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Transportation Technology Center, Inc. (TTCI) conducted a baseline fiber optic broken rail detection evaluation on the High Tonnage Loop (HTL). Three different Distributed Acoustic Sensing (DAS) systems were evaluated to show the current state of broken rail detection using DAS systems. Results of the evaluation and a comparison between DAS systems and conventional track circuits identified areas of needed improvement and maturity for DAS systems to be a viable option for train tracking and broken rail detection. Some areas of improvement include increased accuracy of broken rail detection and decreased rate of false alarms.

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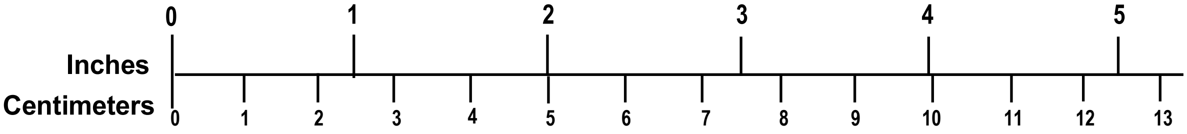
METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC			METRIC TO ENGLISH		
LENGTH (APPROXIMATE)			**LENGTH** (APPROXIMATE)		
1 inch (in)	=	2.5 centimeters (cm)	1 millimeter (mm)	=	0.04 inch (in)
1 foot (ft)	=	30 centimeters (cm)	1 centimeter (cm)	=	0.4 inch (in)
1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
1 mile (mi)	=	1.6 kilometers (km)	1 meter (m)	=	1.1 yards (yd)
			1 kilometer (km)	=	0.6 mile (mi)
AREA (APPROXIMATE)			**AREA** (APPROXIMATE)		
1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)	1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)			
MASS - WEIGHT (APPROXIMATE)			**MASS - WEIGHT** (APPROXIMATE)		
1 ounce (oz)	=	28 grams (gm)	1 gram (gm)	=	0.036 ounce (oz)
1 pound (lb)	=	0.45 kilogram (kg)	1 kilogram (kg)	=	2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)	1 tonne (t)	=	1,000 kilograms (kg)
				=	1.1 short tons
VOLUME (APPROXIMATE)			**VOLUME** (APPROXIMATE)		
1 teaspoon (tsp)	=	5 milliliters (ml)	1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
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 meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)			**TEMPERATURE** (EXACT)		
[(x-32)(5/9)] °F	=	y °C	[(9/5) y + 32] °C	=	x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

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

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

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Transportation Technology Center, Inc. (TTCI) would like to acknowledge the fiber optic vendors that participated in this project. They supplied their Distributed Acoustic Sensing (DAS) systems, as well as installed and calibrated them to the fiber optic test bed at the Transportation Technology Center (TTC), started and stopped data collection during test days, and supported the evaluation of their systems throughout the project.

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Executive Summary

Transportation Technology Center, Inc. (TTCI), under contract to the Federal Railroad Administration (FRA), completed a baseline broken rail detection evaluation on three fiber optic Distributed Acoustic Sensing (DAS) systems. This evaluation was conducted from May 7, 2015, to January 16, 2018. The DAS systems were tested using the fiber optic test bed on the High Tonnage Loop (HTL) at the Transportation Technology Center (TTC) during normal Facility for Accelerated Service Testing (FAST) operations. Two of the DAS systems (DAS 2000 and DAS 2005) were 5 km systems covering one loop of the HTL and the third DAS system (DAS 2003) was a 40-km system covering three loops of the HTL. The evaluation provided results of the broken rail detection capabilities for each system.

In addition to the evaluation completed during normal FAST operations, a 1-week test using a similar FAST consist was conducted to test operations at different operating speeds, with high impact wheels and different size rail gaps at a rail joint. This testing showed that rail gaps do not seem to introduce additional false alarms. However, testing at varying speeds did show that DAS 2000 had trouble tracking trains at lower speeds, and the testing at varying speeds and with high impact wheels appears to increase the false alarm rates for DAS 2003 and DAS 2005.

The baseline evaluation of the DAS systems shows that improvement is needed in both the rail break detection accuracy and the reduction of false alarms, as well as improvement in performance at lower speeds. Raw data from each DAS system throughout the evaluation is available for playback testing of future improvements to the systems.

A comparison between conventional track circuits and DAS systems was completed to determine if DAS systems can perform all functions of track circuits and, if not, what modifications would need to be made to do so. The results of the comparison indicate that DAS systems need to be improved upon as stand-alone systems, or combined with additional technologies, for functions such as track discrimination, precise location determination, recovery from system reboots or power outages, and train tracking at lower speeds. Additional testing with DAS systems would also be needed to determine how the system operates with other train types and track equipment, as well as multiple trains running across parallel tracks. Additional functions that DAS systems may be able to perform that conventional track circuits cannot, are train tracking within a signal block or approaching grade crossings, high impact wheel detection, slide fence detection, monitoring track structure, and trespassing detection.

It is recommended that DAS systems be installed on single track territories or dark territories and be tested/monitored by vendors to improve rail break detection while showcasing some of the other benefits that DAS systems can provide. Additional testing can be conducted at the Transportation Technology Center once the systems have matured, and the results of that testing can be compared to these baselined systems.

1. Introduction

This report describes the testing and analysis that Transportation Technology Center, Inc. (TTCI) completed, under contract to the Federal Railroad Administration (FRA), to evaluate fiber optic Distributed Acoustic Sensing (DAS) broken rail detection systems from May 7, 2015, to January 16, 2018. The report also summarizes a comparison between conventional track circuits and DAS systems to help determine the feasibility of DAS systems performing functions of conventional track circuits.

The broken rail detection testing used the fiber optic test bed previously installed on the High Tonnage Loop (HTL) at the Transportation Technology Center (TTC). The HTL fiber optic test bed was configured for 5 km and 40 km DAS broken rail detection systems. DAS systems use single mode fiber optic cable to detect the acoustic signature generated by a moving train, as well as other events of interest, including rail breaks, by picking up vibrations transmitted from the train and track, through the earth, and to the cable.

Testing of the DAS broken rail detection systems was conducted during normal Facility for Accelerated Service Testing (FAST) operations with each system transmitting broken rail alarms over a wired network to a fiber optic back office system installed at TTC. Broken rail alarms included information about the alarm, such as:

- The origin of the fiber system alarm
- The head and tail Global Positioning System (GPS) location of train at time of alarm
- GPS location of the broken rail alarm
- Timestamp data

Using daily FAST logs and DAS reported logs, a baseline evaluation was conducted to determine the current capabilities of DAS broken rail detection systems.

- DAS 2000
    - Approximately 22,426 train miles of testing, including 22 rail breaks
    - FAST track circuits found 13 rail breaks, while DAS 2000 found 8
    - DAS 2000 had 70 false alarms or 0.31 false alarms per 100 train miles
- DAS 2003
    - Approximately 21,794 train miles of testing, including 22 rail breaks
    - FAST track circuits found 14 rail breaks, while DAS 2003 loops 1 and 2 found 4 and loop 3 found 3
    - DAS 2003 loop 1 had 1,370 false positives or 6.29 false alarms per 100 train miles
    - DAS 2003 loop 2 had 1,082 false positives or 4.96 false alarms per 100 train miles
    - DAS 2003 loop 3 had 1,388 false positives or 6.37 false alarms per 100 train miles
- DAS 2005
    - Approximately 22,680 train miles of testing, including 22 rail breaks

- FAST track circuits found 14 rail breaks while DAS 2005 found 4
- DAS 2005 had 992 false alarms or 4.37 false alarms per 100 train miles

1.1 Background

In 2012 and 2013, a fiber optic test bed was installed around the HTL track, and a feasibility study was conducted to evaluate the potential of DAS technologies to detect broken rails [1]. The HTL was used for the fiber optic test bed and the feasibility study because of the number of broken rails, typically one to two each week, generated from the FAST program testing on that track. FAST typically runs a loaded 90 to 100 car train (number of cars can vary below and above these values) around the 2.7-mile HTL loop four nights a week during the spring and fall months. Figure 1 shows the layout of the fiber optic test bed around the HTL.

The test bed was designed to be configurable for a variety of wayside detection methods which include, but are not limited to, detection of broken rails, flat wheels, train location, and siding roll outs. Testing was conducted at TTC in 2012 and 2013 to determine the viability of using DAS technology to detect broken rails in railroad service lines. The results indicated that, with additional data processing techniques, DAS technology has the potential to detect and alert on broken rails. Since that time, fiber optic DAS vendors have implemented real time broken rail detection capabilities.

Figure 1. Fiber Layout Around the HTL

1.2 Objectives

This evaluation was conducted to baseline the capabilities of current DAS-based broken rail detection systems, identify areas of improvement, and investigate if and how fiber optic-based systems can perform the functions of conventional track circuits.

1.3 Overall Approach

Fiber optic DAS systems with railroad broken rail detection capabilities were identified and a request to participate in the evaluation was extended to the vendors. Three different systems were offered for the evaluation, two systems with broken rail detection capabilities up to 5 km and one system up to 40 km. The evaluation began with vendors integrating their fiber optic broken rail detection systems into the existing fiber optic test bed on the HTL by either connecting their system to a fiber optic cable covering a single loop of the HTL (5 km systems) or a fiber optic cable covering three loops of the HTL (40 km systems).

Each vendor was given access to the track as well as a calibration period during FAST operations to monitor and configure their systems. Vendors were responsible for starting and stopping their systems each test day, and making sure broken rail alarms generated were transmitted to the fiber optic back office. Logs from FAST operations were used along with alarms generated by each system to evaluate the broken rail detection capabilities of each system.

Determining the feasibility of using DAS systems to perform functions of track circuits with at least the same level of performance was completed by developing use cases for track circuit functions and then determining if and how fiber optic systems perform in those use cases.

1.4 Scope

The fiber optic broken rail detection trial only covers a single specific train type (loaded 70 to 99 car unit freight train) operating, for the most part, at 40 mph over the same 2.7 mile loop. Limited evaluation was also completed at speeds of 10 mph, 20 mph, and 30 mph with the same train. The evaluation does not cover other train types, speeds, or tracks.

The comparison between conventional track circuits and DAS systems was conducted by building use cases for track occupancy and broken rails to determine how DAS systems would provide the same functionality as track circuits. From previous fiber optic projects and knowledge of how the technology and systems operate, TTCI determined if and how the DAS systems could provide the same level of functionality. For areas where DAS systems lacked functionality, a recommendation of future changes and/or supplementary technologies is made to satisfy those functions.

1.5 Organization of the Report

Section 1 discusses the introduction and provides a brief overview of the fiber optic test bed, and includes an overview of the project with descriptions of the project objectives, overall approach, and scope.

Section 2 summarizes the fiber optic broken rail detection trial with an analysis of each system tested.

Section 3 covers the comparison completed between conventional track circuits and DAS systems.

Section 4 is a brief conclusion.

Appendix A is an in-depth analysis provided by the vendor for one of the systems.

Appendix B is a compilation of the FAST logs from the testing and can be found via FRA's eLibrary.

2. Fiber Optic Broken Rail Detection Evaluation

The fiber optic DAS broken rail detection evaluation was conducted in three phases. In the first phase, vendors set up and calibrated their systems, detailed in Section 2.1. The second phase consisted of data gathering and analysis during normal FAST operations, detailed in Section 2.2. The third phase involved data gathering and analysis from additional testing, detailed in Section 2.3. Section 2.4 provides general observations from the entire test period.

2.1 Trial Setup and Calibration

The test setup phase consisted of configuring the fiber optic test bed, installing and integrating the DAS broken rail detection systems with the test bed, and calibrating the systems once integrated. This phase of the project also included the setup of a fiber optic back office and integrated each DAS system with the back office. Data collection methods and the test methodology were also defined in the trial setup phase. The following subsections give further detail of the test setup phase.

2.1.1 Fiber Optic Test Bed Overview and Configuration

In prior efforts, TTCI installed a fiber optic test section that roughly parallels the HTL. The cable choice used for the installation was 12-strand Superior Essex® FTTP type. This cable was chosen for its ability to be installed in an outdoor environment without the use of thick outside cladding used in many fiber optic cables as a means of protection and strength. The FTTP cable is a loose tube, gel-filled fiber optic cable that uses solid core fiberglass strengthening members to allow for outdoor use and a high pull rating, greater than 300 pounds. Figure 2 shows a diagram of the cable.

The fiber optic cable deployed at the HTL test site is 3 miles long. A 328-foot section that does not parallel the track directly is used as a transition zone from the test bungalow to the HTL track. The fiber cable is installed, on average, 15 feet from track centerline. The cable is buried at depths from 18 inches to 42 inches, averaging 36 inches deep, in most sections directly paralleling the track. Directional boring was also used as a means of perpendicular track crossings.

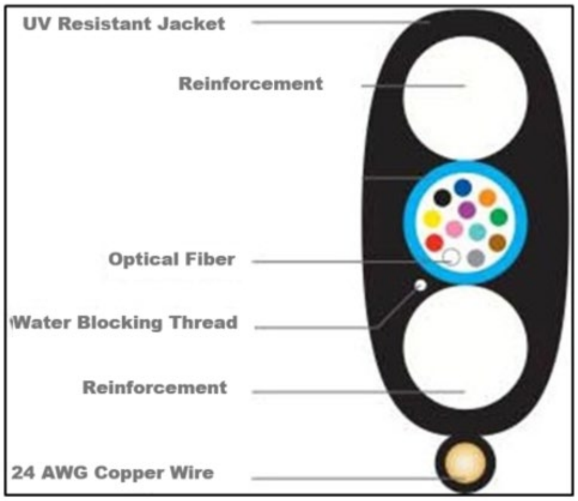


Figure 2. Superior Essex® FTTP

Fiber optic cable buried in an open trench was installed at 36 inches with the exception of one purposefully designed installation depth test zone. This depth test zone is located in section 3 for 650 feet paralleling the track, and it has a double cable of fiber, one at 36 inches deep and a second at 18 inches deep. Installation of the fiber optic cable between sections 35 and 36 was performed using directional boring at a depth of 42 inches. Directional boring was chosen as an installation method in these sections to allow the fiber to be installed at equal distances from both the mainline and bypass sections of the HTL. As the track spacing in this area does not lend itself well to the direct burial installation method, directional boring was used as a means of best-case installation method for this area. Figure 3 shows an overview of the fiber optic cable location around the HTL.

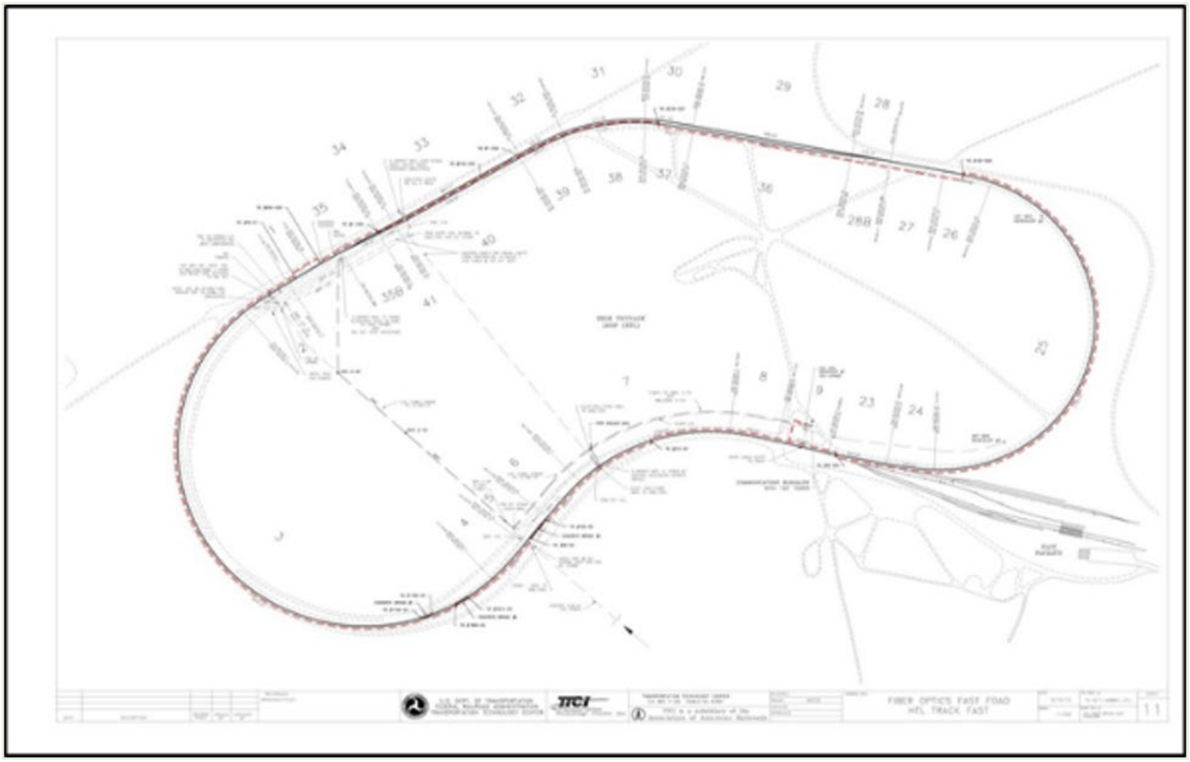


Figure 3. Overview of Fiber Optic Cable Location at the HTL

There are three bridges on the HTL, two precast concrete and one steel in composition. Each of the bridge spans hosts a different set of test objectives and materials. After studying railroad bridge fiber optic transition methods used on revenue service lines, TTCI concluded that the use of a small diameter ridged steel conduit affixed to the lower side of the bridge ballast curb (see Figure 4) was the most practical installation method to use. This installation method coincidentally also provides a secure connection between the bridge structure and the fiber optic cable allowing for a usable amount of acoustic coupling.

For approximately one quarter of the track, the HTL runs parallel to the Railroad Test Track (RTT) with track centerlines separated by about 20 feet. By installing the fiber optic cable under and on the outside of the RTT in a portion of this test section, the cable configuration provides the capability to collect single track data during testing (by excluding RTT traffic during test runs) and offers the potential for acquiring double-track data in future testing, when the defect detection algorithms are more mature.

Figure 4. HTL Bridge with Fiber Optic Conduit

The fiber optic test bed was configured to support DAS systems capable of detecting broken rails at distances of up to 5 km or 40 km. The 5 km systems utilized a single fiber strand making one complete loop around the HTL. The 40 km systems utilized three strands of fiber with reels of fiber in between to cover three loops of the HTL:

- Loop 1 spans 0 km – 4.8 km, a 10-km reel is spliced between loop 1 and loop 2
- Loop 2 spans 14.8 km – 19.6 km, a 15-km reel is spliced between loop 2 and loop 3
- Loop 3 spans 34.7 km – 40.1 km

2.1.2 Installation of Vendor Systems

A total of five DAS systems were installed during the broken rail detection trial. Of these systems, four were installed on a single loop of the track totaling 4.8 km in length. One was installed with a combination of three repeated loops of the track as well as spools of fiber installed between each loop. This configuration allowed for the system to monitor a total of 40 km of fiber. Of the five installed systems, three were used for data analysis once the systems were set up and calibrated. The other two installed systems were used as experimental systems by the vendors. These two systems were used by the vendors to run parallel versions of software, and the vendors were allowed access to make changes during the testing to improve on system capabilities. These two systems were not evaluated during this project.

Prior to vendor system installation, the test bed was optimized to provide the best data results from testing. This optimization included fixing several fusion splices in the fiber optic cable to reduce loss. After upgrading the splice points in the fiber cable, the cable was tested using an

Optical Time Domain Reflectometer (OTDR) to verify that all splice points in the cable tested with <1 db of loss.

Remote access via internet connection was installed for each of the participating venders to allow them to start and stop test systems, as well as transfer rail break data to their home office for further independent research and development.

2.1.3 Calibration of Systems

After the DAS hardware was installed, it required calibration to improve the accuracy of reporting by the DAS system. A typical DAS calibration consists of generating acoustic signals on or near the rail while the DAS system is monitoring and recording the GPS location where the signal is produced. The GPS data is then input to the DAS system as a location point. This method of calibration was utilized as the initial setup.

A second means of calibration was also explored as a means of dynamically calibrating the DAS systems. For this calibration, a light weight rail vehicle instrumented with a GPS receiver was used. A light weight rail vehicle was used because it generates a smaller acoustic signal, due to its size and weight. With a smaller acoustic signal, the spatial accuracy can be improved. The GPS system was set to a sampling rate of 10 times per second. The light weight rail vehicle was operated at 10 mph for a total of two laps around the HTL while the DAS systems recorded data. After calibration data was recorded on both the DAS and GPS units, the data was reassembled by matching the timestamps of the data from both systems. The outcome of this experimental method of DAS calibration was very positive, as it greatly reduced the amount of time required to perform the calibration.

