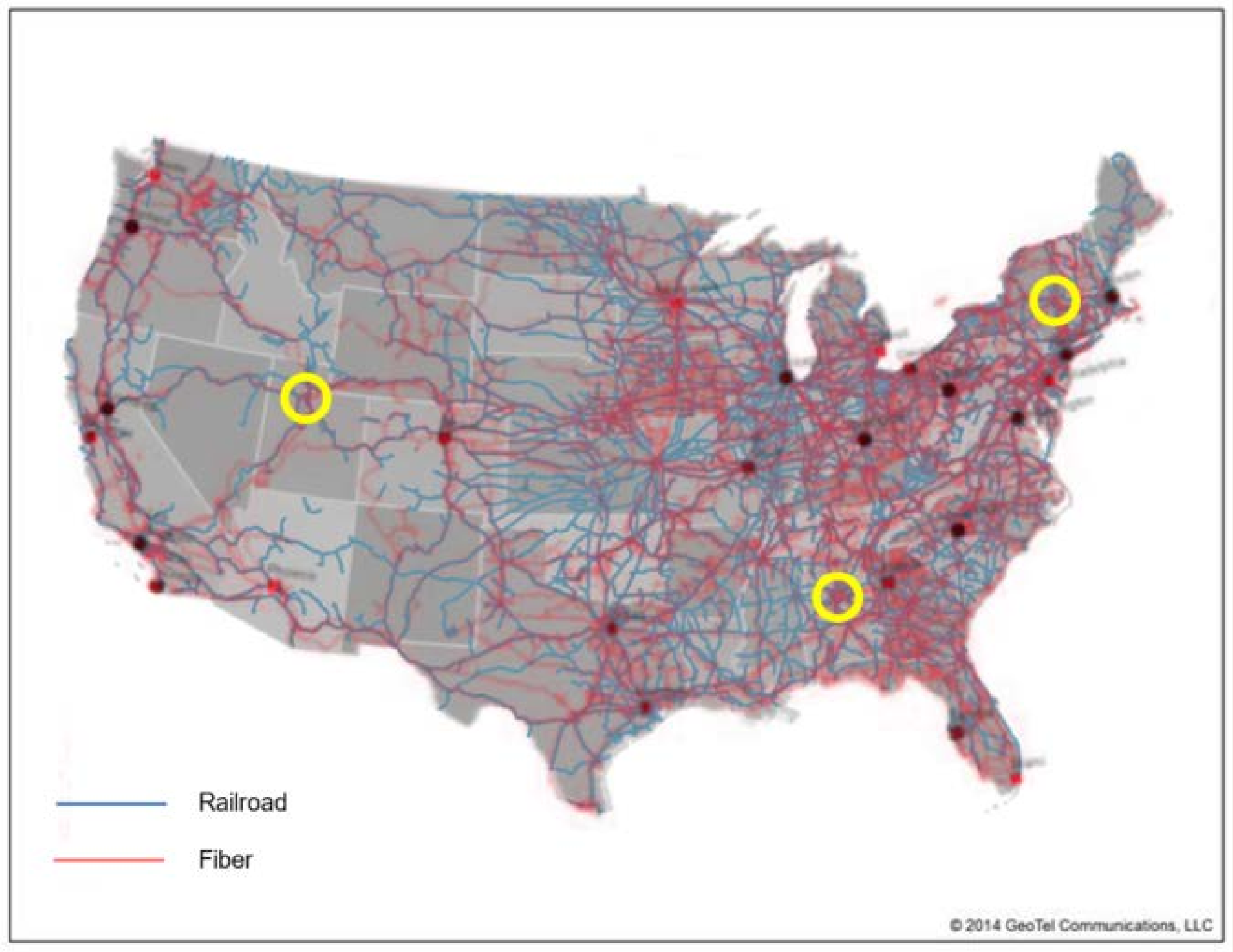


Figure 8. Class I Railroad Track and Fiber Networks Overlaid

It can be seen by the locations of overlap of the rail and fiber routes shown in Figure 8 that several railroad routes potentially have fiber optic cable installed in close proximity. CSX conducted a similar independent study of fiber optic cable located on its network in an effort to determine the feasibility of using FOAD. The red lines in the map shown in Figure 9, courtesy of CSX, indicate the CSX track, with fiber optic cable, is in close proximity to the track.

Figure 9. CSX Track with Fiber Installed

As part of this project, a survey was sent out to North American railroads to inquire about the extent of existing fiber optic cable installed along the U.S. rail network requesting information regarding the total mainline railroad route miles, signal protected miles, dark territory, and the amount of fiber along each. Survey respondents included a subset of the railroads represented on the FOAD task force, which were CP, CN, UP, NS, BNSF, CSX, and Amtrak. The survey is included in Appendix A.

Five railroads responded to the questionnaire about known fiber in their network and reported anywhere from less than 1 percent to as much as 90 percent of route miles having fiber optic cable installed in close proximity Figure 10 shows the values reported by the five railroads. To provide anonymity in reporting results, each railroad was assigned a number, for example, Source 1. This coincides with the significant amount of overlap shown in Figure 8. Note that the reported value for Source 7 was below 1 percent, and therefore, does not show a bar on the plot. This value was observed to be significantly less than the values reported by other railroads, and warrants further investigation for future studies. Railroads could use the lengths of track with fiber optic cable already installed for deployment of a FOAD system, and benefit from reduced costs associated with installing fiber optic cable. The ever-increasing demand for broadband and increased data traffic fuels the expansion of the fiber optic cable network (Ross, S. S., and M., Zager, 2013). As development of FOAD technology in railroad applications continues, the expanding fiber network may provide even more opportunities to use FOAD technology in the railroad industry.

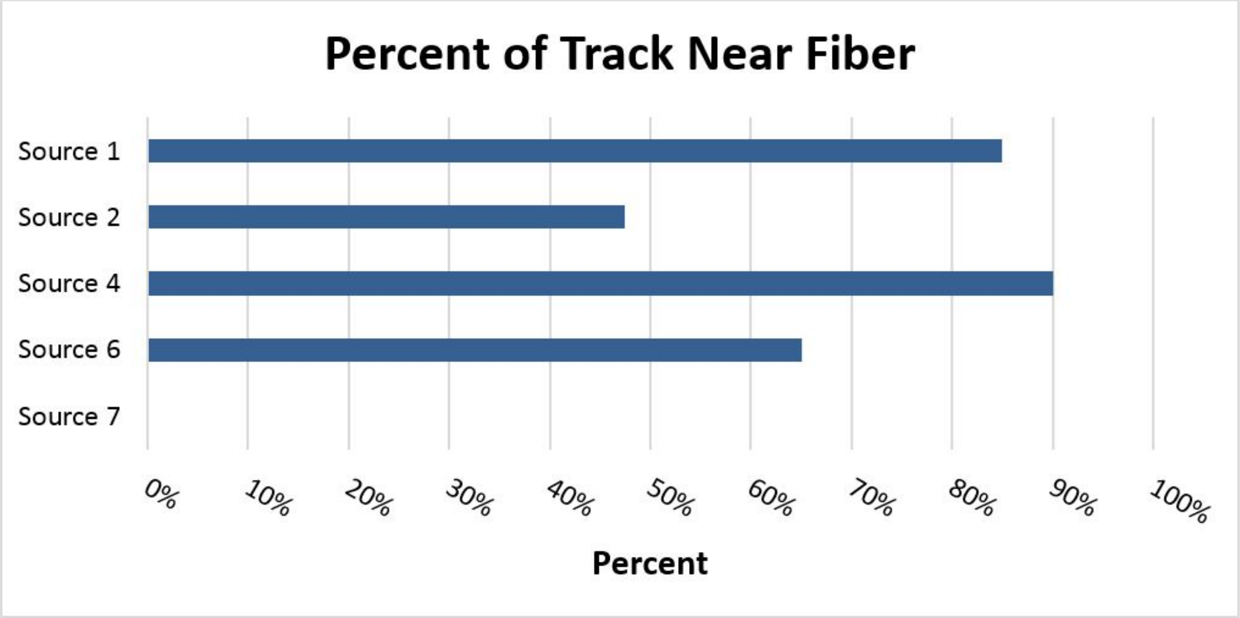


Figure 10. Percent of Mainline Track Located Near Existing Installed Fiber Optic Cable

Three of the five railroads reported on the percentage of signaled track miles with fiber optic cable in close proximity. The reported percentage of miles that have fiber installed ranged from less than 1 percent to 85 percent. Gathering data with FOAD along railroad routes with established track circuits would allow for development of FOAD system capabilities. Dark territory track could also benefit from the emerging technology. Two of the five railroads reported values of 17 percent and 60 percent of track without signals as having fiber optic cable in close proximity (see Figure 11).