Following the GPS calibration of the systems, the vendors used FAST operations for several weeks to help calibrate other settings within their systems. Once each vendor was satisfied with their calibration setup, they informed TTCI that they were set up and ready for the trial to begin. Subsequent weeks of FAST operations were then used as official trial data.

2.1.4 Fiber Optic Back Office

The back office system was created to match requirements provided by CSX, for this project and future fiber optic testing, to incorporate fiber optic DAS data into the back office. The back office contains over 40 tables for fiber optic, train, and track information. All back office information can be accessed through a structured query language (SQL) interface. The information used to analyze rail break data was pulled from the following tables:

- RAIL_BREAK_DEFECT – contained all the broken rail alarms for all systems. The information in this table includes:
    - Rail Break Alarm ID
    - Time of the alarm in Greenwich Mean Time (GMT)
        - GMT + 0 during winter months
        - GMT + 1 during British summer time
    - Track the alarm occurred on
    - GPS location of the alarm

- TRAIN_INFO – contained GPS locations for the head and tail of the train recorded several times a minute.
- STATUS – used to determine which nights each DAS system operated on.

To differentiate between DAS system alarms within the back office, the rail break alarm ID contains 2000, 2003, or 2005 at the beginning of the ID to identify the system that sent the alarm. ID 2003 corresponds to a long fiber system which utilizes three different loops around the HTL. To differentiate alarms on these loops, the DAS reported a track number of 1, 2, or 3 with each track corresponding to different distances along the fiber. Track 1 spans 0 km–4.8 km, track 2 spans 14.8 km–19.6 km, and track 3 spans 34.7 km–40.1 km along the fiber optic cable. ID 2003 is the only DAS system that could generate alarms on multiple tracks.

2.1.5 Data Collection Methods

Data was collected from three sources: the FAST test logs, the broken rail alarms retrieved from the back office, and the vendors' DAS data. Each vendor collected their own DAS data. This data was used by the vendors to do a more detailed analysis of their alarms, if they so choose. Vendors were also asked to provide supplemental data for this report, to provide insights into the analysis of the raw data. Appendix A contains reports received by the vendors.

The FAST log data provided information about the operation on every night of testing. FAST logs for the test period are available in Appendix B and an example of the FAST logs is detailed in Section 2.2.2. FAST log information included:

- Consist Information
- Number of Laps Completed
- Direction of Consist Travel (Clockwise or Counterclockwise)
- Track Used for Testing (Main or Bypass)
- Number of Broken Rails
- Number of Broken Rails Detected by Track Circuit
- Additional Data for Each Broken Rail

Additionally, a weather station located at FAST was used to record the high and low temperature for each day of testing.

Finally, the RAIL_BREAK_DEFECT table of the back office system, discussed in Section 2.1.4, was used to create a table of all alarms from each system for each day. This information was used during data analysis to determine the validity of each alarm that the systems recorded. Raw DAS data was also recorded and saved during the trial and is available to the vendors for playback on their systems to test modifications to their systems and algorithms in the future.

2.1.6 Test Methodology

Using information from the sources outlined in Section 2.1.5, tables were constructed and a data analysis was completed to determine the validity of all alarms that were recorded. Each DAS system alarm was evaluated and assigned one of three results:

- True Positive – An alarm present at the location and within the time tolerance of a broken rail
- False Positive – An alarm present in a location or time where a broken rail did not occur
- False Negative – A broken rail on track with no alarms from the system at that location within the time tolerance

DAS systems were evaluated daily to determine the number of occurrences of each of these results.

The DAS units are only able to pinpoint alarms within a certain spatial range, since the acoustic response from the train at a location on the track excites the fiber in both directions for a distance along the fiber. After communicating with the vendors, a range of 450 feet from a broken rail was set as the spatial tolerance. This means any alarms that were within ±450 feet of a broken rail were evaluated to determine if they were within the time tolerance of the rail break. The time tolerance was determined based on whether the rail break was detected by the FAST signaling system or by the FAST train crew. When a broken rail is found during FAST operations, the operations personnel stop the train to fix the broken rail. If an alarm occurred after the train had stopped, it was marked as a false positive. If a broken rail was found by the signaling system, any alarms within the distance tolerance and within two hours of the break were marked as true positives. If a broken rail was found through crew detection, it is possible that the break could have occurred any time since the beginning of that day of operations. As such, any alarms that were within range and detected before the crew stopped the train were marked as true positives.

2.2 Data Gathering and Analysis from Normal FAST Operations

The data gathering and analysis from the FAST operations phase started when the vendor of each system was satisfied with their calibration setup. This phase included a total of 93 test days, starting in November 2016 and ending in November 2017, and included 29 broken rails. Due to system calibration completion dates, communication issues with the back office, and hardware issues, each system includes a unique set of the dates tested during the trial.

The data gathering and analysis from the FAST operations phase consisted of gathering FAST daily logs and documenting broken rails, storing DAS system broken rail alarms in a SQL database, analysis of DAS system broken rail alarms, broken rail detection evaluation of each DAS system, and recording overall observations from the trial. The following subsections detail each of the tasks of the data gathering and analysis from the FAST operations phase.

2.2.1 FAST Operational Data

The FAST train, comprising three SD70 locomotives and 70 to 99 315,000-pound cars, is operated over a 2.7-mile long mainline quality track at an average speed of 40 mph. FAST operations last approximately 9 hours each night. The oval-shaped HTL, where the FAST train is operated, is comprised of moderate curves and tangent track with new and untried track and bridge components and designs.

Each day of operations at FAST produces a test log that provides details about operations, such as the direction of travel (either clockwise or counterclockwise), consist information, number of laps completed, number of broken rails and detection method for broken rails, and if the train ran on the HTL mainline or the HTL bypass. Using weather data during the time FAST ran each night, the high and low temperature were also recorded. Table 1 provides a summary of the data recorded from FAST operations during the trial period.

Table 1: Summary of FAST Operations

Date	Consist Info (3 Locos)	Number of Laps Completed	Temp. Low (°F)	Temp High (°F)	Clockwise (CW) Counterclockwise (CCW)	Main (M) Bypass (B)	Number of Broken Rails	Broken Rails Detected by Track Circuit
10/31/16	75 Cars	124	45.0	82.0	CCW	M	0	0
11/1/16	75 Cars	102	39.9	66.0	CCW	M	1	1
11/2/16	76 Cars	124	37.9	66.9	CW	M	0	0
11/3/16	75 Cars	112	41.0	71.1	CW	B	0	0
11/9/16	73 Cars	84	27.0	66.9	CW	M	2	2
11/10/16	74 Cars	111	46.0	72.0	CW	B	0	0
11/14/16	75 Cars	123	35.1	72.0	CCW	B	0	0
11/15/16	74 Cars	112	34.0	78.1	CCW	M	0	0
11/16/16	74 Cars	108	51.1	75.0	CW	M	0	0
11/17/16	70 Cars	88	30.0	39.9	CW	M	2	2
12/5/16	70 Cars	30	45.3	66.6	CCW	M	0	0
12/6/16	70 Cars	13	10.3	42.4	CCW	M	1	1
12/7/16	73 Cars	15	18.8	34.2	CCW	M	0	0
12/8/16	73 Cars	25	17.3	33.6	CCW	M	1	1
2/13/17	85 Cars	126	40.4	52.7	CCW	M	0	0
2/14/17	87 Cars	92	32.4	67.0	CCW	B	1	1
2/15/17	86 Cars	110	36.0	71.2	CW	B	0	0
2/16/17	84 Cars	125	37.4	71.1	CW	M	0	0
2/21/17	84 Cars	122	54.3	71.9	CCW	M	0	0
2/22/17	87 Cars	127	41.1	71.2	CW	B	0	0
2/23/17	87 Cars	104	25.3	64.5	CW	B	1	1
2/27/17	86 Cars	124	36.7	69.9	CCW	M	1	1
2/28/17	86 Cars	120	24.3	59.0	CCW	B	0	0
3/1/17	86 Cars	47	26.7	64.3	CCW	B	0	0
3/2/17	86 Cars	126	28.4	70.2	CW	M	0	0
3/6/17	85 Cars	126	30.5	57.1	CCW	M	0	0
3/7/17	85 Cars	124	37.3	71.6	CCW	M	0	0

Date	Consist Info (3 Locos)	Number of Laps Completed	Temp. Low (°F)	Temp High (°F)	Clockwise (CW) Counterclockwise (CCW)	Main (M) Bypass (B)	Number of Broken Rails	Broken Rails Detected by Track Circuit
3/8/17	85 Cars	128	38.3	72.6	CW	M	0	0
3/9/17	82 Cars	108	39.1	76.4	CW	M	1	0
3/13/17	80 Cars	97	36.8	71.8	CCW	M	1	1
3/14/17	79 Cars	101	44.9	76.4	CCW	M	1	1
3/15/17	81 Cars	103	51.2	78.4	CW	M	0	0
3/16/17	83 Cars	117	50.0	77.7	CW	M	0	0
3/27/17	84 Cars	115	47.5	70.4	CCW	M	0	0
3/28/17	84 Cars	104	42.9	50.0	CCW	M	1	1
3/29/17	84 Cars	116	39.6	64.8	CW	M	0	0
3/30/17	83 Cars	121	44.9	71.9	CW	B	0	0
4/3/17	84 Cars	54	38.7	60.5	CCW	B	2	1
4/4/17	84 Cars	130	36.4	52.1	CCW	B	0	0
4/5/17	85 Cars	127	38.1	60.0	CW	B	0	0
4/6/17	82 Cars	124	44.6	72.3	CW	B	0	0
4/17/17	84 Cars	124	53.3	72.6	CCW	B	0	0
4/18/17	83 Cars	128	53.1	72.8	CCW	B	0	0
4/19/17	83 Cars	98	54.3	75.0	CW	B	0	0
4/20/17	85 Cars	117	49.4	60.3	CW	B	0	0
4/24/17	85 Cars	104	52.6	71.6	CCW	B	0	0
4/25/17	85 Cars	105	39.7	52.3	CCW	B	1	0
4/26/17	85 Cars	110	48.1	69.4	CW	B	0	0
4/27/17	85 Cars	130	42.4	64.5	CW	B	0	0
5/1/17	86 Cars	69	46.2	73.0	CCW	M/B	0	0
5/2/17	84 Cars	127	48.9	64.6	CCW	B	0	0
5/3/17	84 Cars	127	39.7	62.4	CW	B	0	0
5/4/17	84 Cars	125	49.3	73.0	CW	B	0	0
5/15/17	83 Cars	54	60.5	75.4	CW	M/B	0	0
5/16/17	84 Cars	123	54.8	71.6	CCW	M	0	0
5/17/17	84 Cars	130	53.4	72.4	CCW	B	0	0
5/18/17	82 Cars	113	44.3	50.9	CW	M	0	0
6/5/17	85 Cars	92	63.5	74.7	CCW	M	0	0
6/6/17	85 Cars	102	58.5	71.4	CCW	B	0	0

Date	**Consist Info (3 Locos)**	**Number of Laps Completed**	**Temp. Low (°F)**	**Temp High (°F)**	**Clockwise (CW) Counterclockwise (CCW)**	**Main (M) Bypass (B)**	**Number of Broken Rails**	**Broken Rails Detected by Track Circuit**
6/7/17	82 Cars	120	61.9	71.9	CW	B	0	0
6/8/17	80 Cars	123	61.3	72.4	CW	M	0	0
6/12/17	82 Cars	120	65.3	79.9	CCW	M	0	0
6/13/17	82 Cars	69	56.0	78.6	CCW	B	1	0
6/14/17	82 Cars	129	64.3	79.0	CW	B	0	0
6/15/17	80 Cars	127	65.1	79.5	CW	M	0	0
9/18/17	88 Cars	84	52.0	71.6	CCW	M	1	0
9/19/17	88 Cars	126	45.3	71.1	CCW	M	0	0
9/20/17	87 Cars	105	46.8	69.6	CW	M	0	0
9/21/17	86 Cars	105	62.2	71.6	CW	M	0	0
9/25/17	90 Cars	120	49.3	57.0	CCW	M	0	0
9/26/17	88 Cars	100	56.0	63.2	CCW	B	1	0
9/27/17	89 Cars	127	52.7	56.4	CW	M	0	0
9/28/17	89 Cars	130	52.6	55.8	CW	M	0	0
10/9/17	94 Cars	94	31.4	41.9	CCW	B	2	2
10/10/17	92 Cars	117	34.7	51.1	CCW	B	0	0
10/11/17	92 Cars	130	49.9	65.8	CW	B	0	0
10/12/17	91 Cars	130	49.2	67.5	CW	B	0	0
10/16/17	91 Cars	124	42.1	59.4	CW	M	0	0
10/17/17	90 Cars	21	45.0	56.2	CCW	M	2	1
10/18/17	91 Cars	130	54.1	61.4	CCW	M	0	0
10/19/17	92 Cars	130	39.9	72.0	CW	M	0	0
10/23/17	94 Cars	47	33.1	39.9	CCW	M	0	0
10/24/17	94 Cars	91	32.0	43.0	CCW	M	1	1
10/25/17	95 Cars	131	44.1	70.0	CW	B	0	0
10/26/17	96 Cars	60	34.0	41.0	CW	M	2	1
10/30/17	98 Cars	102	34.0	39.9	CCW	M	0	0
10/31/17	95 Cars	100	30.9	55.9	CCW	M	0	0
11/1/17	97 Cars	116	54.0	78.1	CW	B	1	1
11/2/17	97 Cars	110	34.0	55.0	CW	M	0	0
11/6/17	98 Cars	117	37.0	52.0	CCW	M	0	0
11/7/17	98 Cars	85	30.9	37.9	CCW	M	1	1

Date	Consist Info (3 Locos)	Number of Laps Completed	Temp. Low (°F)	Temp High (°F)	Clockwise (CW) Counterclockwise (CCW)	Main (M) Bypass (B)	Number of Broken Rails	Broken Rails Detected by Track Circuit
11/8/17	99 Cars	117	28.9	39.9	CW	B	0	0
11/9/17	99 Cars	91	30.9	39.0	CW	M	1	0

2.2.2 Documentation of Broken Rails During FAST Operations

During the calibration and evaluation period, 35 broken rails were documented. Three of these events had to be removed from consideration. Two of the breaks that were removed occurred in a location where there is no fiber optic cable alongside the track (beginning of section 9). The other break that had to be removed occurred when the fiber optic DAS systems were not running. Figure 5 illustrates the layout of the fiber and the location of the remaining 32 broken rail events that were recorded during the calibration and evaluation period. A subset of these broken rails was used for the evaluation of each system, depending on the evaluation start date and the daily recording state of each system.

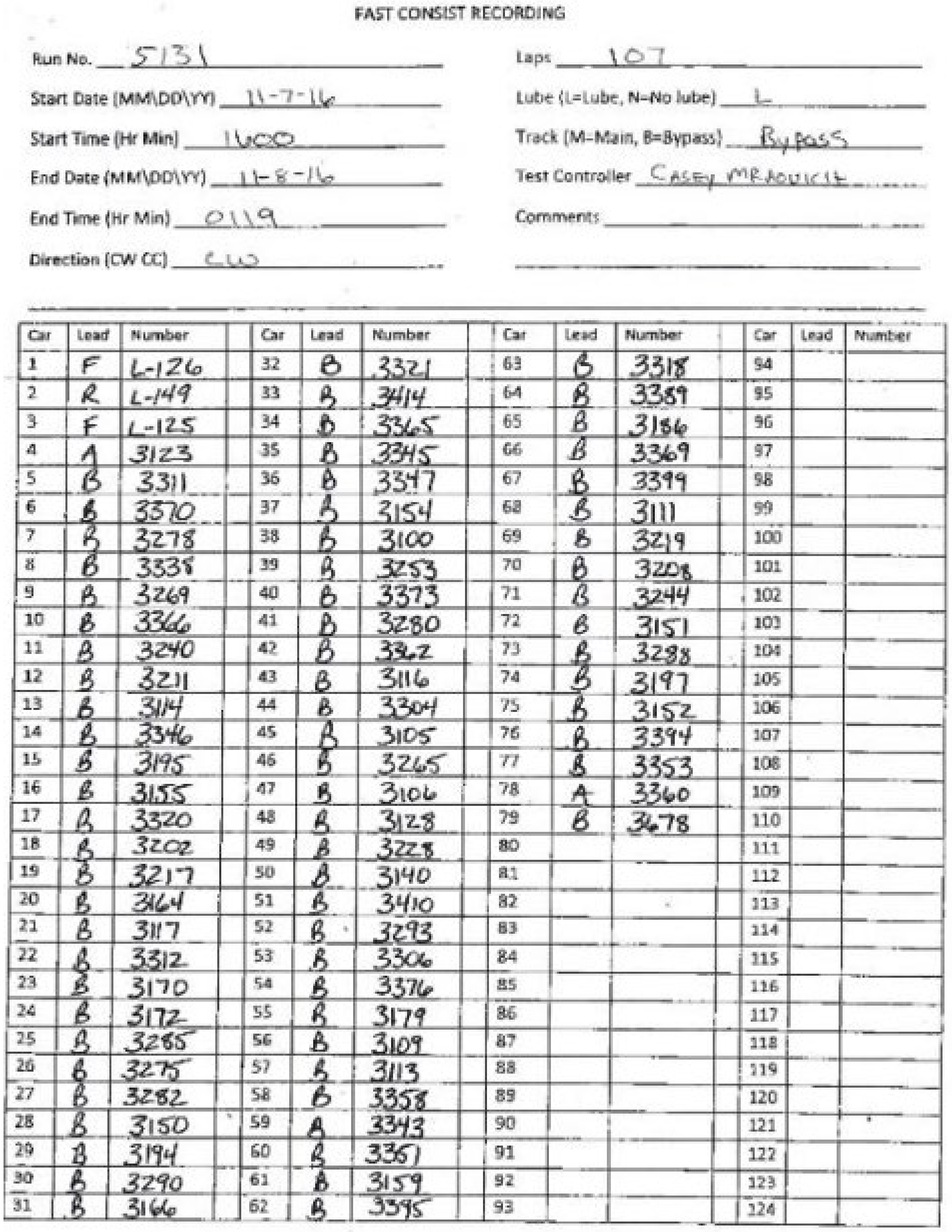
Figure 5. HTL with Broken Rail Locations

For the purposes of this project, a broken rail refers to an event in which the rail is either completely severed or damaged significantly to the point where the risk of severing the rail appears to be imminent. Therefore, this evaluation not only included events when the rail itself had broken, but there were also broken welds in the rail. These have proven to be weak spots in the rail susceptible to failure. The HTL at TTC has approximately 1,000 welds along its 2.7 mile length, which is approximately 7 welds for every 100 feet of track. The probability that one of these will fail during FAST operations is relatively high. As a result, the majority of broken rails that occur on the HTL are indeed actually broken welds.

When a broken rail occurs during FAST operations, it is recorded in a log book. Figure 6 through Figure 9 shows an example of the FAST logs for a night that had a broken rail during testing. Figure 6 provides an overview of that night's test with a detailed list of all the cars and locomotives in the train. For this example, the test run number was 5131 and testing began the night of November 7, 2016, and ended the morning of November 8, 2016. The train consisted of 3 locomotives and 76 cars and completed 107 laps around the HTL in the counterclockwise direction, while using lubrication and the bypass portion of the track.

Figure 7 provides a detailed description of the test's events throughout the night in chronological order. The night begins when everyone arrives, followed by a pretest meeting, a brake test, and the train starting laps on the HTL. Throughout the night, the test crew regularly checks bridges, monitors bearing temperature sensors, and measures rail deflection. In this particular case, the logs indicate a broken rail was detected at 12:35 a.m. during lap 108 and the train stopped at 12:38 a.m.

Figure 8 and Figure 9 provides more details about the broken rail per Appendix B. The HTL is equipped with track circuits that are designed to detect broken rails. However, in this instance the track circuit failed to detect the broken rail as noted in Appendix B under "Time of Red Signal" as "N/A." Appendix B includes additional information from the test controller about the broken rail. In this case, the broken rail occurred at a field weld and a defect in the base of the rail was identified. Other information recorded includes location, weld information (if applicable), air and rail temperature at time of repair, a drawing, gap lengths and rail size, along with any other comments the test controller deems necessary. In some cases, rail breaks can occur at weld locations where two different sizes of rail are welded together (e.g., a transition from 136-pound rail to 141-pound rail). For these breaks, the POS value refers to the size of the rail for the side of the break that has the larger rail and the NEG value refers to the size of the rail for the side that has the smaller rail. If both the POS value and NEG value are equal, then the size of the rail was the same on both sides of the broken rail. In this example, the broken field weld occurred in section 3, at or near tie 1108 on the outside rail. It was weld #2615-16, installed on January 18, 2016. The rail and air temperatures were 67 °F and 34 °F, respectively. There was no gap at the head and web, but there was a 1/8-inch gap at the base. Finally, both sides of the weld were 141-pound rail. Further comments indicated that this break was detected by a test crew member and there was no red signal (from the track circuit). In addition to the notes, the test controller also provided pictures of each break. Figure 10 is a picture of the broken rail for this example. All the test logs and accompanying pictures of all 32 breaks can be found in Appendix B, which is separate from this report.