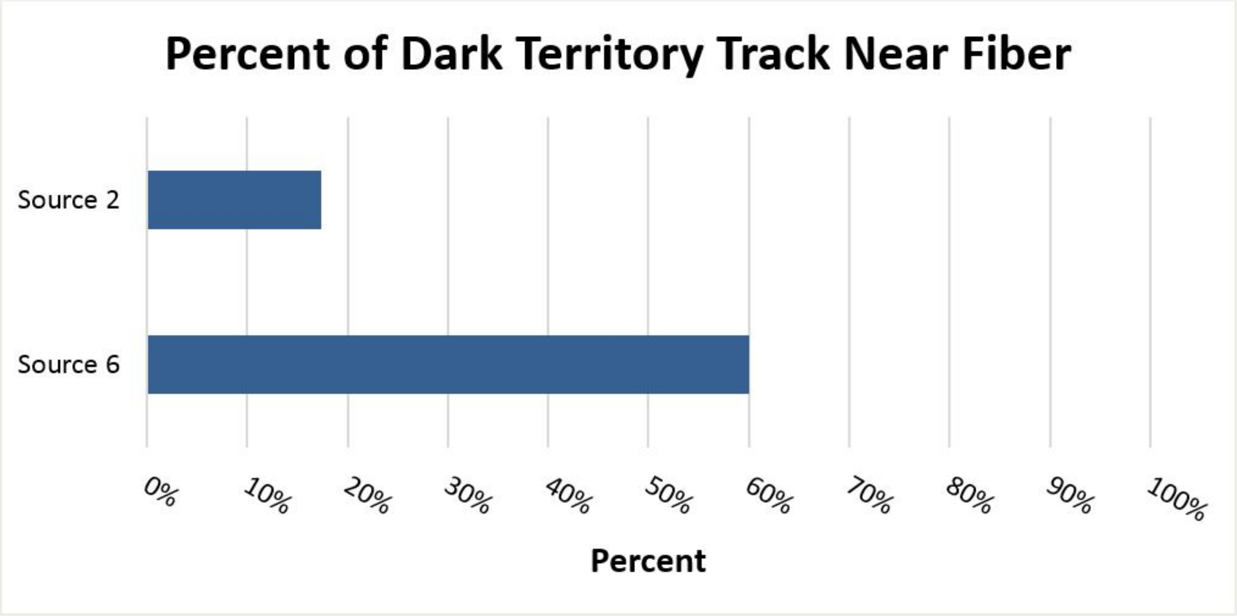


Figure 11. Percent of Dark Territory Mainline Track Near Existing Installed Fiber Optic Cable

The installation of an OptaSense® system by BNSF for rock fall detection in Wyoming, as described in Section 2.3, is an example of the safety benefits that a FOAD system can provide in dark territory.

3.3.1 Typical Railroad Fiber Optic Cable Installation Methods and Characteristics

The survey sent to the North American railroads also requested installation details of the existing fiber optic cable near track in order to better understand how and where single-mode fiber is installed along their rights of way. The findings of the survey provided somewhat ambiguous results and are as follows:

- Depth: 3.3 ft. to 6.6 ft.
- Distance to center of track: 6.6 ft. to 39.4 ft.
- Methods for installation:
  - Conduit
  - Direct Buried
  - Inner Duct Directional Bore
  - Direct Lay in water
- Distance between repeaters: 1 mile to 49.7 miles, with a 24.9-mile (40 km) average on long-haul fibers

The survey responses provided information of the many ways fiber optic cabling is installed along the railroads. It can be inferred that the variation is due, in part, to suit the purpose of the installation as well as the cost of installation. The railroads were asked the typical distance fiber is laid from centerline of the track and the typical buried depth. According to the responses, the distance from centerline varied from 7.9 ft. to 37.4 ft., with an average of 21.7 ft., while the depth of fiber varied from 3 ft. to 4.6 ft. with an average of 3.6 feet. The depths and distances from centerline of track reported by each railroad are shown in Figure 12. Each colored dot represents the typical fiber optic cable installation depth and distance from centerline of track for each reporting railroad, as well as for the fiber optic test beds at TTC.

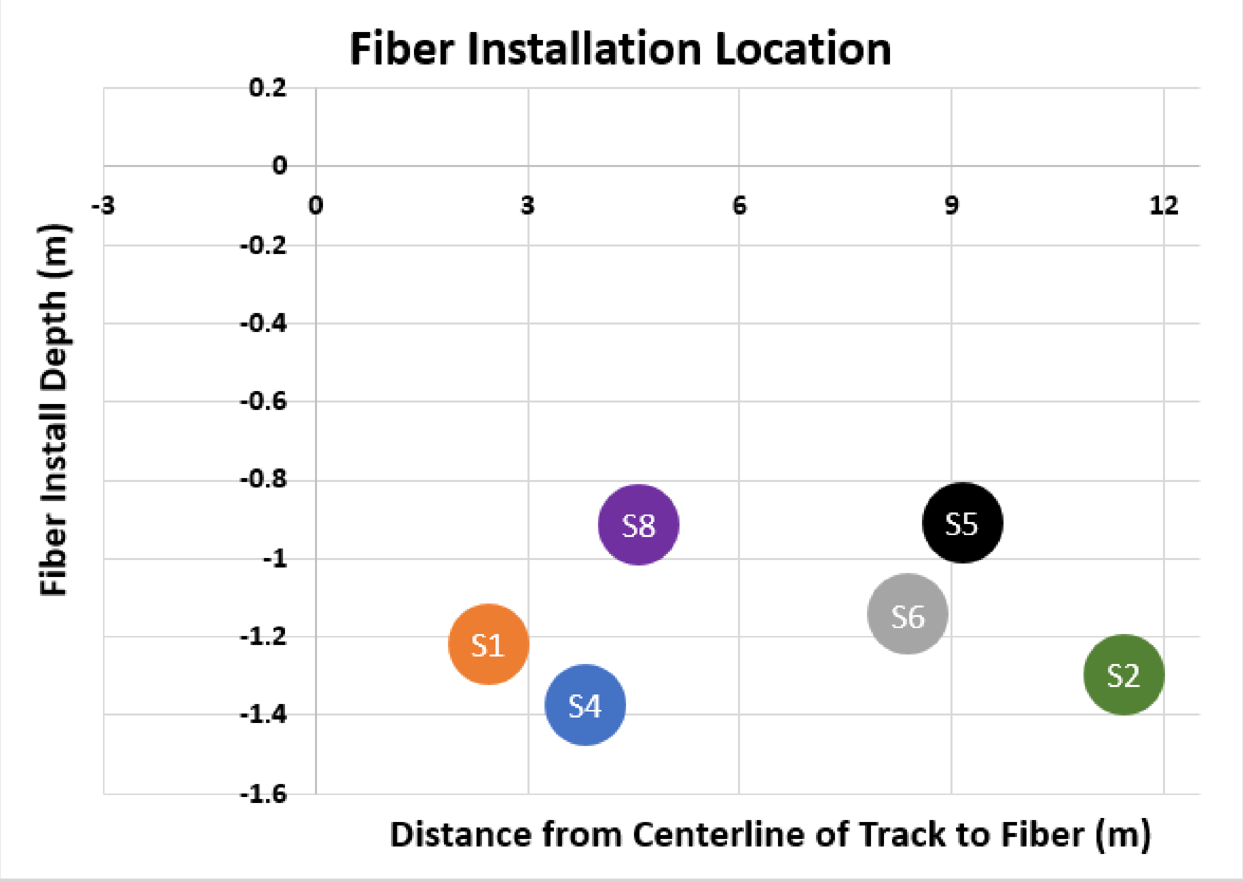


Figure 12. Depth Location of Fiber

3.3.2 Recommended FOAD Fiber Installation

Cable Selection

There are a large variety of fiber optic cable types available for use. This section highlights the types of cable that have been recommended for use from FOAD suppliers. For FOAD monitoring purposes, cable selection with good acoustic coupling properties are preferred. To achieve this, the following cable type is generally preferred, and is shown in Figure 13:

- Gel-filled, loose tube
- Single jacket
- Single armor
- At least one dark fiber core

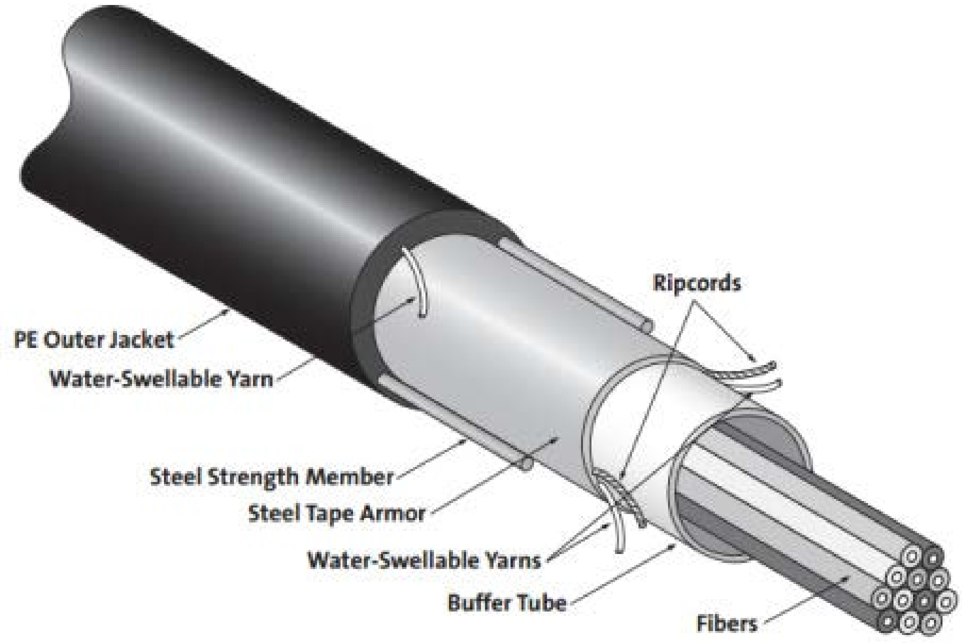


Figure 13. Fiber Cable Construction (Piran, W., and Richard, M., 2015)

Fiber optic cable can be broken down into two main groups or medium types: multi-mode and single-mode. The main difference between multi-mode and single-mode optical fiber is that the former has a much larger core diameter, typically 50 micrometers to 100 micrometers, which is much larger than the wavelength of the light carried in it. Because of the large core and the possibility of large numerical aperture, multi-mode fiber has higher "light-gathering" capacity than single-mode fiber. In practical terms, the larger core size simplifies connections and also allows the use of lower-cost electronics, such as light-emitting diodes (LEDs) and vertical-cavity surface-emitting lasers (VCSELs), which operate at the 850 nanometer (nm) and 1,300 nm wavelength. Single-mode fibers, used in telecommunications typically operate at 1,310 nm or 1,550 nm. However, due to multimode fiber having a larger core-size than single-mode fiber, it supports more than one propagation mode, and it is limited by modal dispersion, while single-mode is not. Multimode fiber is not the optimal choice for FOAD use, as its properties allow multiple propagation modes, and thereby introduce unneeded complexity to the signal with no benefit.

Data transmission speeds influence the maximum distance of multimode, but it is typically considered to have data capabilities of up to 1.2 miles at 100 megabit per second speeds. Due to its distance limitations, multimode cable is not suitable for long-haul application, such as along railroads, and is most commonly found in indoor applications. Single-mode fiber is preferred for FOAD use. It is constructed to be used as a long-haul fiber and can successfully propagate optical signals longer than 31.1 miles. Consequently, single-mode is the type of fiber most often found trackside, either for railroad use or as third party telecommunication network fiber. Having a much smaller core size (8–10 mm), and thus limiting the amount of modular dispersion, single-mode fiber retains the precision of each light pulse over longer distances than multi-mode. The increased precision allows for higher bandwidth at greater distances. FOAD technology makes use of the benefits of single-mode fiber to propagate light pulses up to 31.1 miles.

Connector Selection

FOAD technology uses an optical physics property known as Rayleigh backscatter. As a result, the systems are highly sensitive to reflected light. There are two groups of fiber optic connectors available, Ultra Physical Contact (UPC) and Angle Physical Contact (APC). Angled connectors are recommended for optimal performance of FOAD. Cut at an 8-degree angle, these connectors allow reflective light energy to disperse into the fiber clad, rather than directly back to the FOAD optical receiver. Figure 14 depicts the differences between APC and UPC connector types.

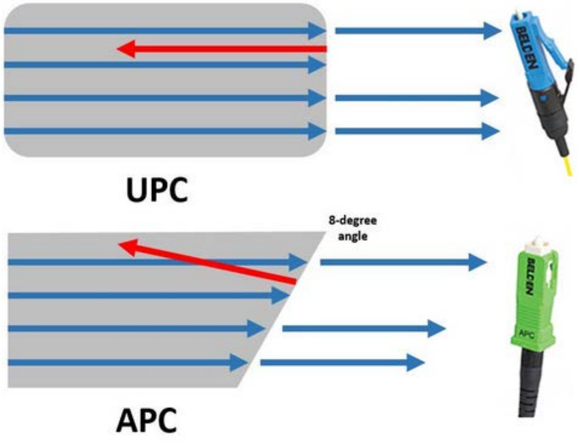


Figure 14. Fiber Optic Connector Types

Cable Installation Methods

Fiber optic cable can be installed using several different methods. This section details the most common types of fiber cable installations, and the advantages and limitations associated with each, with regard to FOAD.

Ducted Cable

Ducted cable is cable installed in conduit and then either buried or encased in concrete, shown in Figure 15. It is widely used in areas where excavation is difficult, or an extra means of cable protection is warranted. Some of the characteristics of ducted cable with FOAD include:

- Cable duct will reduce the amount of acoustic energy that is able to reach the fiber cores used with FOAD. While ducted cable will be less responsive, it is still a usable means of installation for FOAD fiber as the system could be calibrated for the expected acoustic sensitivity requirements.
- Cable type will generally have a greater effect on system performance than ducting.
- Smooth duct will yield a higher acoustic response than ribbed duct (Piran, W., and Richard, M., 2015).

Figure 15. Concrete-Encased Fiber Conduit

Troughed Cable

Cable troughs are generally used in areas where easy access to cable is needed, or excavation is difficult. A cable trough, see Figure 16, is an above-grade box or pipe that is usually constructed of concrete, fiberglass, or plastic. Troughed fiber optic cable is a suitable means of cable deployment for FOAD, although there will be a reduction in acoustic energy transfer from the ground to the cable. A FOAD system will need to be appropriately calibrated for use with troughed cable.

Figure 16. Fiber Optic Cable Wayside Enclosure

Overhead / Aerial Cable

Overhead fiber installations, see Figure 17, are the least desirable installation type for FOAD (Piran, W., and Richard, M., 2015). Acoustic energy, originating from train and/or track events, dissipates more quickly in the air than in the ground as a result of the relatively lower density of air. Despite this disadvantage, Frauscher is researching the use of aerial fiber installations with FOAD for flash over detection on overhead catenary systems.

Figure 17. Overhead Fiber

Direct Buried Cable

In this method, the fiber optic cable is directly buried into the soil, and is typically done via plow or trench methods. Directly burying the cable into the ground and then backfilling with wet compaction is the preferred method for FOAD fiber installation. This method creates the lowest loss of acoustic coupling between the cable and the acoustic or seismic events created from train or track. Depth of direct bury fiber does have an impact on acoustic response. The farther the fiber is from the track, the less acoustic energy will reach the fiber optic cable. It is recommended to bury fiber optic cable between 1 ft. and 1.6 ft. deep, and 6.6 ft. to 16.4 ft. from track center for best performance of the system (Piran, W., and Richard, M., 2015). A visual diagram showing the optimal installation characteristics is shown in Figure 18.

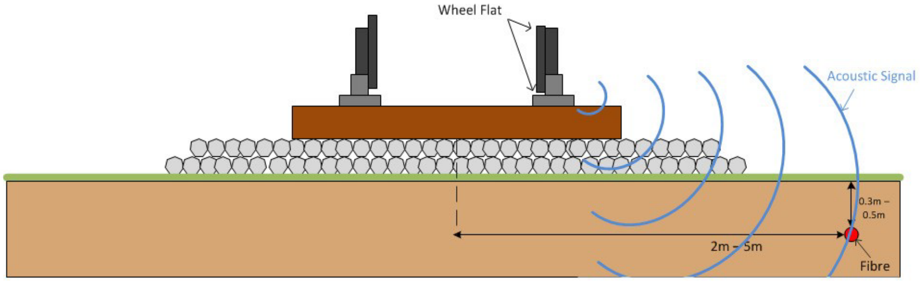


Figure 18. Optimal Fiber Installation Location (Piran, W., and Richard, M., 2015)

FOAD with Varied Fiber Installations

The Class I railroads in North America install trackside fiber in a diverse array of configurations. Examples of any or all of the aforementioned installation types may be used depending on terrain, application need, etc.

Although some of the current Class I railroad fiber installations are not optimal, much of it is still usable. Depending on the intended use of FOAD, it can be calibrated to adjust for variability in fiber installation and soil conditions. There is a large margin of what is acceptable fiber installation for use with FOAD that has not been fully explored. OptaSense® has supplied the cross references shown in Table 1 below, which highlight the versatility and suitability of FOAD systems per fiber installation method.

Table 1. Fiber Installation Method and FOAD Versatility (Piran, W., and Richard, M., 2015)

Application	Direct Buried	Buried in ducting	Deployed in concrete trough
Third Party Intrusion	Yes	Yes	Yes*
Rock Fall	Yes	Yes	Yes
Train Tracking	Yes	Yes	Yes
Cable Theft	N/A	Yes	Yes
Development Application	**Direct Buried**	**Buried in ducting**	**Deployed in concrete trough**
Rail Break	Yes	Yes	Yes
Wheel Flats	Yes	Yes	Yes

** Only applicable to activities directly on or adjacent to the trough.*

4. Potential Application of FOAD Technology in the Railroad Industry

The application of FOAD technology in the railroad industry has the potential to replace, or at least supplement, several existing systems. One of the initial tasks of the FOAD task force was to identify and prioritize the potential applications to better focus further research and development efforts of FOAD in the railroad industry. These applications span several categories. In order of importance, as determined by the FOAD task force, the categories are: broken rail detection, train tracking, equipment health, track integrity, security, and environmental hazards.