FAST CONSIST RECORDING

Run No. 5131

Laps 107

Start Date (MM\DD\YY) 11-7-16

Lube (L=Lube, N=No lube) L

Start Time (Hr Min) 1600

Track (M-Main, B=Bypass) Bypass

End Date (MM\DD\YY) 11-8-16

Test Controller CASEY MRAOVICH

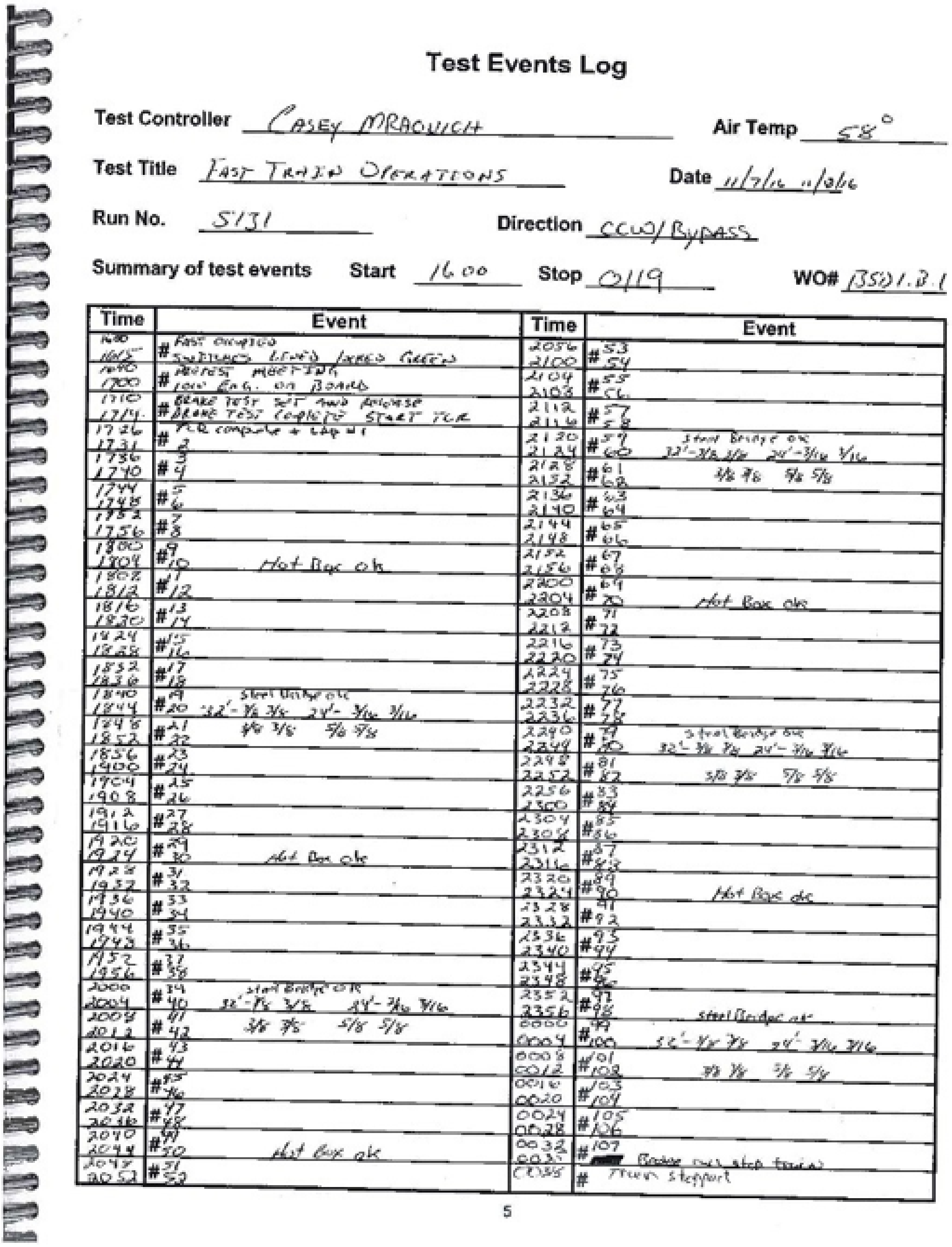
End Time (Hr Min) 0119

Comments

Direction (CW CC) CW

Car	Lead	Number	Car	Lead	Number	Car	Lead	Number	Car	Lead	Number
1	F	L-126	32	B	3321	63	B	3318	94		
2	R	L-149	33	B	3414	64	B	3389	95		
3	F	L-125	34	B	3365	65	B	3186	96		
4	A	3123	35	B	3345	66	B	3369	97		
5	B	3311	36	B	3347	67	B	3399	98		
6	B	3370	37	B	3154	68	B	3111	99		
7	B	3278	38	B	3100	69	B	3219	100		
8	B	3338	39	B	3253	70	B	3208	101		
9	B	3269	40	B	3373	71	B	3244	102		
10	B	3366	41	B	3280	72	B	3151	103		
11	B	3240	42	B	3362	73	B	3288	104		
12	B	3211	43	B	3116	74	B	3197	105		
13	B	3114	44	B	3304	75	B	3152	106		
14	B	3346	45	B	3105	76	B	3394	107		
15	B	3195	46	B	3265	77	B	3353	108		
16	B	3155	47	B	3106	78	A	3360	109		
17	B	3320	48	B	3128	79	B	3678	110		
18	B	3202	49	B	3228	80			111		
19	B	3217	50	B	3140	81			112		
20	B	3164	51	B	3410	82			113		
21	B	3117	52	B	3293	83			114		
22	B	3312	53	B	3306	84			115		
23	B	3170	54	B	3376	85			116		
24	B	3172	55	B	3179	86			117		
25	B	3285	56	B	3109	87			118		
26	B	3275	57	B	3113	88			119		
27	B	3282	58	B	3358	89			120		
28	B	3150	59	A	3343	90			121		
29	B	3194	60	B	3361	91			122		
30	B	3290	61	B	3159	92			123		
31	B	3166	62	B	3395	93			124		

Figure 6. Example FAST Consist Recording



Test Events Log

Test Controller Casey Mraovich **Air Temp** 58°

Test Title Fast Train Operations **Date** 11/7/16 11/8/16

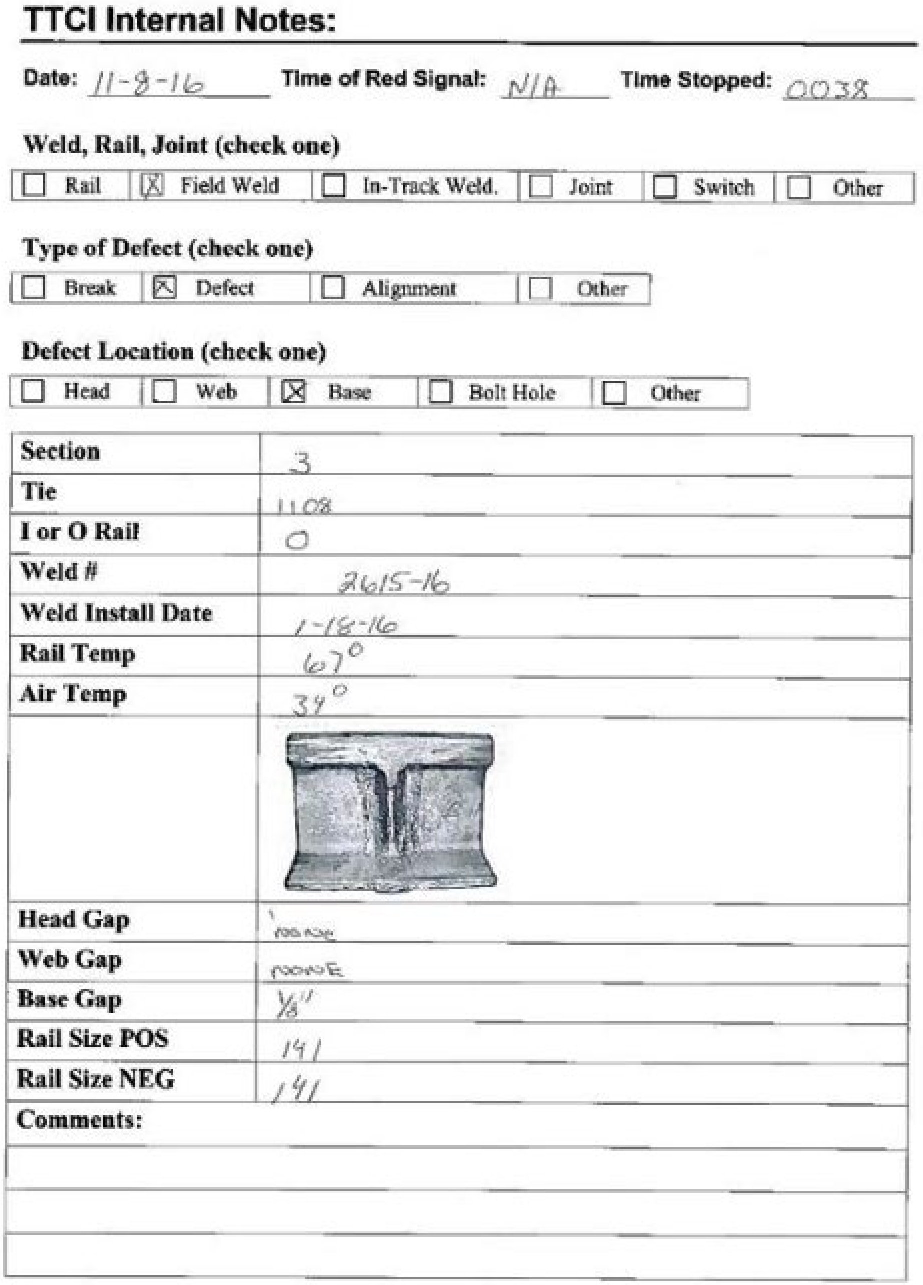
Run No. 5131 **Direction** CCW/Bypass

Summary of test events **Start** 16:00 **Stop** 0119 **WO#** 13501.B.1

Time	Event	Time	Event
1630 1645	# Fast on 4100 Switches lined [illegible] Green	2056 2100	# 53 54
1640 1700	# Pretest meeting Loco Eng. on Board	2104 2108	# 55 56
1710 1714	# Brake test set and release Brake test complete start TCR	2112 2116	# 57 58
1726 1731	# TCR complete + lap #1 2	2120 2124	# 59 60 Steel Bridge ok 32'-3/8 3/8 24'-3/16 3/16
1736 1740	# 3 4	2128 2132	# 61 62 3/8 3/8 5/8 5/8
1744 1748	# 5 6	2136 2140	# 63 64
1752 1756	# 7 8	2144 2148	# 65 66
1800 1804	# 9 10 Hot Box ok	2152 2156	# 67 68
1808 1812	# 11 12	2200 2204	# 69 70 Hot Box ok
1816 1820	# 13 14	2208 2212	# 71 72
1824 1828	# 15 16	2216 2220	# 73 74
1832 1836	# 17 18	2224 2228	# 75 76
1840 1844	# 19 Steel Bridge ok 20 32'-3/8 3/8 24'-3/16 3/16	2232 2236	# 77 78
1848 1852	# 21 3/8 3/8 5/8 5/8 22	2240 2244	# 79 Steel Bridge ok 80 32'-3/8 3/8 24'-3/16 3/16
1856 1900	# 23 24	2248 2252	# 81 82 3/8 3/8 5/8 5/8
1904 1908	# 25 26	2256 2300	# 83 84
1912 1916	# 27 28	2304 2308	# 85 86
1920 1924	# 29 30 Hot Box ok	2312 2316	# 87 88
1928 1932	# 31 32	2320 2324	# 89 90 Hot Box ok
1936 1940	# 33 34	2328 2332	# 91 92
1944 1948	# 35 36	2336 2340	# 93 94
1952 1956	# 37 38	2344 2348	# 95 96
2000 2004	# 39 Steel Bridge ok 40 32'-3/8 3/8 24'-3/16 3/16	2352 2356	# 97 98 Steel Bridge ok
2008 2012	# 41 42 3/8 3/8 5/8 5/8	0000 0004	# 99 100 32'-3/8 3/8 24'-3/16 3/16
2016 2020	# 43 44	0008 0012	# 101 102 3/8 3/8 5/8 5/8
2024 2028	# 45 46	0016 0020	# 103 104
2032 2036	# 47 48	0024 0028	# 105 106
2040 2044	# 49 50 Hot Box ok	0032 0035	# 107 [illegible] stop train
2048 2052	# 51 52	0035	# Train stopped

5

Figure 7. Example Test Events Log



TTCI Internal Notes:

Date: 11-8-16 **Time of Red Signal:** N/A **Time Stopped:** 0038

Weld, Rail, Joint (check one)

☐ Rail ☒ Field Weld ☐ In-Track Weld. ☐ Joint ☐ Switch ☐ Other

Type of Defect (check one)

☐ Break ☒ Defect ☐ Alignment ☐ Other

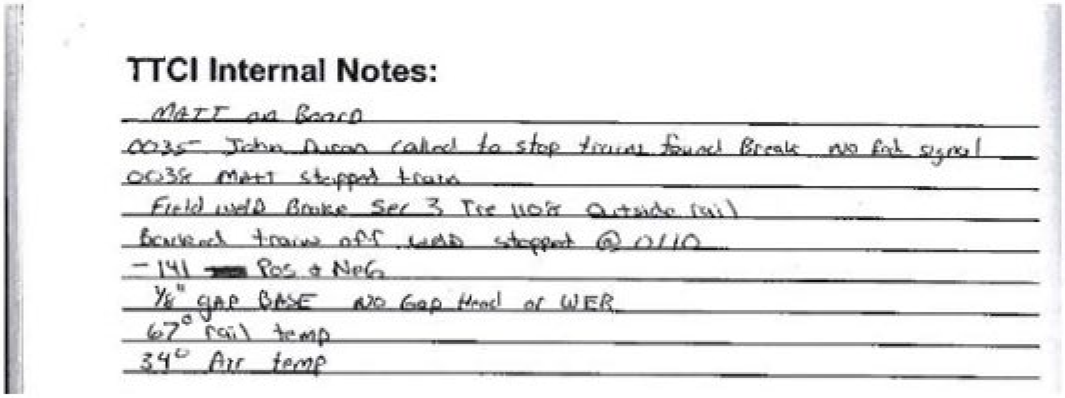
Defect Location (check one)

☐ Head ☐ Web ☒ Base ☐ Bolt Hole ☐ Other

Section	3
Tie	1108
I or O Rail	O
Weld #	2615-16
Weld Install Date	1-18-16
Rail Temp	67°
Air Temp	34°
Head Gap	none
Web Gap	none
Base Gap	1/8"
Rail Size POS	141
Rail Size NEG	141

Comments:

Figure 8. Example Broken Rail TTCI Internal Notes



TTCI Internal Notes:

MATT on Board
0035 John Duran called to stop train found Break no Red signal
0038 MATT stopped train
Field weld Broke Sec 3 Tie 108 Outside rail
Backed train off, weld stopped @ 0110
-141 [redacted] Pos + NeG
1/8" gap BASE no Gap Head or WEB
67° rail temp
34° Air temp

Figure 9. Example Additional TTCI Internal Notes

Figure 10. FAST Log Broken Rail Picture

Table 2 provides a summary of the FAST log data for the 32 rail breaks detected. The detection method refers to how the break was found. If the train stopped because the track signal went to red, it was detected by the track circuit, otherwise the broken rail was detected by the crew. GPS location was not included in the FAST logs, but the section and tie number was used by an engineer to acquire the GPS data after the fact.

Table 2: Summary of Broken Rails During Trial

FAST Run #	Time of Detection	Detection Method	Latitude	Longitude	Section	TIE	Rail	Type	Defect	Head Gap	Web Gap	Base Gap	Rail Size POS	Rail Size NEG	Rail Temp	Air Temp
5128	11/2/16 12:14 AM	Track Circuit	38.45431	-104.34542	32	6	Outside	Field Weld	Base	1/2	1/2	1/2	136	141	58	41.3
5131	11/8/16 12:38 AM	Crew	38.4466	-104.35275	3	1108	Outside	Field Weld	Base	0	0	1/8	141	141	67	34
5132	11/9/16 1:23 AM	Track Circuit	38.45385	-104.34685	33	59	Outside	In-Track Weld	Web/Base	1/8	1/8	1/8	136	136	37	32
5133	11/9/16 10:28 PM	Track Circuit	38.44869	-104.34015	9	168	Outside	Field Weld	Base	3/8	¼	1/4	136	136	41	34
5133	11/9/16 11:44 PM	Track Circuit	38.4509	-104.35281	3	114	Outside	Field Weld	Web	1	1	1	141	141	43.8	34
5138	11/17/16 5:37 PM	Track Circuit	38.44684	-104.3529	3	1072	Outside	Field Weld	Base	1/4	¼	1/4	141	141	26	30
5138	11/17/16 11:41 PM	Track Circuit	38.45324	-104.3394	25	1572	Outside	Field Weld	Base	2 1/2	2 ½	2 1/2	136	136	31	27
5140	12/6/16 7:13 AM	Track Circuit	38.453706	-104.34714	33	104	Inside	-	-	-	-	-	-	-	-	-
5143	12/8/16 1:39 PM	Track Circuit	38.453942	-104.34652	32	150	Inside	-	-	-	-	-	-	-	-	-
5145	2/14/17 8:08PM	Track Circuit	38.445717	-104.35056	3	1469	Outside	Field Weld	Base	5/8	5/8	1/2	136	136	40	32
5150	2/23/17 10:17 PM	Track Circuit	38.453395	-104.34769	40	250	Inside	Field Weld	Base	3/4	3/4	3/4	141	136	14	20
5151	2/28/17 1:47 AM	Track Circuit	38.452408	-104.33482	25	1254	Outside	In-Track Weld	-	3/4	3/4	5/8	136	136	37	29
5159	3/9/17 11:04 PM	Crew	38.45186	-104.33448	25	1122	Outside	Rail	Base	1/16	1/16	1/16	136	136	52	45
5160	3/13/17 12:20 AM	Track Circuit	38.45443	-104.34539	31	266	Outside	Field Weld	Base	1/8	1/8	1/8	141	141	57	34
5161	3/14/17 10:38 PM	Track Circuit	38.45415	-104.34106	29	296	Inside	Field Weld	Base	1/4	1/4	1/4	136	136	57	40

FAST Run #	Time of Detection	Detection Method	Latitude	Longitude	Section	TIE	Rail	Type	Defect	Head Gap	Web Gap	Base Gap	Rail Size POS	Rail Size NEG	Rail Temp	Air Temp
5165	3/28/17 10:20 PM	Track Circuit	38.44596	-104.35153	3	1319	Outside	Rail	Base	1/2	1/2	1/2	136	136	51	40
5168	4/4/17 3:12 AM	Track Circuit	38.44754	-104.35351	3	899	Outside	Field Weld	Base	3/8	3/8	3/8	136	141	45	36
5168	4/4/17 3:12 AM	Crew	38.45345	-104.33662	26	38	Outside	Field Weld	Web	0	0	0	136	136	40	32
5177	4/26/17 3:57 AM	Crew	38.44858	-104.33949	23	101	Inside	Rail	Head	1/4	1/4	1/4	136	136	33	34
5196	6/14/17 2:57 AM	Crew	38.4457	-104.34924	3	1669	Outside	Rail	Head	0	0	0	136	136	89	52
5199	9/19/17 6:11 AM	Crew	38.45084	-104.35295	3	104	Outside	In-Track Weld	Web	1/16	1/16	1/16	141	141	80.3	47
5204	9/27/17 5:15 AM	Crew	38.44609	-104.34784	3	1901	Outside	Field Weld	Head	0	0	0	136	136	70.2	52
5207	10/9/17 10:18 PM	Track Circuit	38.44861	-104.33909	23	166	Inside	Field Weld	Base	5/8	5/8	5/8	136	136	35.9	35
5207	10/10/17 1:20 AM	Track Circuit	38.44839	-104.33867	24	19	Outside	Field Weld	Base	1/2	1/2	1/2	136	136	36.7	27.5
5212	10/17/17 11:23 PM	Crew	38.44674	-104.35286	3	1081	Inside	In-Track Weld	Web	3/8	3/8	3/8	141	141	61.6	41
5212	10/18/17 3:37 AM	Track Circuit	38.44905	-104.34266	7	522	Inside	In-Track Weld	Web	1/2	1/2	1/2	136	136	41	41
5216	10/25/17 12:46 AM	Track Circuit	38.44838	-104.33825	24	89	Inside	Shop Weld	Web	1/2	1/2	1/2	136	136	43.8	36
5218	10/26/17 7:09PM	Track Circuit	38.4529	-104.33533	25	1438	Outside	Field Weld	Base	3/4	3/4	3/4	136	136	40	36
5218	10/26/17 10:48 PM	Crew	38.44747	-104.35345	3	935	Outside	In-Track Weld	Web	0	0	0	136	136	49.5	33
5221	11/2/17 12:52 AM	Track Circuit	38.44733	-104.34631	5	46	Inside	Rail	Head	1/16	1/16	1/16	136	136	70.4	56
5224	11/7/17 8:15 AM	Track Circuit	38.4473	-104.34633	5	62	Inside	Rail	Web/Base	1/2	1/2	1/2	136	136	42.5	32

FAST Run #	**Time of Detection**	**Detection Method**	**Latitude**	**Longitude**	**Section**	**TIE**	**Rail**	**Type**	**Defect**	**Head Gap**	**Web Gap**	**Base Gap**	**Rail Size POS**	**Rail Size NEG**	**Rail Temp**	**Air Temp**
5226	11/9/17 11:08 PM	Crew	38.44591	-104.35137	3	1349	Outside	Rail	Base	0	1/8	1/8	136	136	68	34

2.2.3 Documentation of Broken Rail Alarms from Fiber Optic Systems during FAST Operations

Table 3 contains daily data for broken rails, track circuit alarms, and alarm counts for each DAS system, taken from the RAIL_BREAK_DEFECT table in the fiber optic back office through February 2017. DAS system 2003 was a long fiber system that looped the HTL three times and alarms for DAS 2003 are split between the individual loops. Table entries with an N/A indicated the system was not operating during testing on that day.