4.1 Broken Rail Detection

Broken rails present a significant safety hazard and financial cost to the railroad industry, as they are the primary cause for derailments in North America (Barkan, C. P.L., Rapik Saat, M., and Xiang, L., 2012). According to the FRA, from 2006 to 2015, the total cost to the industry of derailments due to broken rails was $519,717,218 (Administration, n.d.). Having a reliable broken rail detection system is vital to the railroads. Although there are currently methods for detecting broken rails already used throughout the industry, FOAD may have the potential to provide this capability and provide additional advantages.

Broken rails produce acoustic signals detectable by FOAD as a train passes over the broken section of rail. The impact of wheels on the broken region is the source of an impulse signal that can be detectable by FOAD. This makes it possible to detect and alarm on broken rails as they occur under a train.

The current technology used to detect broken rails is the track circuit, which was invented in 1872 by William Robinson to determine whether or not a train occupied a section of rail (American Association of Railroads, 1922). Without a train present, the rails have a strong, consistent current running through them that can be observed remotely. However, once a train enters the track circuit, the current is diverted by the wheels and axles and the system is short circuited. This current can be monitored and information transmitted to the locomotive engineer by signal and/or digitally, using Positive Train Control (PTC) technology.

Track circuits can often detect if a rail is broken, because the current will be interrupted by the discontinuity of the rail. Although this technology has been established and practiced for a long period of time and is considered one of the most reliable safety systems in the railroad industry, it still has several limitations that may be overcome by FOAD. In order to maintain the current in the ideal range without much variation, all equipment must be in good working condition. The rail and ballast must both be sufficiently clean. If the ballast has excessive moisture and/or is fouled, then the resistance in the material may be too low. Thus, the system may be compromised and will not perform as expected (Kumar, U., and Patra, A. P., 2010).

In order for the track circuit to detect a broken rail, there must be a discontinuity in the circuit. Some broken rails do not create discontinuities. For example, some transverse fissures do not create gaps in the rail. The broken ends of the rail in these cases remain in contact and thus maintain the continuity of the circuit, see Figure 19 for an example of a transverse fissure.

Figure 19. Transverse Fissure

It is also possible for a broken rail to occur over a tie plate or a joint bar where there may be a separation of the rail but the continuity of the circuit is maintained through the tie plate or joint bar.

Finally, there are certain areas on a track that are simply not covered by track circuits for broken rail detection. For instance, in order to maintain continuity across a moveable point frog, that area of the track is bypassed by the circuit creating a "dead" section in the rail. The circuit is not capable of detecting a broken rail in these sections.

In each of the above cases, the FOAD system is not limited in the same way as the track circuit, and is capable of detecting broken rails in each case.

Other problems that arise with track circuits include false alarms, broken insulated joints, and equipment malfunctions. Insulated joints are small, special sections of the rail that provide electrical isolation and separate the track into individual electrically isolated blocks for monitoring. Though necessary for the track circuit system, they typically have a relatively low lifespan for high tonnage traffic areas (~500 MGT) (Akhtar, M., and Davis, D., 2010).

Another enhancement of broken rail detection provided by FOAD over track circuits is precision, both spatial and temporal. Due to the nature of track circuits, it is only possible to detect that a rail break has occurred somewhere within the block that the circuit spans. It cannot determine where in the block the break occurred, and track circuits are typically over a mile (5,280 ft.) in length. The spatial resolution of FOAD is limited to the pulse width of the light emitted by the laser traveling through the fiber optic cable. Currently, this resolution for broken rail detection ranges approximately from 6.6 feet to 65.6 feet.

The temporal resolution of FOAD is limited to the rate at which the laser is pulsed. This resolution is on the order of thousandths of a second. Therefore, it is theoretically possible for FOAD to detect a broken rail to within about 32.8 ft. of accuracy and fractions of a second from the time it occurred. Further development of FOAD technology for detection of broken rails is required to ensure the system does not produce an unacceptable number of false alarms. The ability to detect the specific location of a rail break makes FOAD technology of particular interest for moving block train control in the future.

In addition to broken rail signals caused from the interaction of the wheel with the broken region of the rail, broken rails caused by thermal contraction or expansion need to be considered as well. When a broken rail of this type occurs, it is very likely that it will rapidly release a significant amount of energy in the form of an acoustic wave. Though significant effort may be required to characterize the signal produced by this type of break, it is still unclear as to whether or not FOAD can detect an event of this nature. To date, the only research and development that has been conducted concerning broken rails are those under a moving train. The limitations of a track circuit to detect an event of this type are the same as those mentioned above, concerning circuit continuity.

FOAD does have its own limitations when it comes to broken rail detection. If, for some reason, the wheel impacts do not result in a significant acoustic signal, it may not be possible for a FOAD system to detect it. Another issue can arise from track structures, for example, level crossings and frogs that normally produce wheel impacts; a signal of an actual broken rail that occurs at these locations can possibly be masked by the signal produced from these track structures.

FOAD also uses an event-based detection methodology, as opposed to the status-based detection methodology of track circuits, which may result in certain limitations. FOAD is designed to detect the event of the rail breaking, but not to constantly monitor the condition of the rail, as track circuits do. If, for some reason, the event is not detected, FOAD would not recognize a rail break that otherwise may be detected by a track circuit.

Finally, track circuits perform functions aside from detecting broken rails, such as a means for track signaling; they perform a vital function, and are designed to be fail-safe. Ongoing research efforts continue for the possible use of FOAD to perform the other functions currently provided by track circuits.

4.2 Train Tracking

Receiving accurate, real time or near real time information on train location and speed is invaluable to the railroads. Having confidence in knowing the location and speed of the train allows dispatchers to maximize traffic efficiency, recognizing that improvements in capacity will be limited by the train control system in place.

A moving train produces significant acoustic signals, primarily from the wheels rolling on the rail. These signals allow for the determination of the head and rear of the train with an accuracy ranging from 6.6 feet to 65.6 feet in near real time. With an increased awareness of train presence and location on track, more trains may be allowed to move at minimum safe braking distances. This capability could also reduce the amount of stopping and starting of trains. As mentioned previously, improvements to capacity will be limited by train control systems. Current track circuit technology does not provide these capabilities. At best, a track circuit can only provide information on which circuits are being shunted by the axles of the train. This provides limited information about the general location and direction of travel.

There are some FOAD limitations when it is applied to train tracking. First, unless the train is moving it does not produce an acoustic signal. This could be overcome by tracking the train's history of movement. Secondly, there is some uncertainty in accurately locating the first and last axle of the train due to pulse width resolution and the acoustic waves produced by the train, traveling ahead and behind the train, as it traverses the track. More significantly is the limitation of FOAD in its ability to discriminate track occupancy in multiple track territory. The system is essentially a spatially one-dimensional sensor. In other words, it is capable of detecting acoustic signal arriving at the fiber optic cable along its length. With only one fiber and no prior knowledge of the signal source, the ability of FOAD to determine how far away the signal originated from the fiber is unreliable. For this reason, FOAD cannot yet, on its own, reliably discriminate track occupancy of trains in multiple track territory, and it is not currently a fail-safe system. As FOAD technology is enhanced, these capabilities may be possible.

4.3 Equipment Health

FOAD has the potential to monitor and detect a variety of rail equipment defects. Perhaps some of the most critical components of vehicles that need to be monitored closely are wheels. Damaged wheels can lead to further vehicle and cargo damage and possibly even derailment, as well as damage to the track. Flat wheel and out of round wheels are perhaps the most common defect that cause repetitive impacts between the wheel and the rail as the train travels on the track. These impacts can damage the rail as well as the vehicle. If left undetected, the wheel can completely break, causing a derailment. The impacts produced are significant impulsive acoustic signals that are detectable by a FOAD system.

The current technology used as the standard for detecting and measuring wheel impacts is the WILD. In the 1980s, use of WILD among railroads was beginning and in 1993, and then again in 2004, condemnable values were established in the *Field Manual of the AAR Interchange Rules* specifically for the readings made on wayside detectors, such as WILD (Ackerman, N. A., 1987) (Association of American Railroads, 2016). Four levels of increasing degree were established for which a wheel can be condemned. These levels are dictated by the amount of force, measured in kilo pounds (referred to as kips), the wheel puts on the rail, with higher kip measurements indicating a more severe wheel condition. There are various types of WILD detectors, such as: strain gages, load shank measurements or strain bars, and accelerometers.

The WILD is effective at detecting flat wheels and measuring their impacts (Wiley, R.B., and Elsaleiby, A., 2012). It can provide an impact measurement for each wheel in the train consist. However, it is effectively a point sensor, as it is installed at a single site and can only measure impacts at that specific location. There is not a standard recommended distance between WILD systems, but there are currently ~177 systems in the United States monitoring 1.5 million cars of the fleet of 1.8 million cars. A wheel may travel thousands of miles between WILD sites, leaving the potential for further damage to occur without detection. Multiple passes of a wheel through a WILD site may be needed to increase the probability of an optimum measurement opportunity, i.e., to measure the maximum potential impact force caused by the wheel defect. A WILD makes 16 measurements of a wheel as it passes through a WILD site. It is possible that the location on the wheel that results in the greatest impact force may pass through a WILD site and impact in between the measurement sensors. By providing continuous monitoring and measurements of wheel impacts over multiple miles, FOAD may have the potential opportunity to measure the maximum potential impact force of a wheel defect more quickly than WILD.

Conversely, one FOAD sensor can offer coverage up to approximately 24.9 miles (40 km). A network of FOAD sensors can offer coverage for an entire rail network. Unfortunately, the current capability of FOAD to locate the defective wheel within the train is unpredictable due to the same challenges mentioned in Section 4.2, concerning locating the first and last axle of the train, and track discrimination. It may not provide cost benefit to railroads to replace current WILD systems with FOAD; however, FOAD may be able to replace the existing WILD systems as they the reach the end of their life cycle, or FOAD may supplement the current WILD systems along regions of rail that are currently not monitored.

Dragging equipment is also a concern for the railroads. Depending upon the equipment that is dragging, the consequences can be catastrophic. Dragging equipment can possibly damage the track and even cause derailments. If the dragging equipment produces acoustics that significantly differ from that of the general signal of the train, it is possible that a FOAD interrogator can detect this. As with flat and out of round wheels, the current technology for detecting dragging equipment is a point sensor whereas FOAD could potentially detect dragging equipment across a network.

Another possibility for FOAD concerning equipment health is the possibility of monitoring the condition of wheel bearings. Given the relatively “quiet” signal produced by defective bearings, it is unlikely that FOAD can detect this with a buried fiber installation. In order for technology to be used in this application, if at all, it is very likely that there will need to be a special configuration of the fiber bringing it closer to the bearings and allowing it to receive the signal with greater strength.

4.4 Track Integrity

The sensitivity of a FOAD interrogator provides a unique opportunity to remotely monitor track conditions. As the train passes over the track there are many track defects that produce many signals with an amplitude high enough above normal signals produced by that of the train for a FOAD interrogator to discriminate. Among the potential defects detectable by a FOAD interrogator are:

- Broken ties and loose ties
- Ballast degradation causing “pumping” and “hanging” ties
- Broken and loose tie plates
- Loose and missing joint bars
- Rail defects, including
  - Pitting
  - Shelling
  - Cracking
  - Deteriorating welds
  - Crushed head
- Thermal misalignment

Based on the results from data collection and analysis, all of these defects produce a detectable signal within the fiber. Some signals are unique while others are very similar to one another. It may be possible that a FOAD interrogator will be able to show how these defects deteriorate over time by assuming that, as the defect progresses, its signal is likely to change over time as well. However, the current analysis and results have been anecdotal and suggest the need for further research into this capability. Significant data collection and testing will be required to develop the capability to discriminate between specific track degradation events such as those listed above.

4.5 Security

Railroads cover vast distances occupying significant property. Managing the security of this property is a significant task. FOAD can provide another tool to do this, as it has already proven security applications used by the military. It can easily provide intrusion detection along a railway, especially in remote locations where there is very little ambient activity. The technology has already been applied on foreign railways for security purposes as well (OptaSense®, 2014). FOAD is capable of discriminating between a person walking, running, digging, and even cutting through cabling (Fotech Solutions, 2012).

4.6 Environmental Hazards

Environmental hazards pose a significant risk to the railroads. They are unpredictable and can result in significant delays and damage. In mountainous terrain, rock fall is a serious concern. Rock fall has the potential to completely destroy large sections of track. In areas prone to flash flooding, track structure can be washed away or become dangerously unstable.

The conventional system used for detection of rock falls is a slide fence consisting of parallel wires, varying in design on the basis of the characteristics of the slopes being monitored. The parallel wires form a circuit that is integrated into the signal system, and when the fence is hit from a rock fall, the circuit is opened resulting in a restrictive indication for the section of track governed by the signal. Once the slide fence has been activated, it must be repaired by maintenance personnel in order to resume normal traffic flow and to display a less restrictive signal. Repair is often time consuming and can be difficult for the more complicated fence designs. These significant disadvantages led BNSF to consider potential alternatives to the traditional slide fence technology (Akkerman, J., and Prahl, F., 2013).

A major advantage to using FOAD for rock fall detection is that the system does not have to be repaired once activated, which in turn, reduces exposure of maintenance personnel to trackside hazards. During 2012, the BNSF and OptaSense® team, previously discussed in Section 2.3, gathered and analyzed data from rock fall drop testing, and from naturally occurring rock falls along the monitored section of track. The detection algorithms were adjusted to reduce false alarms. By January 2013, the system had a 95 percent probability of detecting rock fall activity with an average of one false alarm per day, except during seasonal changes when more false alarms were activated. The original goal for the system was to achieve a 95 percent probability of detection with a maximum of five false alarms per day (Akkerman, J., and Prahl, F., 2013).

Other environmental hazards, such as farm machinery causing obstruction or damage to the track, or herds of animals obstructing the track, could potentially be detected with FOAD.

5. Cost Driver Comparison of FOAD to WILD Systems and Track Circuits

The growing interest and research into the potential capabilities of FOAD in the rail industry has spurred the need for a first-order comparison of the cost drivers of FOAD to the cost drivers of existing systems performing functions that would be well-suited to FOAD. The use of FOAD for detecting rail breaks, train presence, and flat wheels, has been an area of high interest in the railroad industry, as well as research and development, and demonstrated prospective capabilities of the technology in railroad applications, as described in Section 2. Today, track circuits provide train presence and rail break detection, while WILD provides detection of wheel impacts.

Though the use of FOAD in the future may include improvements to efficiency in train movements, through greater accuracy of train monitoring, this study does not suggest that FOAD could currently replace track signaling systems or that it is a fail-safe system. As future developments and research with FOAD unfold, its capabilities will be better understood. Along sections of railroads without track circuits and WILD detectors, with continued development, FOAD has the potential to provide a more economical option for monitoring train presence, broken rails, and wheel impacts, than the installation of the current systems. As development of FOAD continues, the installation of a FOAD system may provide additional safety features and functions, such as detection of rock falls and/or dragging equipment. Under this project, a high-level comparison of the cost drivers of two existing systems, track circuits and WILD systems, are compared to the cost drivers associated with a FOAD system.

The following surveys were generated, disseminated, and used to gather information from the applicable party to determine current cost drivers of each system:

- Railroad Survey to gather information on installation and yearly maintenance costs associated with track circuits and WILD systems. See Appendix A.
- FOAD Vendor Survey to gather information on installation and yearly maintenance costs associated with a FOAD system. See Appendix A.
- Fiber Optic Cable Installation Company Survey and yearly maintenance costs associated with installation of fiber optic cable. See Appendix A.

Survey respondents represented by the FOAD task force included a subset of the following railroads: CP, CN, UP, NS, BNSF, CSX, and Amtrak. The railroads are competitors, and the data provided by each railroad contained confidential cost information. The manner for presenting the data was approved by the AAR and participating railroads, and is intended to maintain confidentiality of the data provided by the railroads, yet provide meaningful comparisons of the costs associated with FOAD and existing non-FOAD systems providing a similar railroad functions.

In subsequent sections, the cost information reported on the surveys for installation and yearly maintenance and inspections of track circuits and WILD systems are individually compared to similar costs associated with FOAD. In 2009, Cambridge Systematics studied the costs associated with wayside detectors and generated the report for TTCI titled *Post-Audit of Wayside Detector Costs and Benefits*. This report provides an additional source of cost driver information for WILD systems that were used in the cost comparisons (Aeppli, A., Little, P., and Robert, W., 2009). Per the survey responses, 15 years is reportedly the average expected life span of the WILD and the FOAD interrogator units. This was used for comparing the accumulated costs due to installation, maintenance and inspection, of all systems over time. The costs of FOAD are expressed as a percent difference from the costs of the existing systems. Note that a formal cost benefit analysis was not conducted. The following results use a high-level comparison of the cost driver information for each system that was gathered from the survey results.

5.1 FOAD Cost Drivers

The two key components associated with FOAD installation are: (1) the FOAD interrogator unit and (2) the fiber optic cable, which also comprise the majority of the installation costs. The reported FOAD yearly maintenance and inspection costs include software updates, warranty and technical support, periodic verification and adjustment of system calibration, and associated labor costs. As the use of FOAD in the railroad environment matures, these costs may decrease.

5.1.1 Fiber Optic Cable Installation Costs

Several fiber installation companies were contacted to obtain pricing estimates for installation of fiber in various soil types; four responses were received. The average cost of direct bury installation of fiber optic cable is between $36,000 to $45,000 per mile, and increases 20 percent on average for installation in a gravel/rock and dirt mix. Cost increases further for installation in rock and along special structures, such as bridges, tunnels and across swamps.

Typically, FOAD can be used to monitor a 24.9-mile (40 km) section of track per detection site. For the cost comparison, a typical installation rate of $36,000 to $45,000 per mile from the companies surveyed for direct buried cable in dirt was assumed to calculate the fiber optic cable installation costs along 24.9 miles (40 km).

5.1.2 FOAD Interrogator Cost

FOAD interrogator units and installation costs were gathered from two competing vendors. To protect this confidential pricing information, at the request of the vendors, the average cost is not reported directly, but is used for the cost comparison to WILD systems and track circuits in the following sections.