Table 3: Daily Record of Broken Rails and DAS System Alarms Through February 2017

Date	**Broken Rails**	**Track Circuit**	**2000**	**2003 0 km 4.8 km**	**2003 14.8 km 19.6 km**	**2003 34.7 km 40.1 km**	**2005**
12/5/2016	0	0	0	21	33	65	14
12/6/2016	1	1	0	75	72	62	10
12/7/2016	0	0	0	60	64	62	9
12/8/2016	1	1	3	5	19	18	4
2/13/2017	0	0	1	N/A	N/A	N/A	8
2/14/2017	1	1	1	13	11	19	18
2/15/2017	0	0	1	28	22	15	8
2/16/2017	0	0	1	8	9	4	3
2/21/2017	0	0	0	N/A	N/A	N/A	N/A
2/22/2017	0	0	1	8	9	7	10
2/23/2017	1	1	0	28	20	19	12
2/27/2017	1	1	1	11	7	25	6
2/28/2017	0	0	1	26	10	13	19
3/1/2017	0	0	7	26	7	20	15
3/2/2017	0	0	0	14	9	12	6
3/6/2017	0	0	0	11	11	22	4
3/7/2017	0	0	0	13	4	19	6

Date	Broken Rails	Track Circuit	2000	2003 0 km 4.8 km	2003 14.8 km 19.6 km	2003 34.7 km 40.1 km	2005
3/8/2017	0	0	0	12	7	17	3
3/9/2017	1	0	0	17	9	22	13
3/13/2017	1	1	0	3	1	7	1
3/14/2017	1	1	2	13	11	15	8
3/15/2017	0	0	0	4	7	8	11
3/16/2017	0	0	0	19	10	9	2
3/27/2017	0	0	1	5	8	13	13
3/28/2017	1	1	4	15	8	18	12
3/29/2017	0	0	0	16	9	15	6
3/30/2017	0	0	0	13	11	13	4
4/3/2017	2	1	3	13	5	13	15
4/4/2017	0	0	0	11	11	10	27
4/5/2017	0	0	0	16	11	12	17
4/6/2017	0	0	0	8	9	11	23
4/17/2017	0	0	0	10	5	14	8
4/18/2017	0	0	0	7	2	12	7
4/19/2017	0	0	0	16	9	7	3
4/20/2017	0	0	0	23	20	18	10
4/24/2017	0	0	0	16	6	9	19
4/25/2017	1	0	0	28	32	33	24
4/26/2017	0	0	4	10	12	26	33
4/27/2017	0	0	4	8	7	15	19
5/1/2017	0	0	8	16	18	26	18
5/2/2017	0	0	0	19	9	14	7
5/3/2017	0	0	0	23	8	18	14
5/4/2017	0	0	0	26	4	16	17
5/15/2017	0	0	12	9	13	24	22
5/16/2017	0	0	0	18	17	11	11
5/17/2017	0	0	1	30	10	14	10

Date	Broken Rails	Track Circuit	2000	2003 0 km 4.8 km	2003 14.8 km 19.6 km	2003 34.7 km 40.1 km	2005
5/18/2017	0	0	1	7	9	11	13
6/5/2017	0	0	0	11	5	16	14
6/6/2017	0	0	1	10	4	24	11
6/7/2017	0	0	3	8	13	10	5
6/8/2017	0	0	1	6	2	4	5
6/12/2017	0	0	3	18	14	16	6
6/13/2017	1	0	0	24	13	23	18
6/14/2017	0	0	1	7	3	9	4
6/15/2017	0	0	1	7	6	4	3
9/18/2017	1	0	1	34	28	33	3
9/19/2017	0	0	0	26	16	16	4
9/20/2017	0	0	1	12	17	14	9
9/21/2017	0	0	1	16	18	17	16
9/25/2017	0	0	0	18	25	10	13
9/26/2017	1	0	0	22	28	27	6
9/27/2017	0	0	0	15	15	9	6
9/28/2017	0	0	0	21	16	8	8
10/9/2017	2	2	2	N/A	N/A	N/A	N/A
10/10/2017	0	0	0	23	23	17	26
10/11/2017	0	0	1	13	4	14	13
10/12/2017	0	0	0	4	2	7	3
10/16/2017	0	0	0	25	8	26	13
10/17/2017	2	1	2	8	12	8	5
10/18/2017	0	0	1	21	14	12	16
10/19/2017	0	0	0	8	8	13	2
10/23/2017	0	0	0	8	15	9	10
10/24/2017	1	1	0	23	23	19	21
10/25/2017	0	0	0	17	17	19	9
10/26/2017	2	1	1	17	12	26	21

Date	Broken Rails	Track Circuit	2000	2003 0 km 4.8 km	2003 14.8 km 19.6 km	2003 34.7 km 40.1 km	2005
10/30/2017	0	0	N/A	N/A	N/A	N/A	15
10/31/2017	0	0	N/A	N/A	N/A	N/A	37
11/1/2017	1	1	N/A	45	18	27	12
11/2/2017	0	0	2	18	21	29	22
11/6/2017	0	0	0	40	33	20	21
11/7/2017	1	1	1	36	27	23	38
11/8/2017	0	0	0	38	21	46	39
11/9/2017	1	0	2	N/A	N/A	N/A	N/A

During testing and analysis of rail break alarms from the DAS systems, certain areas were found to experience a larger number of false alarms. After examining the track and locations where a larger number of alarms were found, 12 areas of particular note were identified. In addition to the analysis of the DAS systems completed for all alarms, additional data analysis was performed for alarms in these areas, to determine the number and percentage of alarms that occurred in these areas.

The areas identified as experiencing an increased number of alarms included switches, lubricators, insulated joints, fiber configuration, and bridges. Table 4 shows the number of alarms that occur for each track feature. Figure 11 shows a map of the HTL and the starting and ending location for each track feature. A few of the areas identified in the table are areas where track circuits also have trouble identifying rail breaks, due to jumpers around the features. These areas include switches, frogs, crossings, and bridge sections. Some areas have a larger number of alarms due to track features or fiber layout and these alarms might be eliminated with better fiber installation or improved configuration of the system.

Table 4: Overview of Alarms Caused by Track Features

	Track Feature	DAS 2000	DAS 2003 0 km–4.8 km	DAS 2003 14.8 km–19.6 km	DAS 2003 34.7 km–40.1 km	DAS 2005	Alarms per Feature
1	**Switch to Frog**	0	30	10	15	71	6
2	**Rail Lubricator**	1	13	6	6	0	26
3	**Crossing/Rail lubricator**	0	55	52	18	32	157
4	**Switch**	2	8	10	30	2	52
5	**Level Crossing**	1	4	1	25	14	45
6	**Insulated Joints**	3	73	135	320	237	768
7	**Switch**	0	2	2	2	0	6
8	**Bridge 1**	0	13	25	10	19	67
9	**Bridge 2**	0	8	24	92	71	195
10	**Bridge 3**	11	2	14	129	91	247
11	**Fiber Depth Change**	3	19	21	9	6	58
12	**Fiber Crosses RTT**	3	94	88	123	34	342
	Total Alarms per DAS System within Track Features Listed	24	321	388	779	577	
	Total alarms per DAS System during Trial	79	1377	1086	1388	996	
	Percentage of alarms within Track Features listed	30.4%	23.3%	35.7%	56.1%	57.9%	

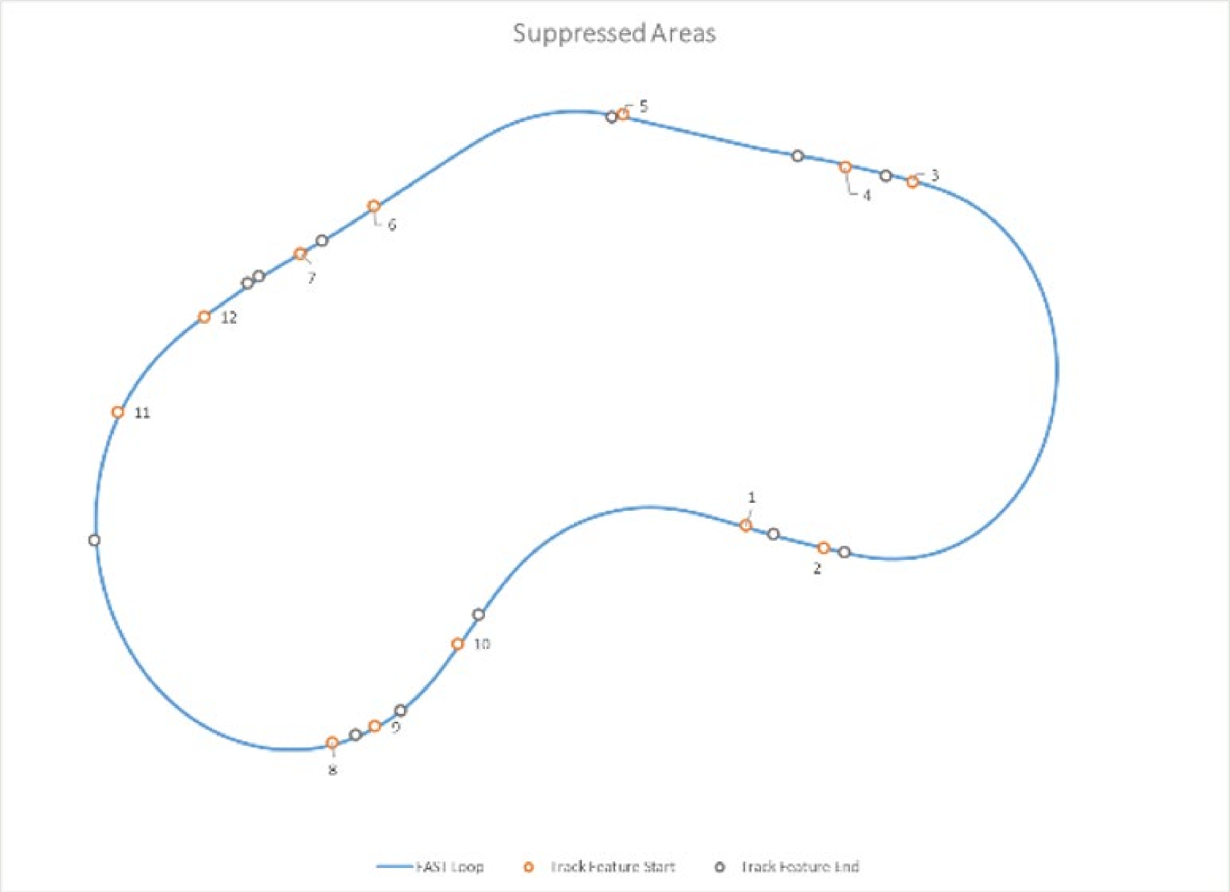


Figure 11. Location of Suppressed Areas

2.2.4 Data Analysis from Normal FAST Operations

Data from the daily FAST logs and DAS system rail break alarms from the RAIL_BREAK_DEFECT table in the fiber optic back office database were used to determine the validity of each alarm.

For each DAS system, GPS location and timestamp data from the rail break alarms were used to determine the location and time of the broken rail alarm. If an alarm was within 450 feet of an actual rail break and within two hours of the break being detected by the track circuit system, the alarm was recorded as a true positive. If an alarm was within 450 feet of an actual rail break that the track circuit did not detect and the alarm was prior to the broken rail being found by the test crew, the alarm was recorded as a true positive. Rail breaks that the DAS system did not alarm on were recorded as false negatives and all other alarms were recorded as false positives.

Table 5 provides an overview of the results from each DAS system during the trial for the dates each DAS system was active (i.e., after their final software updates and system configuration). For DAS system 2000, the system was active and the analysis included data from February 13, 2017, and later. For DAS systems 2003 and 2005, the system was active and the analysis included data from December 5, 2016, and later. The “Rail Breaks Detected” column in Table 5 corresponds to the number of rail breaks detected by each system, and the “True Positives” column corresponds to the number of alarms that were caused by actual rail breaks. In cases where the number of true positives are greater than the number of broken rails detected, the systems alarmed multiple times for one or more of the individual rail breaks. The "False Negatives" column in Table 5 correspond to the number of actual rail breaks each system missed, meaning the system did not alarm for the rail break. Any alarm from a DAS system that was not a true positive was determined to be a false positive.

Table 5: Overview of Trial Results

	Rail Breaks	Rail Breaks Detected	True Positives	False Positives	False Positives	Total Number of Alarms	Number of Alarms in Track Features (Table 4)	Alarms Outside Track Features (Table 4)
2000	22	8	9	70	14	79	24	55
2003 0 km–4.8 km	22	4	7	1370	18	1377	321	1056
2003 14.8 km–19.6 km	22	4	4	1082	18	1086	388	698
2003 34.7 km–40.1 km	22	3	10	1378	19	1388	779	609
2003	22	6	21	3830	16	3851	1488	2363
2005	22	4	4	992	18	996	577	419

Data Analysis for DAS System 2000

Data analysis on DAS system 2000 included data from February 13, 2017, to November 9, 2017. Over this period, DAS 2000 was active for 76 days and the train operating on the HTL completed 8,306 laps, which equates to approximately 22,426 train miles. Weekly summary data from the trial for DAS system 2000 is included in Table 6. As shown in Table 5 and Table 6, the FAST program observed 22 rail breaks during the 76 days DAS system 2000 was active and, of those 22 rail breaks, the track circuit identified 13 and the DAS system identified 8. The data in the table also shows that the track circuit had 9 false negatives and the DAS system had 14 false negatives and 70 false positives. Normalizing the false positives to a false alarm rate per 100 train miles, DAS system 2000 had a false alarm rate of 0.31 false alarms per 100 train miles.

Table 6: DAS System 2000 Data from February 2017–November 2017

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Track Features (Table 4	Alarms Outside Track Features (Table 4)
2/13/2017-2/16/2017	1	1	0	1	3	0	4	2	2
2/21/2017-2/23/2017	1	1	0	0	1	1	1	1	0
2/27/2017-3/2/2017	1	1	0	0	9	1	9	4	5
3/6/2017-3/9/2017	1	0	1	0	0	1	0	0	0
3/13/2017-3/16/2017	2	2	0	1	1	1	2	1	1
3/27/2017-3/30/2017	1	1	0	0	5	1	5	5	0
4/3/2017-4/6/2017	2	1	1	1	2	1	3	0	3
4/17/2017-4/20/2017	0	0	0	0	0	0	0	0	0
4/24/2017-4/27/2017	1	0	1	0	8	1	8	0	8
5/1/2017-5/4/2017	0	0	0	0	8	0	8	2	6
5/15/2017-5/18/2017	0	0	0	0	14	0	14	5	9
6/5/2017-6/8/2017	0	0	0	0	5	0	5	0	5
6/12/2017-6/15/2017	1	0	1	0	5	1	5	1	4
9/18/2017-9/21/2017	1	0	1	1	2	0	3	1	2
9/25/2017-9/28/2017	1	0	1	0	0	1	0	0	0
10/9/2017-10/12/2017	2	2	0	1	2	1	3	1	2
10/16/2017-10/19/2017	2	1	1	1	2	1	3	1	2
10/23/2017-10/26/2017	3	2	1	1	0	2	1	0	1

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Track Features (Table 4	Alarms Outside Track Features (Table 4)
11/2/2017	0	0	0	0	2	0	2	0	2
11/6/2017-11/9/2017	2	1	1	2	1	1	3	0	3
Total	22	13	9	9	70	14	79	24	55

Analyzing the alarms further, the data shows that 24 of the 79 alarms, or approximately 30 percent, were located within track features that were identified as being particularly susceptible to higher alarm rates, per the discussion in Section 2.2.3. These alarms can be eliminated from the system by having them suppressed, but each area that is suppressed would then not have broken rail detection from the system. Raw data from the system can be used by the vendor to improve system configuration and response to reduce false alarms and improve the accuracy of broken rail detection.

Data Analysis for DAS System 2003

Data analysis on DAS system 2003 included data from December 5, 2016, to November 9, 2017. Over this period, DAS 2003 was active for 77 days and the train operating on the HTL completed 8,072 laps, which equates to approximately 21,794 train miles. DAS 2003 covered a wider date range and was active for an additional day than DAS 2000, but had fewer laps and miles during the trial. This is because the number of laps varies on a day by day basis depending on what testing was being completed and how many times the train had to stop during that day of testing. For the days DAS 2003 was active, there were fewer laps completed than when DAS 2000 was active.

Loop 1 0 km–4.8 km

Weekly summary data from the trial for DAS system 2003, loop 1, is included in Table 7. As shown in Table 5 and Table 7, the FAST program observed 22 rail breaks during the 77 days DAS system 2003 was active, and of those 22 rail breaks, the track circuit identified 14 and the DAS system identified 4. The data in the tables also shows that the track circuit had 8 false negatives and the DAS system had 18 false negatives and 1,370 false positives. Normalizing the false positives to a false alarm rate per 100 train miles, DAS system 2003, loop 1, had a false alarm rate of 6.29 false alarms per 100 train miles.

Table 7: DAS System 2003, Loop 1, Data from December 2016–November 2017

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Track Features (Table 4	Alarms Outside Track Features (Table 4)
12/5/2016-12/8/2016	2	2	0	0	161	2	161	63	98
2/14/2017-2/16/2017	1	1	0	0	49	1	49	5	44
2/22/2017-2/23/2017	1	1	0	0	36	1	36	1	35
2/27/2017-3/2/2017	1	1	0	0	77	1	77	23	54
3/6/2017-3/9/2017	1	0	1	0	53	1	53	16	37
3/13/2017-3/16/2017	2	2	0	0	39	2	39	14	25
3/27/2017-3/30/2017	1	1	0	0	49	1	49	15	34
4/3/2017-4/6/2017	2	1	1	2	46	1	48	17	31
4/17/2017-4/20/2017	0	0	0	0	56	0	56	13	43
4/24/2017-4/27/2017	1	0	1	2	60	0	62	22	40
5/1/2017-5/4/2017	0	0	0	0	84	0	84	5	79
5/15/2017-5/18/2017	0	0	0	0	64	0	64	5	59
6/5/2017-6/8/2017	0	0	0	0	35	0	35	3	32
6/12/2017-6/15/2017	1	0	1	1	55	0	56	11	45
9/18/2017-9/21/2017	1	0	1	2	86	0	88	30	58
9/25/2017-9/28/2017	1	0	1	0	76	1	76	14	62

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Track Features (Table 4	Alarms Outside Track Features (Table 4)
10/10/2017-10/12/2017	0	0	0	0	40	0	40	5	35
10/16/2017-10/19/2017	2	1	1	0	62	2	62	10	52
10/23/2017-10/26/2017	3	2	1	0	65	3	65	10	55
11/1/2017-11/2/2017	1	1	0	0	63	1	63	16	47
11/6/2017-11/8/2017	1	1	0	0	114	1	114	23	91
Total	22	14	8	7	1370	18	1377	321	1056

Loop 2 14.8 km–19.6 km

Weekly summary data from the trial for DAS system 2003, loop 2, is included in Table 8. As shown in Table 5 and Table 8, the FAST program observed 22 rail breaks during the 77 days DAS system 2003 was active, and of those 22 rail breaks, the track circuit identified 14 and the DAS system identified 4. The data in the tables also shows that the track circuit had 8 false negatives and the DAS system had 18 false negatives and 1,082 false positives. Normalizing the false positives to a false alarm rate per 100 train miles, DAS system 2003, loop 2, had a false alarm rate of 4.96 false alarms per 100 train miles.