5.1.3 Track Circuit Cost Drivers

Two railroads responded to the survey with information about the installation cost of track circuits, as well as estimated yearly maintenance and inspection costs. Table 2 shows the percent difference of FOAD cost drivers, including the installation costs of fiber optic cable, compared to the cost drivers of track circuits for 24.9 miles (40 km). The first column compares approximate installation costs only and the second column compares the combined installation, maintenance, and inspection costs of FOAD with track circuits, over 15 years. The last two columns do the same, but without fiber optic cable installation costs considered. Data marked with a dash represents information that was not reported. Negative percentages shown in the tables in the following sections indicate cost savings associated with FOAD, while positive percentages indicate FOAD costs greater than the system(s) to which it is being compared.

Table 2. Track Circuit Versus FOAD Approximate Cost Comparison per 24.9 Miles (40 km)

Relative percent cost increase (+) or decrease (-) of FOAD cost drivers compared to track circuit cost drivers $\left(\frac{FOAD - TRK}{TRK}\right) \times 100$	**Including Costs to Install Fiber along Track**		**Without Costs to Install Fiber. Use Existing Fiber Along Track**	
	System Installation Only	**Combined Install/ Maintain/ Inspect Costs over 15 years**	**System Installation Only**	**Combined Install/ Maintain/ Inspect Costs over 15 years**
Source 1	74%	91%	-71%	-26%
Source 2	-4%	27%	-84%	-51%
Source 3	-	-	-	-
Source 4	-	-	-	-
Source 5	-	-	-	-
Source 6	1%	-	-83%	-

** Negative percentages shown in the table indicate the percent decrease of FOAD costs compared to similar track circuit costs. The positive percentages show the percent increase of FOAD costs compared to similar track circuit costs. **Further research and development of FOAD, and possibly combining FOAD with other technologies will be required in order for it to fully replace the functionality of the systems to which it is being compared.*

In Table 2, column 1, it can be seen that the expected installation costs for FOAD, including fiber optic cable installation costs, compared to the installation costs associated with track circuits varies significantly. The percent difference in costs ranges from FOAD installation costs being four percent less and up to 74 percent higher than track circuit installation cost.

When comparing installation costs of FOAD to track circuit costs along sections of track in which existing fiber optic cable can be used, the variation in the percent difference of cost is narrower, ranging from FOAD costs being 71 percent less to 84 percent less than track circuits, see the third column of values in Table 3. Similarly, in column 4, the percent difference between FOAD and track circuit costs for installation, maintenance and inspection over 15 years, when existing fiber optic cable can be used, ranges from FOAD being 26 percent less to 51 percent less. The decreased variation in percent differences in columns 3 and 4, as well as the consistent negative percentages, may indicate a stronger potential for FOAD to provide cost benefit to railroads along sections of track with existing fiber optic cable that do not currently have track circuits deployed, or in which the track circuits need to be replaced. Note that FOAD has not currently been shown to be fail-safe; it cannot at this time replace all track circuit functionality in most applications.

Track circuit installation costs vary significantly, and can be observed in the variations shown in column 1 of Table 2. Reported yearly maintenance and inspection costs of track circuits are primarily labor costs, and are not significant when compared to the initial installation costs. However, the yearly maintenance and inspection costs associated with FOAD are more substantial. This is reflected by the relative increase of FOAD costs when comparing the percent differences for installation, maintenance and inspection costs (shown in columns 2 and 4) to the respective installation costs only (columns 1 and 3). Track circuit maintenance and inspection items that were included in the analysis were limited to what was reported on the surveys, and included inspection of all associated track structure and electrical testing of components, but does not include quarterly circuit calibration, insulated joint maintenance/replacement, or cable repair/replacement.

5.2 WILD Cost Drivers

Various options can be included in WILD systems, such as truck hunting detection, and can influence the cost of the system. Additionally, installation cost can depend on the condition of the location, for example, subgrade remediation and/or improvements to the available communications may be required. A WILD system monitors wheel impacts at a single location, and typically there are several hundred miles between WILD systems. For the purposes of this comparison, the costs of a single WILD system are compared to the costs of a typical FOAD system which monitors 24.9 miles (40 km) of track.

Five railroads responded with installation, and yearly maintenance and inspection costs for installed WILD systems. Values from the cited report *Post-Audit of Wayside Detector Costs and Benefits* are included as a sixth source (Aeppli, A., Little, P., and Robert, W., 2009). Some of the sources reported a range of costs or different levels of cost detail, for installation and/or for yearly inspection and maintenance. For the purposes of this comparison, these values were averaged for each source.

Table 3 shows the percent difference of FOAD cost drivers, including installation costs of fiber optic cable, compared to the cost drivers of a WILD system. The first column compares installation costs only and the second column compares the combined installation, maintenance, and inspection costs of FOAD with WILD over 15 years. The third and fourth columns provide the same comparison, but without fiber cable installation costs considered.

Table 3. WILD Versus FOAD Approximate Cost Comparison per 24.9 Miles (40 km)

Relative percent cost increase (+) or decrease (-) of FOAD cost drivers compared to WILD cost drivers. $\left(\frac{FOAD - WILD}{WILD}\right) \times 100$	**Including Costs to Install Fiber along Track**		**Without Costs to Install Fiber. Use Existing Fiber Along Track**	
	System Installation Only	**Combined Install/ Maintain/ Inspect Costs over 15 years.**	**System Installation Only**	**Combined Install/ Maintain/ Inspect Costs over 15 years.**
Source 1	112%	98%	-65%	-23%
Source 2	25%	65%	-79%	-36%
Source 3	111%	105%	-65%	-21%
Source 4	-26%	-48%	-88%	-80%
Source 5	98%	105%	-67%	-21%
Source 6	96%	96%	-67%	-24%

* *Negative percentages shown in the table indicate the percent decrease of FOAD costs compared to similar WILD costs. The positive percentages show the percent increase of FOAD costs compared to similar WILD costs.*
***Further research and development of FOAD, and possibly combining FOAD with other technologies will be required in order for it to fully replace the functionality of the systems to which it is being compared.*

It can be seen from Table 3, that the expected installation costs for FOAD, including fiber optic cable installation costs, compared to the installation costs associated with WILD systems varies significantly. The percent difference in costs ranges from FOAD installation costs being 26 percent less to 112 percent higher than WILD installation costs.

However, when comparing installation costs of FOAD to WILD costs along sections of track in which existing fiber optic cable can be used, the variation in the percent difference of cost is narrower, ranging from FOAD costs being 65 percent less to 88 percent less than WILD systems, see the third column of values in Table 3. Similarly, in column 4, the percent difference between FOAD and WILD costs for installation, maintenance, and inspection over 15 year ranges from FOAD being 21 percent less to 81 percent less. The decreased variation in percent differences in columns 3 and 4, as well as the consistent negative percentages, indicate a stronger potential for FOAD to provide cost benefit to railroads along sections of track with existing fiber optic cable that do not currently have WILD systems deployed, or in which the existing WILD systems have reached the end of their life cycle and require replacement.

Maintenance and inspection items reported on the surveys for WILD systems included inspection and testing as needed, of the RF antennas, talker circuit, and surge protector. Repairs are completed as needed, and/or the equipment is recalibrated.

5.3 Multiple System Cost Driver Comparison – FOAD System Versus WILD System and Track Circuits

The potential cost-saving benefits of FOAD are strengthened by its possible use for more than one application in the railroad industry. In the sections above, the installation costs of FOAD were individually compared to the installation costs of WILD systems and track circuits. Table 4 shows percent differences of FOAD installation costs compared to the combined costs for track circuits and WILD systems. Similar to the results reported in Table 2 and Table 3, the first and second column include the approximate costs associated with fiber optic cable installation, while the third and fourth column on the right provide a comparison of costs for track with existing fiber optic cable ready for use with a FOAD interrogator.

Table 4. Combined Track Circuits and WILD Versus FOAD Approximate Cost Comparison per 24.9 Miles (40 km)

Relative percent cost increase (+) or decrease (-) of FOAD cost drivers compared to WILD and track circuit cost drivers $\left(\frac{FOAD - (WILD + TRK)}{(WILD + TRK)}\right) \times 100$	Including Costs to Install Fiber along Track		Without Costs to Install Fiber. Use Existing Fiber Along Track	
	System Installation Only	Combined Install/ Maintain/ Inspect Costs over 15 years	System Installation Only	Combined Install/ Maintain/ Inspect Costs over 15 years
Source 1	-4%	-3%	-84%	-62%
Source 2	-46%	-28%	-91%	-72%
Source 3	-	-	-	-
Source 4	-	-	-	-
Source 5	-	-	-	-
Source 6	-33%	-	-89%	-

** Negative percentages shown in the table indicate the percent decrease of FOAD costs compared to combined WILD and track circuit costs. The positive percentages show the percent increase of FOAD costs compared to combined WILD and track circuit costs. **Further research and development of FOAD, and possibly combining FOAD with other technologies will be required in order for it to fully replace the functionality of the systems to which it is being compared.*

The first column of values in Table 4 shows that the expected installation costs for FOAD, including fiber optic cable installation costs, compared to the combined installation costs associated with WILD systems and track circuits, ranges from FOAD being 4 percent less to 46 percent less. The variation in the percent differences of installation costs, when including fiber optic cable installation costs, is narrower when FOAD is considered to replace two existing systems: track circuits and WILD systems. This can be observed in the range of values displayed in the first columns of Table 2 and Table 3, compared to Table 4.

A comparison of the combined installation, maintenance, and inspection costs over 15 years of FOAD to the similar combined costs for both WILD systems and track circuits, along sections of track in which existing fiber optic cable can be used is shown in column 4 of Table 4. The variation in the percent difference of costs is narrower, ranging from FOAD costs being 62 percent less to 72 percent less than the combined WILD and track circuit costs. The consistent negative percentages seen in Table 4 indicate a stronger potential for FOAD to provide cost benefits to railroads along sections of track that do not currently have WILD systems or track circuits deployed.

The range of costs shown in Table 2, Table 3, and Table 4 indicates that there are many factors that affect the installation, maintenance, and inspection costs associated with each system. The consistent relatively lower cost of FOAD compared to the costs of existing systems, indicated by the negative percentages shown in columns 3 and 4 of each table, shows the technology has the potential to provide a cost benefit to the railroads of North America. Though the functionality of FOAD does not directly compare to the functionality of the technologies to which it is being compared, further research and development may lead to it becoming a viable choice in place of the technologies to which it is being compared. Alternatively, FOAD could possibly supplement or replace existing systems with the potential for providing enhanced future functionality.

A visual representation of the accumulated costs associated with FOAD over 15 years, compared to the combined costs associated with WILD and track circuits, is shown in Figure 20.

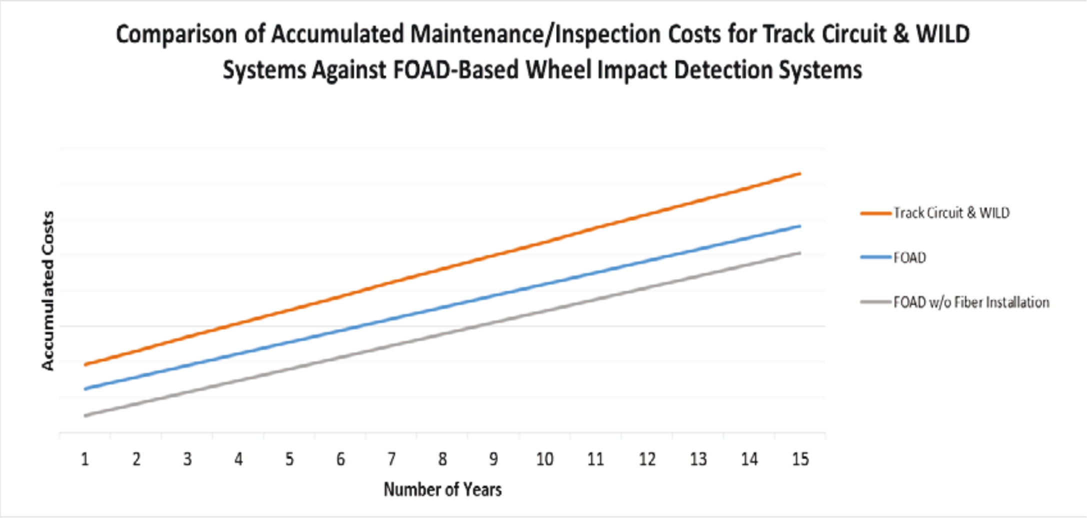


Figure 20. Comparison of Average Costs Over 15 Years

The plot shown in Figure 20 was generated by averaging the reported values for installation, and yearly maintenance and inspection costs for each of the three systems: FOAD, track circuits, and WILD. The units on the vertical axis were intentionally removed to ensure anonymity of railroad data.

This high-level cost comparison indicates there is potential for cost savings if future development of FOAD technology could result in the deployment of FOAD to be used for multiple functions, such as the detection of high impact wheels, train presence, and broken rail, along sections of track that do not have existing systems in place. The possibility of FOAD to be used for additional railroad applications could result in the potential for further cost advantages by reducing costs associated with the installation, maintenance, and inspection of multiple independent current technologies.

5.4 Capability Comparison

Along with the high-level cost comparison between FOAD and competing technologies like WILD and track circuits, it is also important to keep in context the capabilities for each of these systems. Table 5 and Table 6 provide comparisons of current basic capabilities between the respective systems.

Table 5. Capability Comparison of FOAD Versus Track Circuits

Current Capability	FOAD	Track Circuits
Open Circuit Broken Rail Detection	Yes	Yes
Closed Circuit Broken Rail Detection	Yes	No
Detect Broken Rails as they Occur Under a Train	Yes	No
Detect Open Circuit Thermal Breaks ("Pull Aparts")	No	Yes
Detect Broken Rails to within 20 meters of accuracy	Yes	No
Train Tracking	Yes	Yes
Compatible with Signal Systems	No	Yes
Fail-Safe	No	Yes

As mentioned in Section 4, there are different types of broken rails to consider when determining broken rail detection capabilities. Open circuit broken rails refer to those that physically open the track circuit causing a discontinuity, whereas closed circuit broken rails are those which do not, like the one pictured in Figure 19. Currently, it is also not proven if FOAD can detect "Pull Aparts." FOAD is not currently compatible with the signal systems and is not a fail-safe system, however, it may be possible with future research and development.

Table 6. Capability Comparison of FOAD Versus WILD

Current Capability	FOAD	WILD
Detect High Impact Wheels	Yes	Yes
Classify High Impact Wheels	Yes	Yes
Continuous Track Coverage	Yes	No
Count Axles	No	Yes

For the purposes of detecting and classifying high impact wheels, FOAD has this potential capability wherever there is fiber optic coverage along railroad track, whereas a WILD system is effectively a point sensor. Having continuous coverage provides an increased opportunity to prevent track and vehicle damage. Currently, FOAD is not ready for implementation. One deficiency is its inability to be used for accurately counting axles, which prevents it from being a stand-alone system.

6. Conclusion

Though the use of FOAD in the rail industry is relatively new, its capabilities have been established for security applications for many years. Railroad and FOAD vendors alike have recognized the potential benefits and enhancements the technology may bring to the rail industry. The railroads of North America were surveyed to understand their interest on the application of FOAD technology in the railroad industry and the value they anticipate in further research and development of the technology for railroad use. This resulted in a letter of interest from the railroads, which has been included in Appendix C. The priority applications identified by the FOAD task force focused on broken rail detection, train tracking, monitoring equipment health and track integrity, security, and detection of environmental hazards. The prioritized list of applications is included in Appendix B.

During this project, multiple railroads reported on the extent of their rail network with existing fiber optic cable installed in close proximity to the railroad. The reported percentage of route miles with existing fiber optic cable ranged from less than 1 percent up to 90 percent. The prevalence of existing fiber optic cable reduces the installation costs of FOAD significantly and provides the potential for greater economic value to the railroads. The substantial percentage of the network with existing fiber optic cable presents opportunities for the railroads as they consider implementation of FOAD technology.

The high-level cost drivers of two existing systems, track circuits and WILD systems, were compared to the cost drivers associated with a FOAD system. In this analysis, a comparison of the estimated combined installation, maintenance, and inspection costs over 15 years of FOAD to the similar estimated combined costs for both WILD systems and track circuits was completed for sections of track in which existing fiber optic cable can be used and for sections of track in which existing fiber optic cable cannot be used. For sections of track where existing fiber optic cable can be used, the percent difference in estimated costs ranges from 62 percent less to 72 percent less costs using FOAD than the combined estimated costs of WILD systems and track circuits. For sections of track where existing fiber optic cable cannot be used, the percent difference in costs ranges from 3 percent to 28 percent less costs using FOAD than the combined WILD and track circuit costs. These values assume deployment of FOAD along sections of railroad in which track circuits and WILD systems are not already deployed.

From the research and the high-level cost driver comparisons performed, the development of FOAD for use in railroad applications may provide:

- The potential for cost benefits to the railroads, assuming a single FOAD system may be able to provide several needed functions, along a section of track in which existing technologies are not installed or are in need of replacement. A greater potential for cost savings may result if existing fiber optic cable can be used for the deployment of FOAD systems.
- Enhanced future capabilities compared to the capabilities currently afforded by track circuits and WILD systems.
- Increased safety through the monitoring and detection of hazards associated with the train, track, and environment. Fewer derailments, and/or accidents, due to safety enhancements may also result in additional economic benefits.

- Increased traffic efficiency if a new type of train control could be implemented to use the increased precision of train location with FOAD, as compared to the precision of train tracking currently afforded with track circuits.

Fueled by the vision of the value the technology could bring to the rail industry, testing, research, and implementation of FOAD have increased at TTC and along railroads in several different countries over the last decade. Further development of FOAD is required in order for the technology to be ready for more widespread implementation by North American railroads. Though it is an information-rich system, considerable efforts will be required to develop signal recognition and signal processing algorithms for the system to be made fail-safe for certain applications.