Table 8: DAS System 2003, Loop 2, Data from December 2016–November 2017

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Track Features (Table 4	Alarms Outside Track Features (Table 4)
12/5/2016-12/8/2016	2	2	0	1	187	1	188	92	96
2/14/2017-2/16/2017	1	1	0	0	42	1	42	11	31
2/22/2017-2/23/2017	1	1	0	0	29	1	29	4	25
2/27/2017-3/2/2017	1	1	0	0	33	1	33	18	15

	Rail Breaks	**True Positive (Track Circuit)**	**False Negatives (Track Circuit)**	**True Positives (DAS)**	**False Positives (DAS)**	**False Negatives (DAS)**	**Total Number of Alarms**	**Number of Alarms in Track Features (Table 4**	**Alarms Outside Track Features (Table 4)**
3/6/2017-3/9/2017	1	0	1	0	31	1	31	15	16
3/13/2017-3/16/2017	2	2	0	0	29	2	29	15	14
3/27/2017-3/30/2017	1	1	0	0	36	1	36	11	25
4/3/2017-4/6/2017	2	1	1	1	35	1	36	17	19
4/17/2017-4/20/2017	0	0	0	0	36	0	36	15	21
4/24/2017-4/27/2017	1	0	1	1	56	0	57	31	26
5/1/2017-5/4/2017	0	0	0	0	39	0	39	14	25
5/15/2017-5/18/2017	0	0	0	0	49	0	49	14	35
6/5/2017-6/8/2017	0	0	0	0	24	0	24	7	17
6/12/2017-6/15/2017	1	0	1	1	35	0	36	6	30
9/18/2017-9/21/2017	1	0	1	0	79	1	79	26	53
9/25/2017-9/28/2017	1	0	1	0	84	1	84	24	60
10/10/2017-10/12/2017	0	0	0	0	29	0	29	2	27
10/16/2017-10/19/2017	2	1	1	0	42	2	42	13	29
10/23/2017-10/26/2017	3	2	1	0	67	3	67	18	49
11/1/2017-11/2/2017	1	1	0	0	39	1	39	1	38
11/6/2017-11/8/2017	1	1	0	0	81	1	81	34	47

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Track Features (Table 4	Alarms Outside Track Features (Table 4)
Total	22	14	8	4	1082	18	1086	388	698

Loop 3 34.7 km–40.1 km

Weekly summary data from the trial for DAS system 2003, loop 3, is included in Table 9. As shown in Table 5 and Table 9, the FAST program observed 22 rail breaks during the 77 days DAS system 2003 was active, and of those 22 rail breaks, the track circuit identified 14 and the DAS system identified 3. The data in the tables also show that the track circuit had 8 false negatives and the DAS system had 19 false negatives and 1,388 false positives. Normalizing the false positives to a false alarm rate per 100 train miles, DAS system 2003, loop 2, had a false alarm rate of 6.37 false alarms per 100 train miles.

Table 9: DAS System 2003, Loop 3, Data from December 2016–November 2017

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Track Features (Table 4	Alarms Outside Track Features (Table 4)
12/5/2016-12/8/2016	2	2	0	0	207	2	207	91	116
2/14/2017-2/16/2017	1	1	0	0	38	1	38	22	16
2/22/2017-2/23/2017	1	1	0	0	26	1	26	12	14
2/27/2017-3/2/2017	1	1	0	0	70	1	70	57	13
3/6/2017-3/9/2017	1	0	1	0	80	1	80	71	9
3/13/2017-3/16/2017	2	2	0	0	39	2	39	28	11
3/27/2017-3/30/2017	1	1	0	0	59	1	59	43	16
4/3/2017-4/6/2017	2	1	1	3	43	1	46	33	13
4/17/2017-4/20/2017	0	0	0	0	51	0	51	33	18

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Track Features (Table 4	Alarms Outside Track Features (Table 4)
4/24/2017-4/27/2017	1	0	1	0	83	1	83	53	30
5/1/2017-5/4/2017	0	0	0	0	74	0	74	33	41
5/15/2017-5/18/2017	0	0	0	0	60	0	60	41	19
6/5/2017-6/8/2017	0	0	0	0	54	0	54	32	22
6/12/2017-6/15/2017	1	0	1	0	52	1	52	29	23
9/18/2017-9/21/2017	1	0	1	6	74	0	80	56	24
9/25/2017-9/28/2017	1	0	1	1	53	0	54	30	24
10/10/2017-10/12/2017	0	0	0	0	38	0	38	16	22
10/16/2017-10/19/2017	2	1	1	0	59	2	59	19	40
10/23/2017-10/26/2017	3	2	1	0	73	3	73	31	42
11/1/2017-11/2/2017	1	1	0	0	56	1	56	21	35
11/6/2017-11/8/2017	1	1	0	0	89	1	89	28	61
Total	22	14	8	10	1378	19	1388	779	609

Additional Analysis for DAS System 2003

Looking at alarms within the track features particularly susceptible to higher alarm rates per the discussion in Section 2.2.3 for each loop, the data shows that loop 1 had 321 of the 1,377 alarms, or approximately 23 percent, within these track features, loop 2 had 388 of the 1,086 alarms, or approximately 36 percent, within these track features, and loop 3 had 779 of the 1,388 alarms, or approximately 56 percent, within these track features.

As each of these loops were monitoring the same track and train, just at different lengths along the fiber, trending analysis can be completed for system performance along the fiber. Looking at broken rail alarms, outside of the track features particularly susceptible to higher alarm rates, DAS system 2003 appears to be less sensitive the further away the fiber gets from the data collector, as seen by the number of alarms in loops 1, 2, and 3, which were 1,056; 698; and 609 alarms, respectively. Conversely, DAS system 2003 appears to be more sensitive to alarms within the track features particularly susceptible to higher alarm rates, as the number and percentage of alarms climbs from 321 and 23 percent for loop 1, to 388 and 36 percent for loop 2, and to 779 and 56 percent for loop 3. Raw data can be analyzed by the vendor to help determine why the system sensitivity changes in these areas.

Alarms in the track features are particularly susceptible to higher alarm rates that can be eliminated by suppressing those areas, which would significantly reduce the total number of alarms by the system, but that would also remove any type of broken rail detection from the system in those areas. The raw data may be used by the vendor to make improvements in the future that can reduce the number of false alarms and increase the accuracy of broken rail detection.

Data Analysis for DAS System 2005

Data analysis on DAS system 2005 included data from December 5, 2016, to November 9, 2017. Over this period, DAS 2005 was active for 80 days and the train operating on the HTL completed 8,400 laps, which equates to approximately 22,680 train miles. Weekly summary data from the trial for DAS system 2005 is included in Table 10. As shown in Table 5 and Table 10, the FAST program observed 22 rail breaks during the 80 days DAS system 2005 was active, and of those 22 rail breaks, the track circuit identified 14 and the DAS system identified 4. The data in the table also shows that the track circuit had 8 false negatives and the DAS system had 18 false negatives and 992 false positives. Normalizing the false positives to a false alarm rate per 100 train miles, DAS system 2005 had a false alarm rate of 4.37 false alarms per 100 train miles.

Table 10: DAS System 2005 Data from December 2016–November 2017

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Masked Area	Alarms Outside Masked Area
12/5/2016-12/8/2016	2	2	0	1	36	1	37	26	11
2/14/2017-2/16/2017	1	1	0	0	37	1	37	19	18
2/22/2017-2/23/2017	1	1	0	0	22	1	22	15	7
2/27/2017-3/2/2017	1	1	0	0	46	1	46	33	13
3/6/2017-3/9/2017	1	0	1	0	26	1	26	12	14

	Rail Breaks	True Positive (Track Circuit)	False Negatives (Track Circuit)	True Positives (DAS)	False Positives (DAS)	False Negatives (DAS)	Total Number of Alarms	Number of Alarms in Masked Area	Alarms Outside Masked Area
3/13/2017-3/16/2017	2	2	0	0	22	2	22	16	6
3/27/2017-3/30/2017	1	1	0	0	35	1	35	20	15
4/3/2017-4/6/2017	2	1	1	1	81	1	82	64	18
4/17/2017-4/20/2017	0	0	0	0	28	0	28	22	6
4/24/2017-4/27/2017	1	0	1	1	94	0	95	41	54
5/1/2017-5/4/2017	0	0	0	0	56	0	56	14	42
5/15/2017-5/18/2017	0	0	0	0	56	0	56	27	29
6/5/2017-6/8/2017	0	0	0	0	35	0	35	17	18
6/12/2017-6/15/2017	1	0	1	0	31	1	31	19	12
9/18/2017-9/21/2017	1	0	1	0	32	1	32	16	16
9/25/2017-9/28/2017	1	0	1	0	33	1	33	20	13
10/10/2017-10/12/2017	0	0	0	0	42	0	42	14	28
10/16/2017-10/19/2017	2	1	1	0	36	2	36	24	12
10/23/2017-10/26/2017	3	2	1	0	61	3	61	34	27
11/1/2017-11/2/2017	1	1	0	0	86	1	86	59	27
11/6/2017-11/8/2017	1	1	0	1	97	0	98	65	33
Total	22	14	8	4	992	18	996	577	419

Analyzing the alarms further, the data shows that 577 of the 996 alarms, or approximately 56 percent, were located within track features that were identified as being particularly susceptible to higher alarm rates, per the discussion in Section 2.2.3. Again, these alarms can be eliminated from the system by having them suppressed, but each area that is suppressed would then not have broken rail detection from the system. Raw data from the system can be used by the vendor to improve system configuration and response to reduce false alarms and improve the accuracy of broken rail detection.

2.3 Data Gathering and Analysis for Additional Testing

The evaluation of the broken rail detection of DAS systems was conducted during normal FAST operations, which means the majority of the testing was completed using a similar train operating at an average speed of 40 mph. A week of additional testing was conducted to see if the introduction of different speeds, high impact wheels, and/or rail joint alignments would result in additional false alarms produced by the DAS systems.

2.3.1 Speed Test

Given that the FAST train normally operates at a constant average speed of 40 mph, it was important to see how the systems performed while monitoring a train at speeds other than 40 mph, as well as during train acceleration and deceleration. This was the focus of testing on December 5, 2016. The locomotive of the FAST train was equipped with a GPS receiver. Figure 12 details the speed plot of the train during testing that day, obtained from the GPS data. The test plan called for the train to proceed at approximately 10 mph, 30 mph, and 20 mph for 10 consecutive laps around the HTL at each speed. Alarms from each system were monitored in the back office and used to determine if speed changes or operating at different speeds resulted in additional broken rail alarms. No broken rails were experienced on this day of testing.

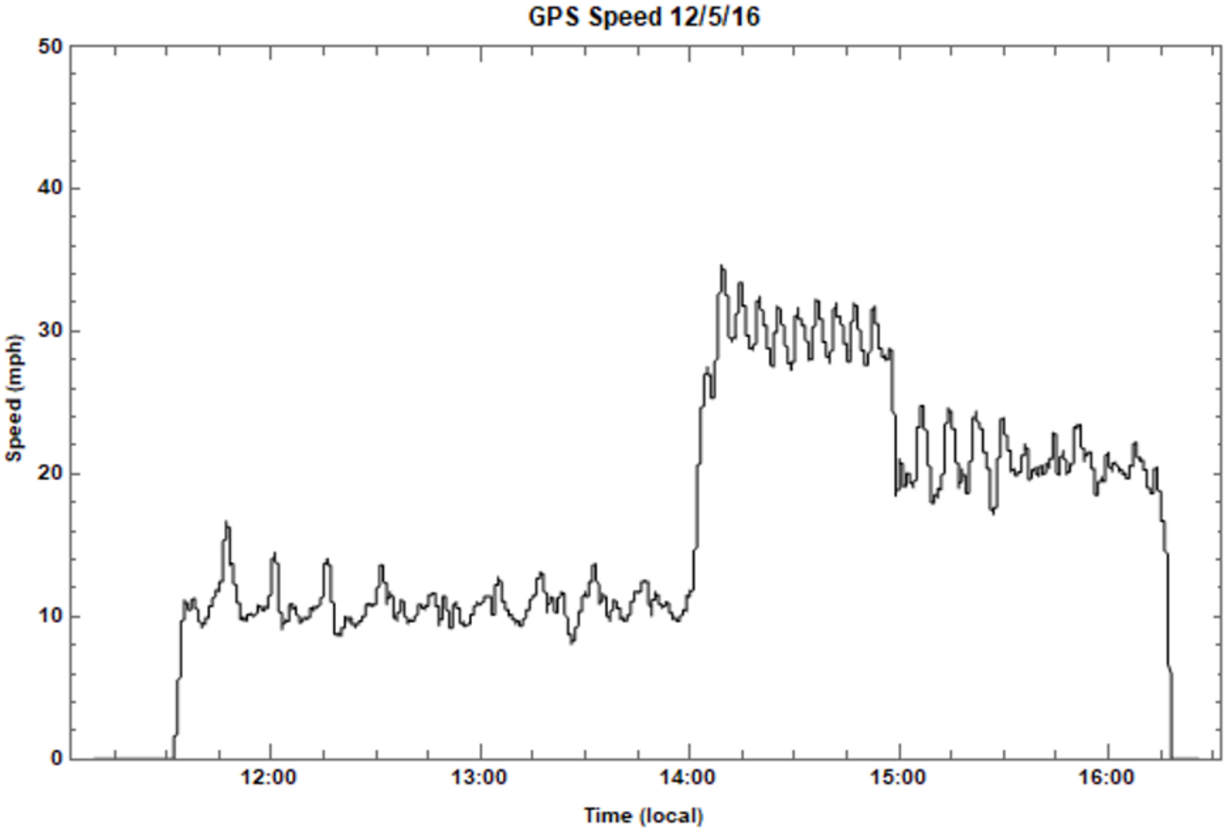


Figure 12. Locomotive GPS Speed

During this day of testing, DAS 2000 had no broken rail alarms. Therefore, it appears the varying speed did not directly result in additional broken rail detection false alarms. However, because the system needs to track the train and determine its speed to perform broken rail detection, it is important to note that the speed data from this system, depicted in Figure 13, shows that the system had issues tracking the train's speed when it was traveling at 10 mph, meaning DAS system 2000 may not be able to provide broken rail detection at slower speeds in its current configuration.

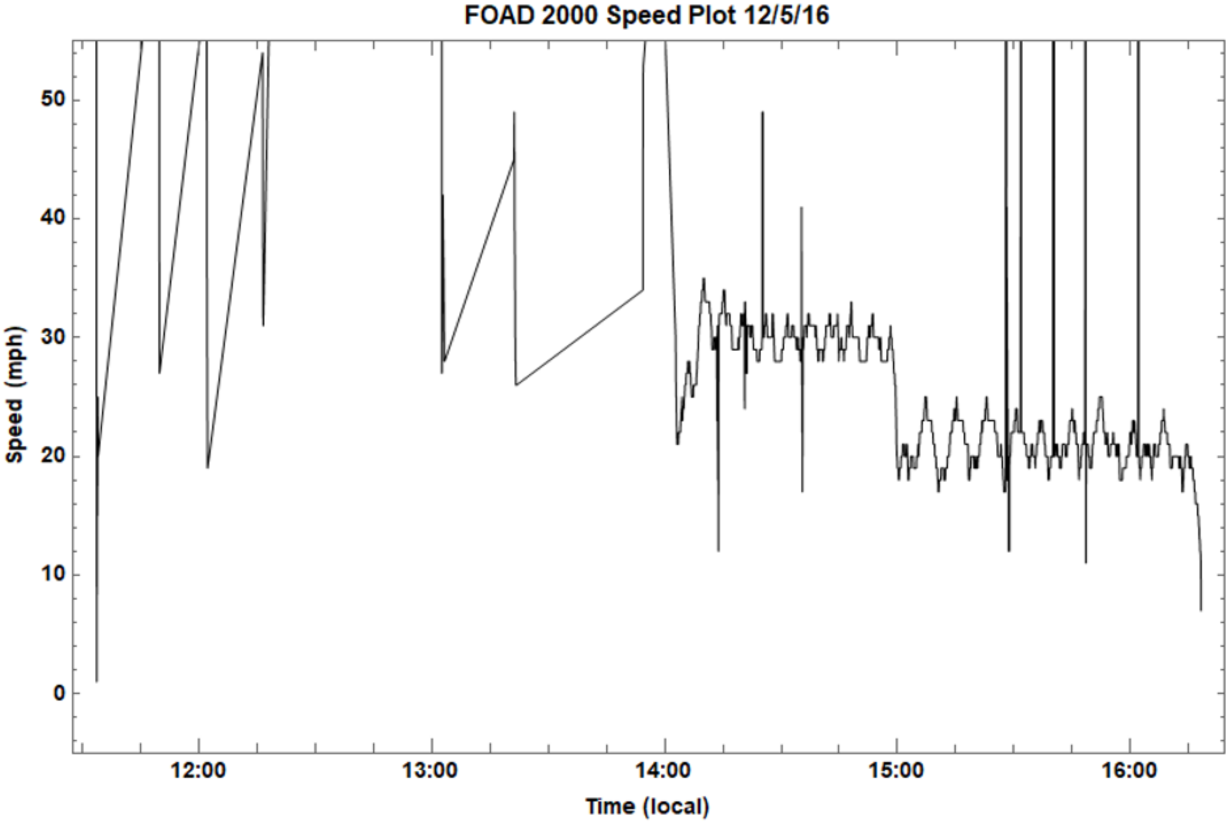


Figure 13. Speed Plot for DAS System 2000

DAS System 2003 did produce false positive broken rail alarms during the speed testing. Plots of broken rail alarms and speed for loops 1, 2, and 3 are shown in Figure 14 through Figure 16, respectively. Looking at the total number of alarms at each speed, in Figure 14, through Figure 16, there is a trend of a higher rate of alarms when operating at lower constant average speeds than at the higher constant average speeds. Furthermore, looking at the number of false alarms during the 30 laps of speed testing, the number of false alarms per 100 train miles for loops 1, 2, and 3 are 38.27 false alarms per 100 train miles, 40.74 false alarms per 100 train miles, and 61.73 false alarms per 100 train miles, respectively. Over the whole trial, DAS 2003 had a false positive rate ranging from 4.96 to 6.37 false alarms per 100 train miles for the FAST train operating mostly at a constant average speed of 40 mph. Therefore, it appears the varying speed testing did result in additional broken rail detection false alarms for DAS 2003.

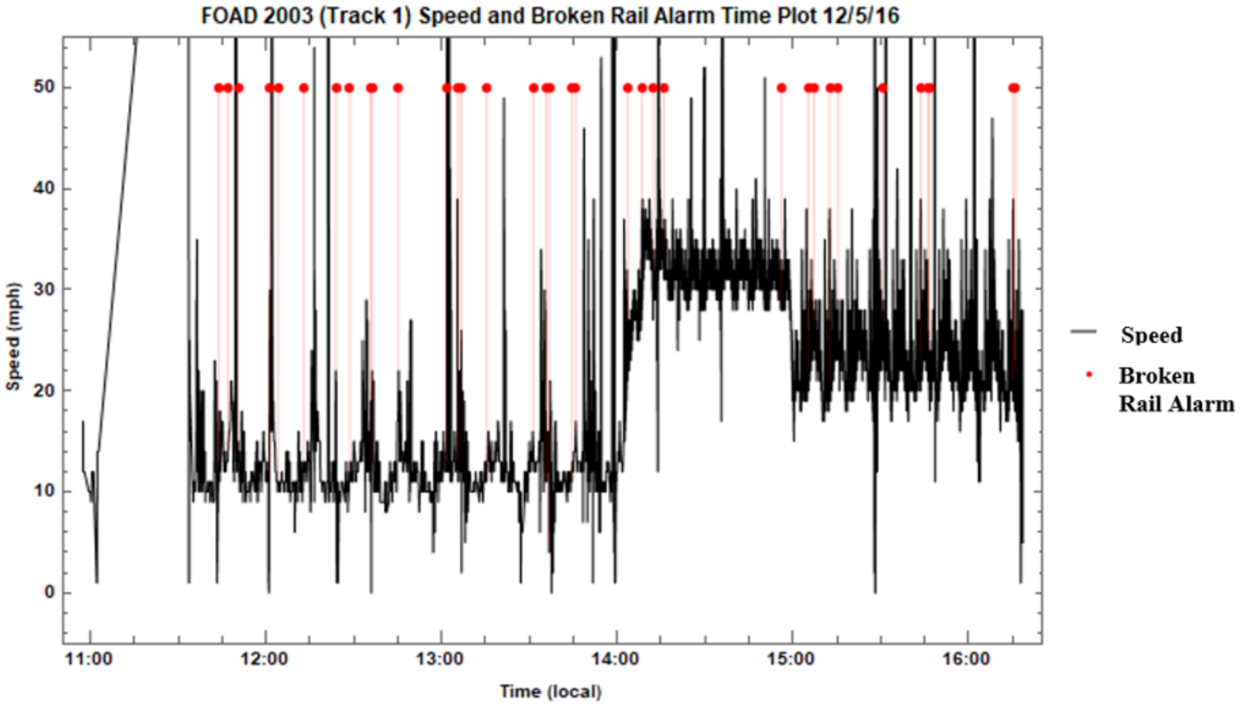


Figure 14. Speed Plot for DAS System 2003 Loop 1

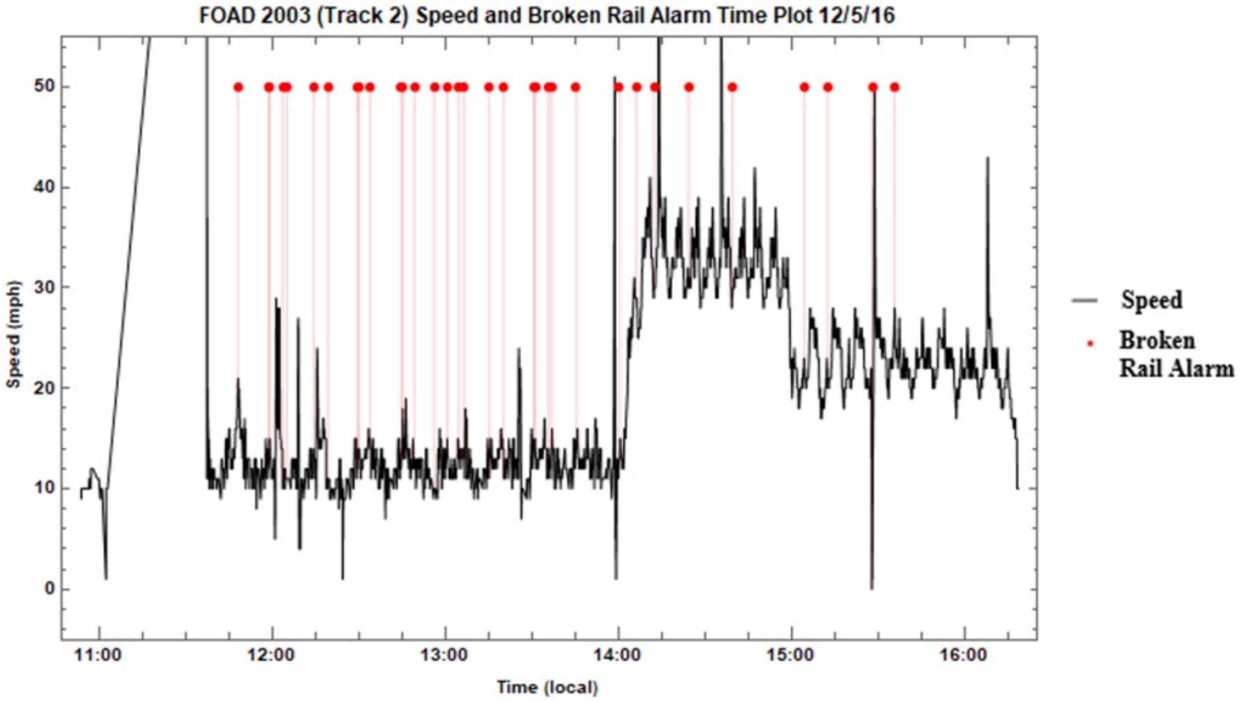


Figure 15. Speed Plot for DAS System 2003 Loop 2

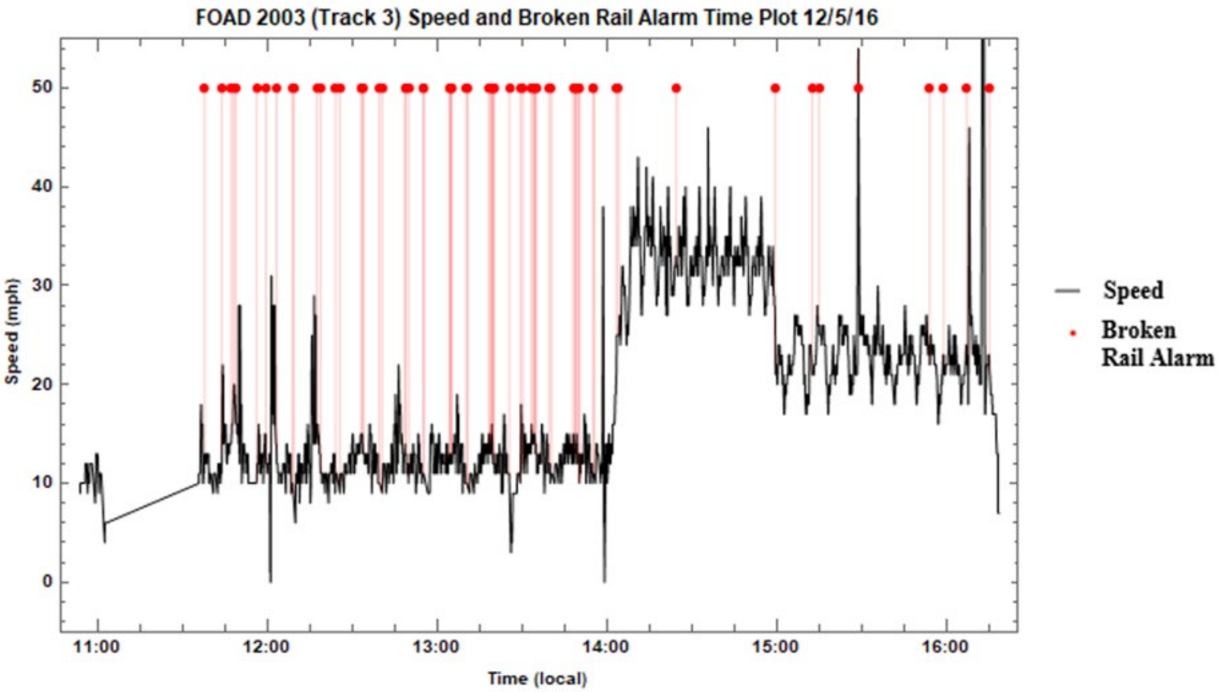


Figure 16. Speed Plot for DAS System 2003 Loop 3

DAS system 2005 also produced false positive broken rail alarms during the speed testing. Figure 17 shows a plot of broken rail alarms and speed reported by DAS system 2005. Looking at the number of false alarms during the 30 laps of speed testing, the number of false alarms per 100 train miles is 17.28 false alarms per 100 train miles. Over the whole trial, DAS 2005 had a false positive rate of 4.37 false alarms per 100 train miles for the FAST train operating mostly at a constant average speed of 40 mph. Therefore, it appears the varying speed testing did result in additional broken rail detection false alarms for DAS 2005.

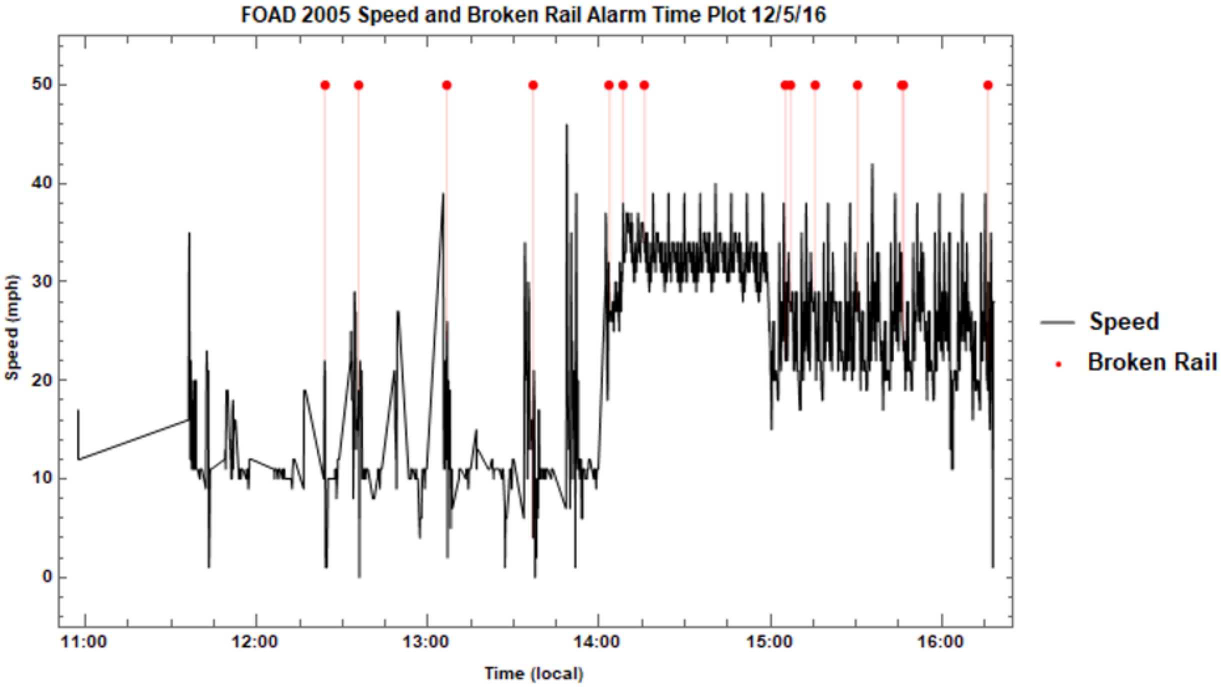
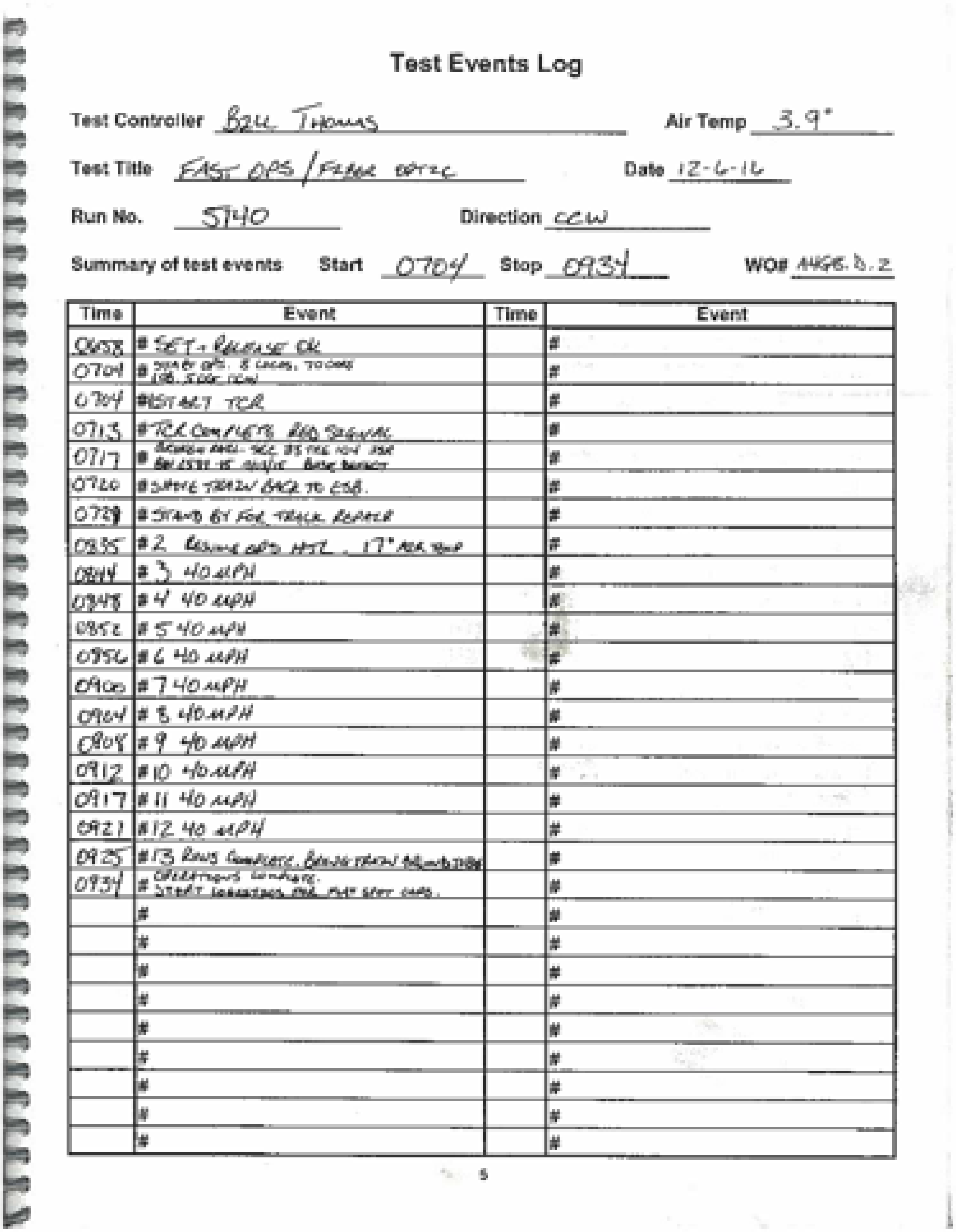


Figure 17. Speed Plot for DAS System 2005

2.3.2 High Impact Wheel Test

From December 6–7, 2016, high impact wheels were introduced into the FAST train and grouped together to see if the high impacts from these wheels produce false broken rail alarms. There was a broken rail, before testing started, during the test conditioning run (TCR) in section 33. There were no additional broken rails experienced during the high impact wheel testing. High impact test run 5140 involved high impact wheels on four cars that had been identified by the FAST crew that were randomly placed in the FAST train. The train ran for 13 laps around the HTL at around 40 mph. Figure 18 is the Test Events Log for run 5140 and Figure 19 is the FAST Consist Recording, with highlighted cars showing where the high impact wheels were located in the train.



Test Events Log

Test Controller BILL THOMAS **Air Temp** 3.9°

Test Title FAST OPS / FIBER OPTIC **Date** 12-6-16

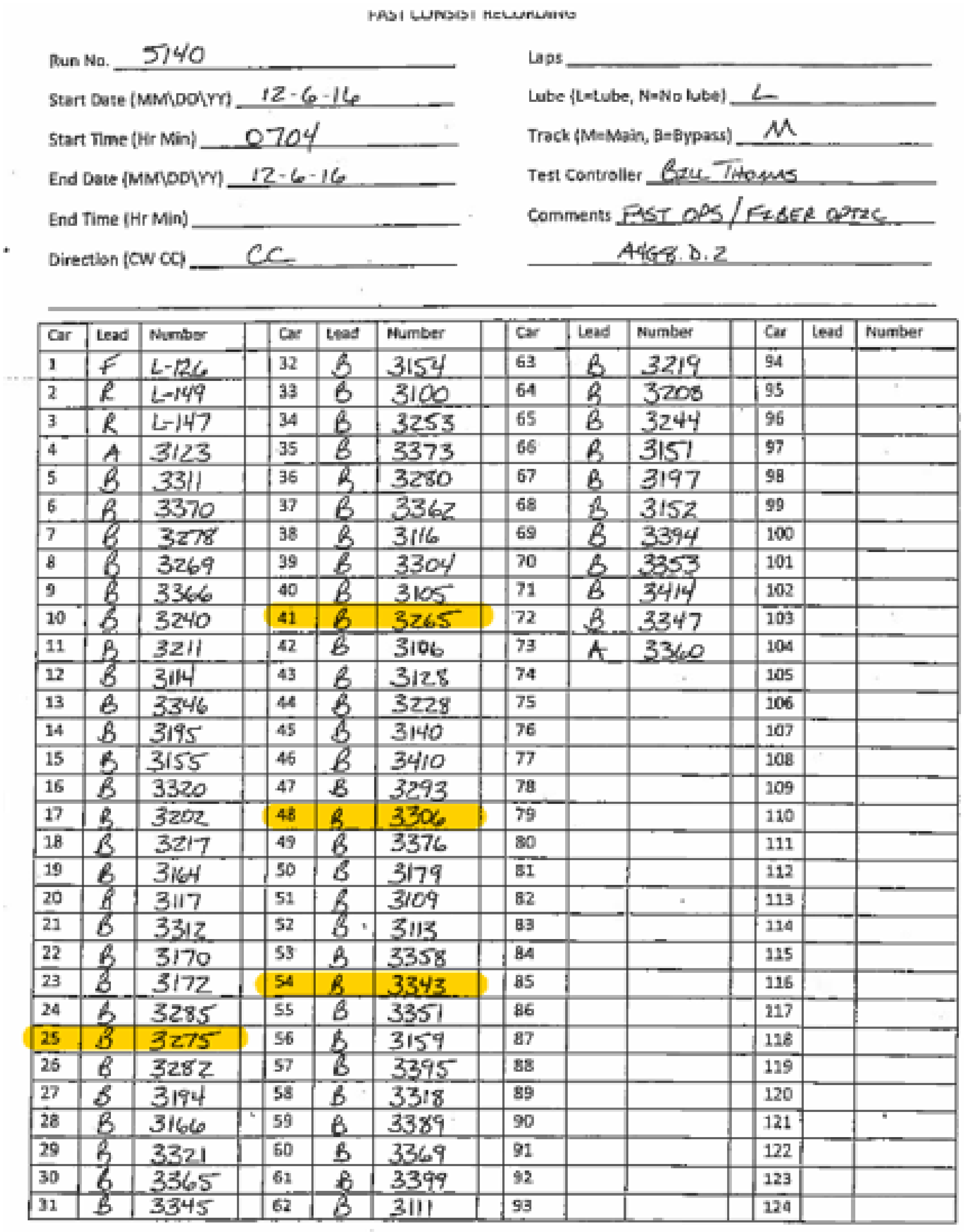
Run No. 5140 **Direction** CCW

Summary of test events **Start** 0704 **Stop** 0934 **WO#** AHGE.b.2

Time	Event	Time	Event
0658	# SET + RELEASE OK		#
0704	# START OPS. 8 LOCOS, 70 CARS [illegible]		#
0704	# START TCR		#
0713	# TCR COMPLETE RED SIGNAL		#
0717	# [illegible]		#
0720	# SHOVE TRAIN BACK TO [illegible].		#
0739	# STAND BY FOR TRACK REPAIR		#
0835	# 2 RESUME OPS HTL . 17° AIR TEMP		#
0844	# 3 40 MPH		#
0848	# 4 40 MPH		#
0852	# 5 40 MPH		#
0856	# 6 40 MPH		#
0900	# 7 40 MPH		#
0904	# 8 40 MPH		#
0908	# 9 40 MPH		#
0912	# 10 40 MPH		#
0917	# 11 40 MPH		#
0921	# 12 40 MPH		#
0925	# 13 RUNS COMPLETE. [illegible]		#
0934	# OPERATIONS COMPLETE. START [illegible] FOR FLAT SPOT CARS.		#
	#		#
	#		#
	#		#
	#		#
	#		#
	#		#
	#		#
	#		#
	#		#

5

Figure 18. Test Events Log for High Impact Wheel Testing Run 5140



FAST CONSIST RECORDING

Run No. 5140

Start Date (MM\DD\YY) 12-6-16

Start Time (Hr Min) 0704

End Date (MM\DD\YY) 12-6-16

End Time (Hr Min)