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Appendix A.
Surveys Questions Distributed to Fiber Optic Acoustic Detection (FOAD) Task Force Members

I. Cost Drivers for Non-Fiber Based Systems in the North American Rail Network for Each Railroad

  A. Wheel Impact Load Detectors (WILD)

    1. Total Installation Cost of Single Site Including All Needed Track Work and Enclosures
    2. Total Number of Systems Currently Deployed On Rail Network
    3. Average Yearly Maintenance Cost
    4. Brief Description of Maintenance Required On System
    5. Average Cost of System Inspection and Calibration Annually
    6. Other Comments or Information Available

  B. Track Circuits

    1. Total Installation Cost per Mile Including All Needed Track Work and Enclosures
    2. Total Number of Miles Covered in Rail Network
    3. Average Yearly Maintenance Cost
    4. Brief Description of Maintenance Required On System
    5. Average Cost of System Inspection and Calibration Annually
    6. Other Comments or Information Available

II. Survey of The Existing Fiber Optic Cable Installations in The North American Rail Network for Each Railroad

  A. General Information

    1. Total Mainline Rail Miles in Network

       [Clarified during AAR FOAD Task Force Calls that the request is for *Route Miles]*

    2. Estimated Percentage of Available Single-mode Fiber in Near Proximity to Rail
    3. Average Signal Block Length in Signaled Territory
    4. Signal Protected Track
       a. Total Estimated Miles
       b. Number of Miles with Fiber Cable Installed Near Track
    5. Dark Territory

            a. Total Estimated Miles
            b. Number of Miles with Fiber Cable Installed Near Track
        6. Estimated Miles of Rock Slide Territory
    B. Mainline Track Info
        1. Average Fiber Installation Depth
        2. Average Distance of Fiber from Centerline of Track
        3. Installation Method Direct Buried / Conduit or Both
        4. Number of WILD Sites in Rail Network
        5. Distance Between Fiber Optic Repeater Stations Near Rail
        6. Other Comments or Information Available
    C. Specialized Track Installations (for Bridges, Tunnels, and Water/Swamp)
        1. Number of Bridges or Tunnels in Network, Or Number of Elevated Earth Miles Through Swamp or Water Crossings
        2. Estimated Number of Bridges or Tunnels with Fiber Cable Installed. Or Number of Swamp or Water Crossings with Fiber Cable Installed in Near Proximity to Rail.
        3. General Practice for Installing Fiber (Conduit, Direct Buried or Direct Lay in Water)
        4. Typical Track Structure Composition (Steel, Concrete, Wood)
        5. Typical Track Installation Type in Listed Area of Interest (Ballast, Slab)
        6. Other Comments or Information Available

III. Survey of Cost Drivers for Fiber Based FOAD Interrogator for Each Supplier
    A. Distributed Acoustic Sensor
        1. Total Installation Cost of Single Site FOAD Interrogator Setup and Calibration Only. Does Not Include Buried Fiber.
        2. What Is the Life Expectancy of a FOAD Interrogator System Before It Reaches EOL?
        3. Average Yearly Maintenance of Software. Include Licensing and Updates and Patches.
        4. Average Yearly Maintenance of Hardware. Include Warranty Cost and/or Component Replacements.
        5. Brief Description of Maintenance Required On Systems, If Any.
        6. Average Cost of System Inspection and Calibration Annually.
        7. Other Comments or Information Available.

IV. Survey for Fiber Optic Cable Installation Companies

- A. FO Cable Mainline Installation Cost Information
    1. Average Installation Cost for Dirt/Sand?
    2. Average Installation Cost for Gravel or Rock Dirt Mix?
    3. Average Installation Cost in Rock?
    4. Average Installation Cost?
    5. Average Yearly Maintenance Costs?
    6. What Maintenance Is Typically Required?
    7. Other Pertinent Cost Information
- B. FO Cable Bridge Installation Cost Information (For Bridges, Tunnels, and Swamp)
    1. Installation Technique / Description
    2. Average Installation Cost?
    3. Average Yearly Maintenance Costs?
    4. What Maintenance Is Typically Required?
    5. Other Pertinent Cost Information

Appendix B.
Priority Railroad Applications Determined by the FOAD Task Force

Category	**Application**	**Description**	**Ranking**
Rail breaks	Under train, as train moves over track	Detection of a rail break event as a train passes over the defect.	**1**
Rail breaks	Thermal breaks	Detection of a rail break event caused by thermal conditions in the absence of a train due to metal contraction or expansion	**2**
Tracking movement over railway	Detecting front and rear	Detection and tracking of the HOT and EOT	**3**
Equipment health	Flat wheels	Identification and classification of a defective axle with a flat spot on a moving train	**4**
Tracking movement over railway	Track identification	Determination of the individual track occupancy of a vehicle or train in multitrack territory	**5**
Equipment health	Dragging equipment	Identification of excessive noise caused by a train dragging equipment along the railway	**6**
Tracking movement over railway	Train speed	Accurate and continuous monitoring of the train velocity and acceleration / deceleration	**7**
Train integrity	Train separation	Identification and classification of changes to the length of a train or the "splitting" of a train	**8**
Equipment health	Wheel breaking off	Identification of a rail car wheel breaking loose of the train	**9**
Track integrity	Environmental Washout	Detection and classification of an environmental event compromising the track substructure (floods, washouts)	**10**
Track integrity	Track degradation	Detection and classification of an environmental event compromising the track substructure (floods, washouts)	**11**
Track integrity	Vehicle hitting track (track alignment)	Detection of roadway vehicles or equipment on the wayside impacting track structure and causing buckling	**12**
Wheel – rail interface	Wheel failures	Detect, predict, or prevent wheel failures resulting from angle of attack and tractive effort	**13**
Equipment health	Bearing health (vibration)	Detection and classification of acoustic signatures of failing wheel bearings (Hot box) and identification of the defective axle	**14**

Category	Application	Description	Ranking
Predictive maintenance	Anything that causes a change in the baseline of the track	seismic survey of the track substructure in order to identify changes over time	**15**
Track integrity	Track buckling	Detection and identification of a thermally caused track buckling event due to metal expansion (sun kink)	**16-18**
Track integrity	Thermal misalignment	Thermal misalignment of track due to the build-up of compressive forces in the rail and the inability of the track structure (ballast, ties, and fasteners) to withstand those forces. (Essentially, the track structure lengthens to relieve the stress from compression).	**16-18**
Environment related	Rock fall detection	Detection, location, and alarming of rock falls onto the track	**16-18**

Appendix C.
Supporting Letter for Continued Research and Development Efforts

North American Railroad Letter of Interest

The advent of fiber optic acoustic detection systems (FOADS) provides a unique opportunity for the railroad industry in wayside event detection. This technology is capable of detecting multiple events that are currently being detected by several other independent discreet sensing systems. Having a multipurpose sensing system of this nature represents an opportunity for a significant savings in the cost of installation and maintenance of a distributed rolling stock and track related defect detection system. FOADS may prove to be a better detection system than some of these current systems it could potentially replace, therefore providing an increase in detection capability. Increased capability equates to increased safety as well as additional cost savings. Furthermore, much of the fiber optic network that could be leveraged for FOADS is already in place, as thousands of rail route miles currently have fiber optic cable installed for other purposes.

Currently this technology still needs more research and development to meet its full potential. Nevertheless, this potential has been recognized by the North American rail industry and significant interest exists in guiding its development. Consequently, an Association of American Railroad's Railway Electronics Standards Committee FOADS task force surrounding this technology has been formed to guide the development of technical standards and documentation involving the FOADS use cases, requirements, architecture, communications protocols, and message sets. Additionally, the FOADS task force will explore possible areas in which the use of fiber optic acoustic detection technology can be used for real time and predictive defect detection.

The AAR FOADS Task Force currently has active membership from the Federal Railroad Administration's Office of Research and Development as well as the following North American Railroad Operators:

- Union Pacific Railroad
- BNSF Railway
- Canadian National Railway
- Canadian Pacific Railway
- CSX Transportation
- Amtrak
- Norfolk Southern Railway

Several key suppliers of the fundamental technology enabling FOADS are also active participants in the AAR FOADS Task force including:

- Frauscher Sensor Technology USA Inc.
- Fotech Solution
- OptaSense
- Silixa

Abbreviations and Acronyms

AAR	Association of American Railroads
Amtrak	National Railroad Passenger Corporation
APC	Angle Physical Contact
BNSF	BNSF Railway
CN	Canadian National Railway
CP	Canadian Pacific Railway
CSX	CSX Transportation
DAS	Distributed Acoustic Sensing
FAST	Facility for Accelerated Service Testing
FOAD	Fiber Optic Acoustic Detection
FRA	Federal Railroad Administration
Frauscher	Frauscher Sensor Technology USA, Inc.
FTS	Frauscher Tracking Solution
FTTP	Fiber-to-the-Premises
GPS	Global Positioning System
HAL	Heavy Axle Load
HTL	High Tonnage Loop
KCS	Kansas City Southern Railway
LED	Light-Emitting Diodes
MGT	Million Gross Tons
MTO	Multiple Track Occupancy
NS	Norfolk Southern Corporation
PTC	Positive Train Control
RESC	Railway Electronics Standards Committee
RTT	Railroad Test Track
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
TTT	Transit Test Track
UP	Union Pacific Railroad
UPC	Ultra Physical Contact
VCSEL	Vertical-Cavity Surface-Emitting Lasers

WILD	Wheel Impact Load Detector