Direction (CW CC) CC

Laps

Lube (L=Lube, N=No lube) L

Track (M=Main, B=Bypass) M

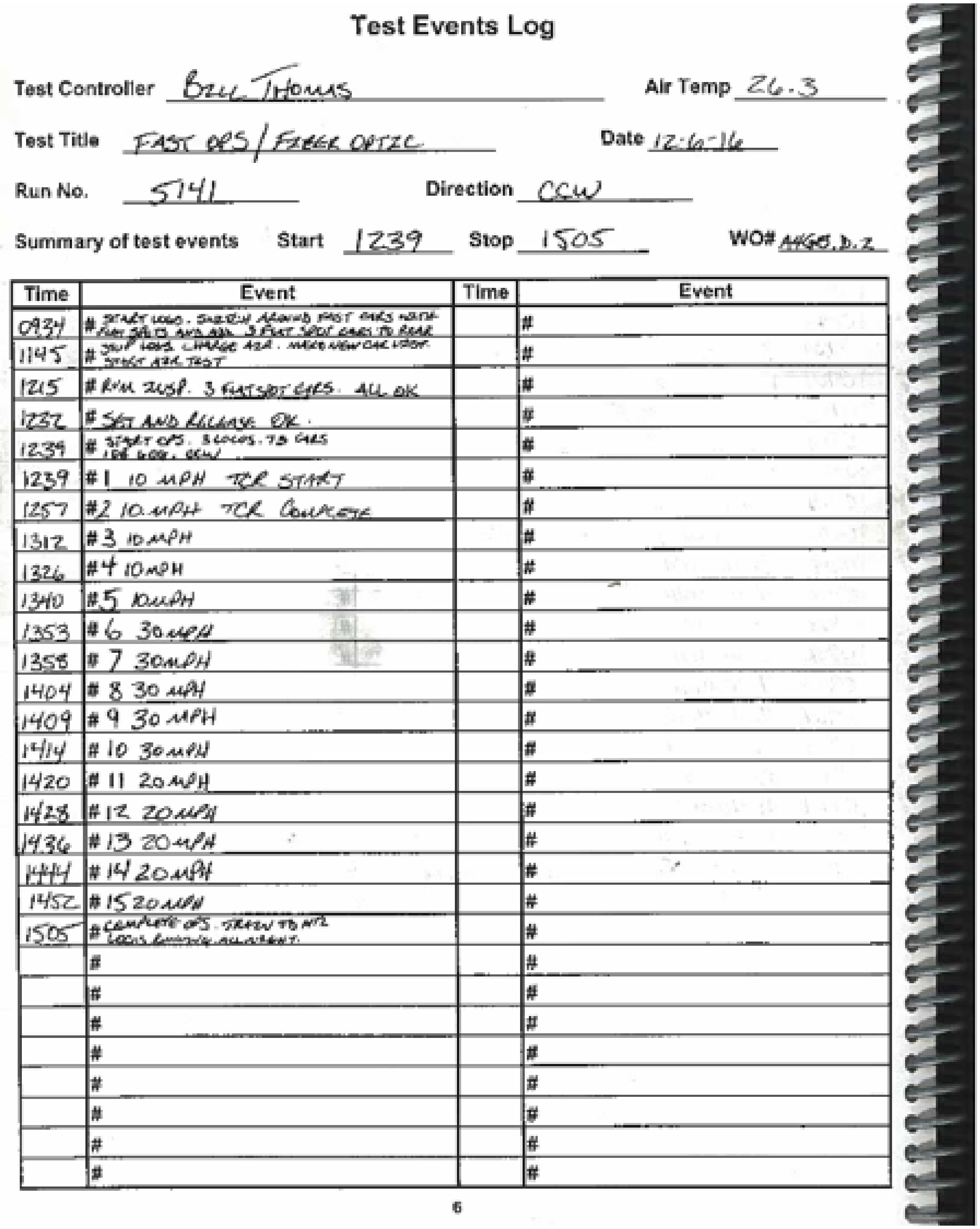
Test Controller BILL THOMAS

Comments FAST OPS / FIBER OPTIC A4G8. D. 2

Car	Lead	Number	Car	Lead	Number	Car	Lead	Number	Car	Lead	Number
1	F	L-126	32	B	3154	63	B	3219	94		
2	R	L-149	33	B	3100	64	B	3208	95		
3	R	L-147	34	B	3253	65	B	3244	96		
4	A	3123	35	B	3373	66	B	3151	97		
5	B	3311	36	B	3280	67	B	3197	98		
6	B	3370	37	B	3362	68	B	3152	99		
7	B	3278	38	B	3116	69	B	3394	100		
8	B	3269	39	B	3304	70	B	3353	101		
9	B	3366	40	B	3105	71	B	3414	102		
10	B	3240	41	B	3265	72	B	3347	103		
11	B	3211	42	B	3106	73	A	3360	104		
12	B	3114	43	B	3128	74			105		
13	B	3346	44	B	3228	75			106		
14	B	3195	45	B	3140	76			107		
15	B	3155	46	B	3410	77			108		
16	B	3320	47	B	3293	78			109		
17	B	3202	48	B	3306	79			110		
18	B	3217	49	B	3376	80			111		
19	B	3164	50	B	3179	81			112		
20	B	3117	51	B	3109	82			113		
21	B	3312	52	B	3113	83			114		
22	B	3170	53	B	3358	84			115		
23	B	3172	54	B	3343	85			116		
24	B	3285	55	B	3351	86			117		
25	B	3275	56	B	3159	87			118		
26	B	3282	57	B	3395	88			119		
27	B	3194	58	B	3318	89			120		
28	B	3166	59	B	3389	90			121		
29	B	3321	60	B	3369	91			122		
30	B	3365	61	B	3399	92			123		
31	B	3345	62	B	3111	93			124		

Figure 19. FAST Consist for High Impact Wheel Testing Run 5140

High impact test run 5141 included the four cars with high impact wheels from test run 5140, grouped together in the middle of the train and three additional cars with artificial high impact defects at the end of the train. The train operated in this configuration for five laps at 10 mph, five laps at 30 mph, and five laps at 20 mph. Figure 20 and Figure 21 shows the Test Events Log and FAST Consist Recording for high impact test run 5141. Figure 22 shows a picture of an artificial high impact defect introduced in a wheel.



Test Events Log

Test Controller BILL THOMAS

Air Temp 26.3

Test Title FAST OPS / FIBER OPTIC

Date 12-6-16

Run No. 5141

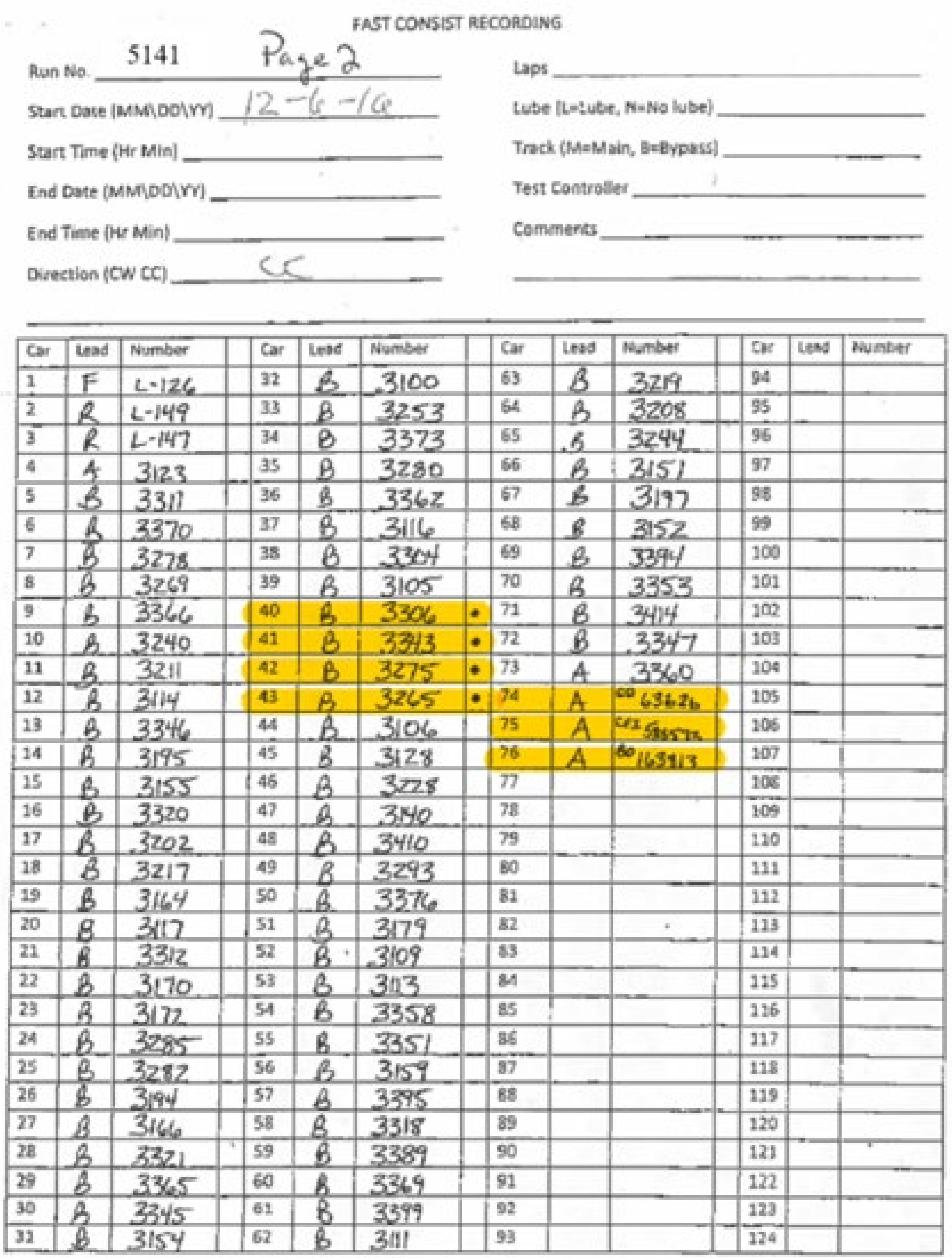
Direction CCW

Summary of test events Start 1239 Stop 1505 WO# A4G6.D.2

Time	Event	Time	Event
0934	# START LOGS. SKETCH AROUND FAST CARS WITH FLAT SPOTS AND ADD 3 FLAT SPOT CARS TO REAR		#
1145	# SHUT LOGS. CHARGE AIR. MAKE NEW CAR LOOP. START AIR TEST		#
1215	# RUN 2USP. 3 FLATSPOT CARS. ALL OK		#
1232	# SET AND RELEASE OK.		#
1239	# START OPS. 3 LOCOS. 73 CARS 108 LOOP. CCW		#
1239	#1 10 MPH TCR START		#
1257	#2 10 MPH TCR COMPLETE		#
1312	#3 10 MPH		#
1326	#4 10 MPH		#
1340	#5 10 MPH		#
1353	#6 30 MPH		#
1358	#7 30 MPH		#
1404	#8 30 MPH		#
1409	#9 30 MPH		#
1414	#10 30 MPH		#
1420	#11 20 MPH		#
1428	#12 20 MPH		#
1436	#13 20 MPH		#
1444	#14 20 MPH		#
1452	#15 20 MPH		#
1505	# COMPLETE OPS. TRAIN TO NTL LOCOS RUNNING ALL NIGHT.		#
	#		#
	#		#
	#		#
	#		#
	#		#
	#		#
	#		#
	#		#

6

Figure 20. Test Events Log for High Impact Wheel Testing Run 5141



FAST CONSIST RECORDING

Run No. 5141 Page 2

Start Date (MM\DD\YY) 12-6-16

Start Time (Hr Min)

End Date (MM\DD\YY)

End Time (Hr Min)

Direction (CW CC) CC

Laps

Lube (L=Lube, N=No lube)

Track (M=Main, B=Bypass)

Test Controller

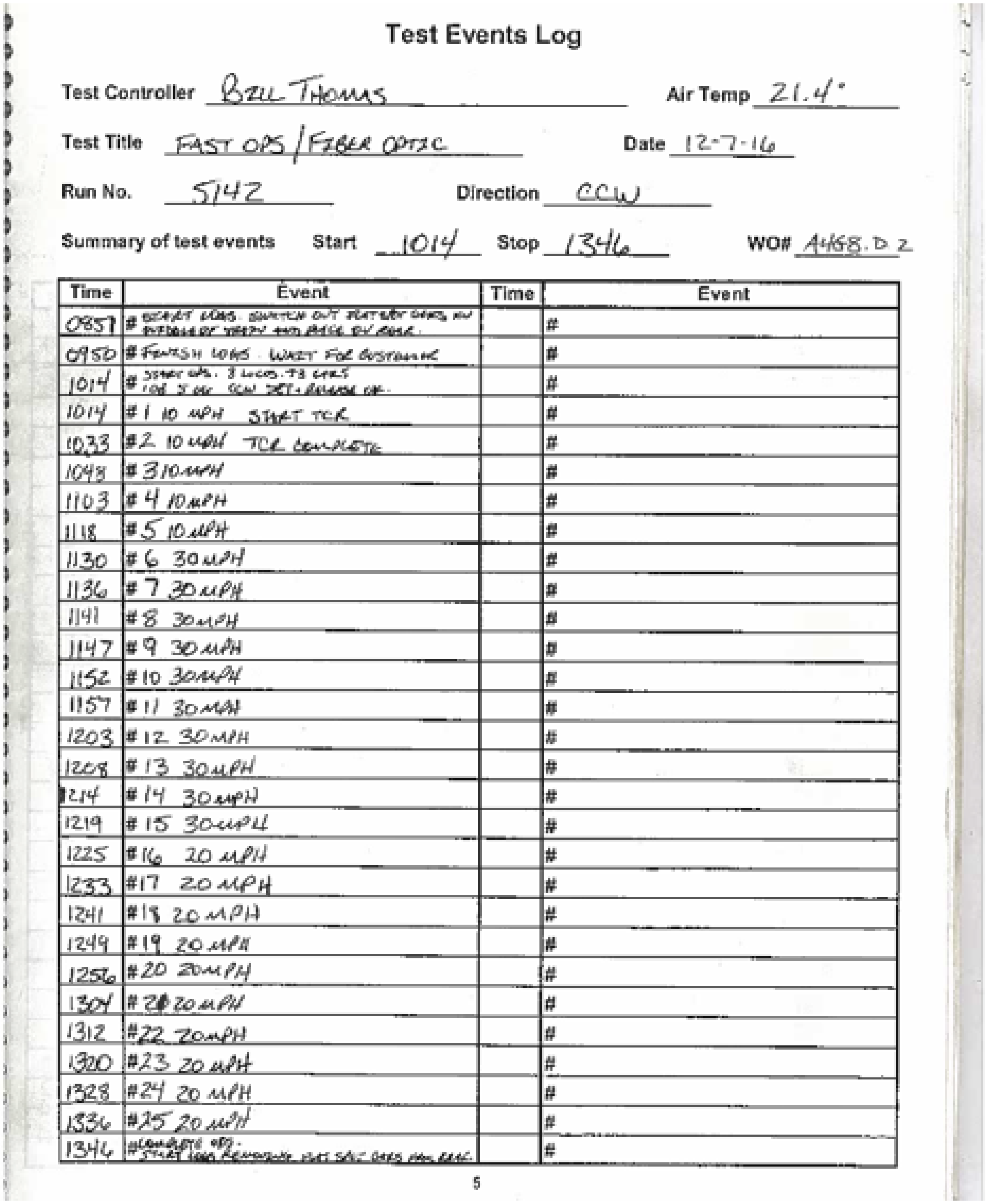
Comments

Car	Lead	Number		Car	Lead	Number		Car	Lead	Number		Car	Lead	Number
1	F	L-126		32	B	3100		63	B	3219		94		
2	R	L-149		33	B	3253		64	B	3208		95		
3	R	L-147		34	B	3373		65	B	3244		96		
4	A	3123		35	B	3280		66	B	3151		97		
5	B	3311		36	B	3362		67	B	3197		98		
6	B	3370		37	B	3116		68	B	3152		99		
7	B	3278		38	B	3304		69	B	3394		100		
8	B	3269		39	B	3105		70	B	3353		101		
9	B	3366		40	B	3306	●	71	B	3414		102		
10	B	3240		41	B	3343	●	72	B	3347		103		
11	B	3211		42	B	3275	●	73	A	3360		104		
12	B	3114		43	B	3265	●	74	A	DD 63626		105		
13	B	3346		44	B	3106		75	A	[illegible]		106		
14	B	3195		45	B	3128		76	A	BO 163913		107		
15	B	3155		46	B	3228		77				108		
16	B	3320		47	B	3140		78				109		
17	B	3202		48	B	3410		79				110		
18	B	3217		49	B	3293		80				111		
19	B	3164		50	B	3376		81				112		
20	B	3117		51	B	3179		82				113		
21	B	3312		52	B	3109		83				114		
22	B	3170		53	B	3113		84				115		
23	B	3172		54	B	3358		85				116		
24	B	3285		55	B	3351		86				117		
25	B	3282		56	B	3159		87				118		
26	B	3194		57	B	3395		88				119		
27	B	3166		58	B	3318		89				120		
28	B	3321		59	B	3389		90				121		
29	B	3365		60	B	3369		91				122		
30	B	3345		61	B	3399		92				123		
31	B	3154		62	B	3111		93				124		

Figure 21. FAST Consist for High Impact Wheel Testing Run 5141

Figure 22. Artificial Flat Used to Cause High Impacts

High impact wheel test run 5142 grouped all seven cars with high impact wheels at the end of the train. The train operated in this configuration for 5 laps at 10 mph, 10 laps at 30 mph, and 10 laps at 20 mph. Figure 23 and Figure 24 show the Test Events Log and FAST Consist Recording for high impact test run 5142.



Test Events Log

Test Controller BILL THOMAS Air Temp 21.4°

Test Title FAST OPS / FIBER OPTIC Date 12-7-16

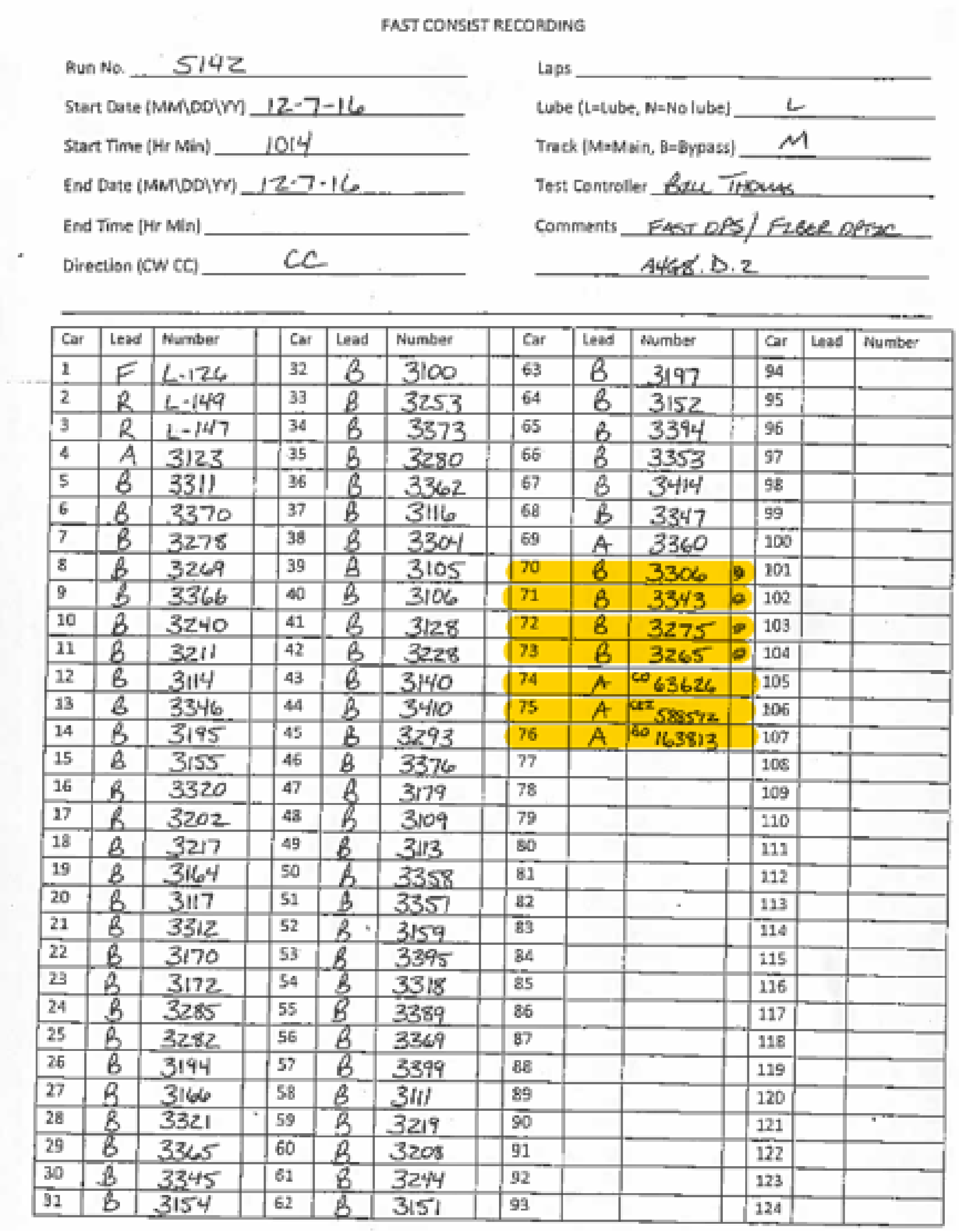
Run No. 5142 Direction CCW

Summary of test events Start 1014 Stop 1346 WO# A468.D2

Time	Event	Time	Event
0851	# START LOGS. SWITCH OUT [illegible] CARS, [illegible]		#
0950	# FINISH LOGS. WAIT FOR CUSTOMER		#
1014	# START OPS. 3 LOCOS. 78 CARS [illegible]		#
1014	# 1 10 MPH START TCR		#
1033	# 2 10 MPH TCR COMPLETE		#
1048	# 3 10 MPH		#
1103	# 4 10 MPH		#
1118	# 5 10 MPH		#
1130	# 6 30 MPH		#
1136	# 7 30 MPH		#
1141	# 8 30 MPH		#
1147	# 9 30 MPH		#
1152	# 10 30 MPH		#
1157	# 11 30 MPH		#
1203	# 12 30 MPH		#
1208	# 13 30 MPH		#
1214	# 14 30 MPH		#
1219	# 15 30 MPH		#
1225	# 16 20 MPH		#
1233	# 17 20 MPH		#
1241	# 18 20 MPH		#
1249	# 19 20 MPH		#
1256	# 20 20 MPH		#
1304	# 21 20 MPH		#
1312	# 22 20 MPH		#
1320	# 23 20 MPH		#
1328	# 24 20 MPH		#
1336	# 25 20 MPH		#
1346	# COMPLETE OPS. START LOGS [illegible]		#

5

Figure 23. Test Events Log for High Impact Wheel Testing Run 5142



FAST CONSIST RECORDING

Run No. 5142

Start Date (MM\DD\YY) 12-7-16

Start Time (Hr Min) 1014

End Date (MM\DD\YY) 12-7-16

End Time (Hr Min)

Direction (CW CC) CC

Laps

Lube (L=Lube, N=No lube) L

Track (M=Main, B=Bypass) M

Test Controller BILL THOMAS

Comments FAST DPS/ FIBER OPTIC

A468.D.2

Car	Lead	Number	Car	Lead	Number	Car	Lead	Number	Car	Lead	Number
1	F	L-126	32	B	3100	63	B	3197	94		
2	R	L-149	33	B	3253	64	B	3152	95		
3	R	L-147	34	B	3373	65	B	3394	96		
4	A	3123	35	B	3280	66	B	3353	97		
5	B	3311	36	B	3362	67	B	3414	98		
6	B	3370	37	B	3116	68	B	3347	99		
7	B	3278	38	B	3304	69	A	3360	100		
8	B	3269	39	B	3105	70	B	3306	101		
9	B	3366	40	B	3106	71	B	3343	102		
10	B	3240	41	B	3128	72	B	3275	103		
11	B	3211	42	B	3228	73	B	3265	104		
12	B	3114	43	B	3140	74	A	CO 63626	105		
13	B	3346	44	B	3410	75	A	CEZ 588572	106		
14	B	3195	45	B	3293	76	A	GO 163813	107		
15	B	3155	46	B	3376	77			108		
16	B	3320	47	B	3179	78			109		
17	B	3202	48	B	3109	79			110		
18	B	3217	49	B	3113	80			111		
19	B	3164	50	B	3358	81			112		
20	B	3117	51	B	3357	82			113		
21	B	3312	52	B	3159	83			114		
22	B	3170	53	B	3395	84			115		
23	B	3172	54	B	3318	85			116		
24	B	3285	55	B	3389	86			117		
25	B	3282	56	B	3369	87			118		
26	B	3194	57	B	3399	88			119		
27	B	3166	58	B	3111	89			120		
28	B	3321	59	B	3219	90			121		
29	B	3365	60	B	3208	91			122		
30	B	3345	61	B	3244	92			123		
31	B	3154	62	B	3151	93			124		

Figure 24. FAST Consist for High Impact Wheel Testing Run 5142

Table 11 shows the number of alarms for each DAS system for the high impact wheel testing.

Table 11: Broken Rail Alarms During High Impact Wheel Testing

System	Run 5140	Run 5141	Run 5142
DAS System 2000	0	0	0
DAS System 2003 Loop 1	1	84	69

System	Run 5140	Run 5141	Run 5142
DAS System 2003 Loop 2	3	69	64
DAS System 2003 Loop 3	4	58	62
DAS System 2005	1	9	9

DAS system 2000 does not appear to have an increased rate of false alarms due to high impact wheels, as evidenced by the fact that it did not produce any alarms during this testing. However, the increase of broken rail alarms from DAS systems 2003 and 2005 when high impact wheels are grouped together warranted further analysis. This analysis consisted of taking timestamps of the GPS locations of the head of the train correlated with the timestamps of the GPS locations of the broken rail alarms provided by each system. Using the GPS locations for the head end of the train and the GPS location for the broken rail alarm, the location relative to the head of the train of each broken rail alarm was calculated. Histograms were plotted representing the counts of broken rail alarms every 25 meters from the head end of the train. Figure 25 shows histograms of broken rail alarms for high impact runs 5141 and 5142 along the train length for DAS system 2003 and Figure 26 shows the same for DAS system 2005. These broken rail alarm locations within the train were then compared to the FAST consist record for each run to determine if the broken rail alarm was located around the high impact wheels.

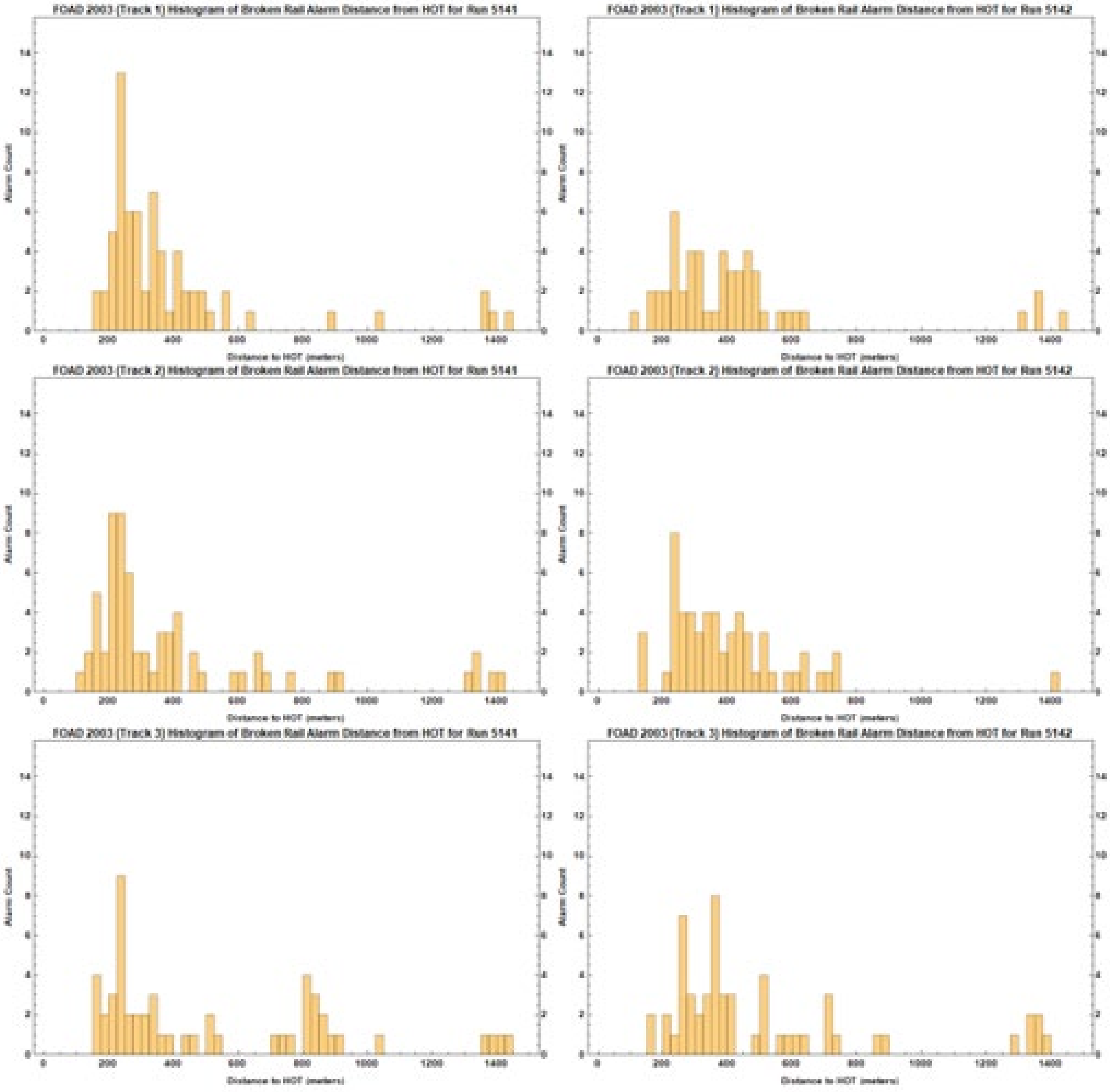


Figure 25. Broken Rail Alarm Histograms for DAS System 2003

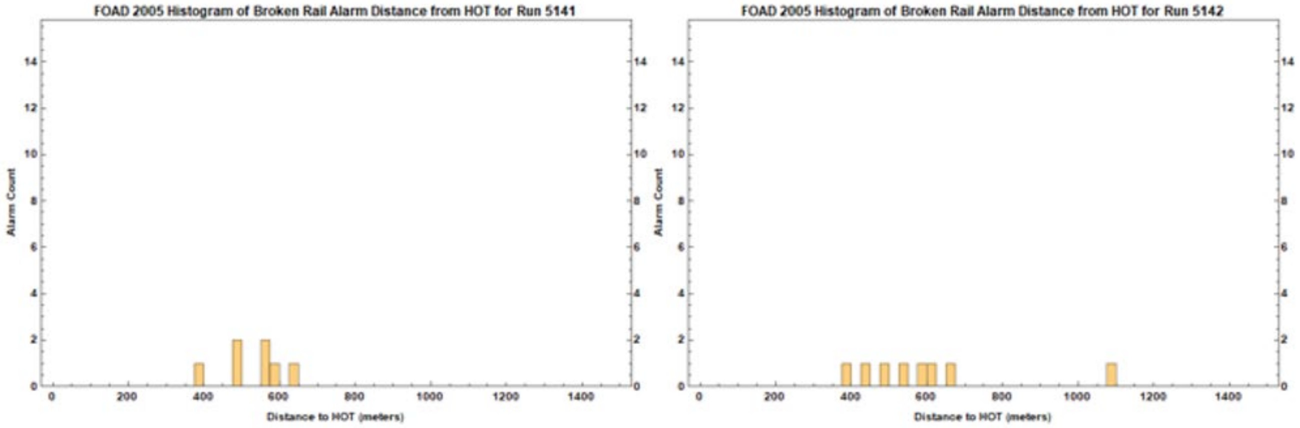


Figure 26. Broken Rail Alarm Histograms for DAS System 2005

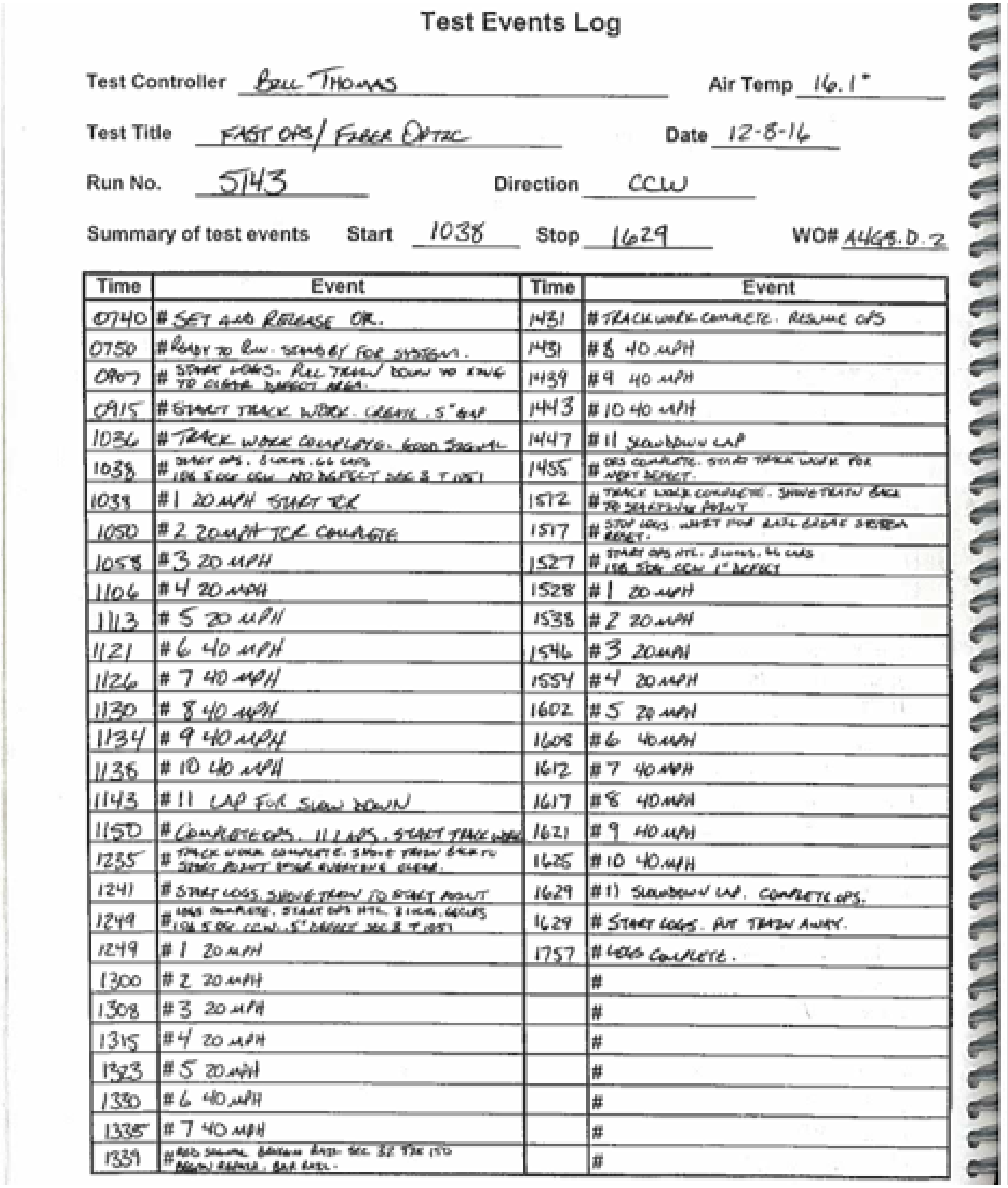
Not every broken rail alarm was included in these histograms, due to missing or very poor train location information provided by the systems for some of the broken rail alarms. The majority of the data however, did have train location information that was correlated with broken rail data to plot these histograms. The train length for the high impact wheel testing was approximately 1,267 meters long. For run 5141, the high impact wheels were located at approximately 658 meters to 724 meters and at 1,217 meters to 1,267 meters from the head of the train. For test run 5142 the high impact wheels were located at approximately 1,152 meters to 1,267 meters from the head of the train. Using the length of the train and the location of the high impact wheels, the histograms were used to observe if there were a high number of alarms located around the high impact wheels.

Histograms for DAS system 2003 show that the majority of the broken rail alarms were located at the front of the train where no high impact wheels were located. In test run 5141, there were high impact wheels located approximately 658 meters to 724 meters from the front of the train, but those high impact wheels were moved to the end of the train for test run 5142. Looking at histograms for test runs 5141 and 5142 and alarms around 600 to 800 meters from the front of the train, there is no noticeable difference in the number of alarms in that range, indicating that these high impact wheels did not seem to cause an increase in the number of broken rail alarms, at the location of high impact wheels located in the middle of the train. For both test runs 5141 and 5142, there are high impact wheels located at the rear of the train and the histograms do show a few broken rail alarms toward the rear of the train which may be caused by these high impact wheels. The histograms also indicate that some of the broken rail alarms occur at a distance beyond the length of the train, which are probably caused by timing and location inaccuracy in the alarms, as well as acoustic signatures extending beyond the end of the train. Looking at the number of false alarms during the 45 laps of testing for test runs 5141 and 5142, the number of false alarms per 100 train miles for loops 1, 2, and 3 are 125.93 false alarms per 100 train miles, 109.47 false alarms per 100 train miles, and 98.77 false alarms per 100 train miles, respectively. Over the whole trial, DAS 2003 had a false positive rate ranging from 4.96 to 6.37 false alarms per 100 train miles for the FAST train operating predominantly at a constant average speed of 40 mph. Therefore, it appears this high impact wheel testing did result in additional broken rail detection false alarms for DAS 2003. Further testing will be required to determine if the additional broken rail alarms were due to the high impact wheels, the test speed, or a combination of both.

Histograms of broken rail alarms for DAS system 2005 indicate that high impact wheels did not appear to cause an increase in the number of false positive alarms at the location of high impact wheels in the trail. However, looking at the number of false alarms during the 45 laps of testing for test runs 5141 and 5142, the number of false alarms per 100 train miles for DAS 2005 is 12.34 false alarms per 100 train miles. DAS 2005 had a false positive rate of 4.37 false alarms per 100 train miles for the FAST train operating mostly at a constant average speed of 40 mph. Therefore, it appears this high impact wheel testing did result in additional broken rail detection false alarms for DAS 2005. Further testing will be required to determine if the additional broken rail alarms were due to the high impact wheels, the test speed, or a combination of both.

2.3.3 Rail Gap Test

On December 8, 2016, the train was operated over a rail joint of varying gap widths to see if gaps at rail joints cause an increase in broken rail alarms. This joint was located in section 3, near tie 1051 on the HTL. Initially, the rails were butted up against each other with no gap. Then gaps of 1/2 inch and 1 inch were introduced. The train was tested over these gaps at speeds of 20 and 40 mph for five laps at each speed. Figure 27 is the Test Events Log for run 5143 for the rail gap testing. The DAS systems did report broken rail alarms during the rail gap testing, but none of the alarms appeared to be caused by the gaps in the rail joint. Figure 28 shows the location of the rail joint under test and the location of broken rail alarms for each DAS system.



Test Events Log

Test Controller BILL THOMAS Air Temp 16.1°

Test Title FAST OPS / FIBER OPTIC Date 12-8-16

Run No. 5143 Direction CCW

Summary of test events Start 1038 Stop 1629 WO# A4G5.D.2

Time	Event	Time	Event
0740	# SET AND RELEASE OR.	1431	# TRACK WORK COMPLETE. RESUME OPS
0750	# READY TO RUN. STANDBY FOR SYSTEM.	1431	# 8 40 MPH
0907	# START LOGS. PULL TRAIN DOWN TO [illegible] TO CLEAR DEFECT AREA.	1439	# 9 40 MPH
0915	# START TRACK WORK. CREATE .5" GAP	1443	# 10 40 MPH
1036	# TRACK WORK COMPLETE. GOOD SIGNAL	1447	# 11 SLOWDOWN LAP
1038	# START OPS. 8 LOCOS. 66 CARS 106 5 DEG CCW. NO DEFECT SEC 3 T [illegible]	1455	# OPS COMPLETE. START TRACK WORK FOR NEXT DEFECT.
1039	# 1 20 MPH START TCR	1512	# TRACK WORK COMPLETE. SHOVE TRAIN BACK TO STARTING POINT
1050	# 2 20 MPH TCR COMPLETE	1517	# STOP LOGS. WAIT FOR RAIL BREAK SYSTEM RESET.
1058	# 3 20 MPH	1527	# START OPS HTL. 8 LOCOS. 66 CARS 106 5 DEG CCW 1" DEFECT
1106	# 4 20 MPH	1528	# 1 20 MPH
1113	# 5 20 MPH	1538	# 2 20 MPH
1121	# 6 40 MPH	1546	# 3 20 MPH
1126	# 7 40 MPH	1554	# 4 20 MPH
1130	# 8 40 MPH	1602	# 5 20 MPH
1134	# 9 40 MPH	1608	# 6 40 MPH
1138	# 10 40 MPH	1612	# 7 40 MPH
1143	# 11 LAP FOR SLOW DOWN	1617	# 8 40 MPH
1150	# COMPLETE OPS. 11 LAPS. START TRACK WORK	1621	# 9 40 MPH
1235	# TRACK WORK COMPLETE. SHOVE TRAIN BACK TO START POINT [illegible] EVERYONE CLEAR.	1625	# 10 40 MPH
1241	# START LOGS. SHOVE TRAIN TO START POINT	1629	# 11 SLOWDOWN LAP. COMPLETE OPS.
1249	# LOGS COMPLETE. START OPS HTL. 8 LOCOS. 66 CARS 106 5 DEG CCW. .5" DEFECT SEC 3 T [illegible]	1629	# START LOGS. PULL TRAIN AWAY.
1249	# 1 20 MPH	1757	# LOGS COMPLETE.
1300	# 2 20 MPH		#
1308	# 3 20 MPH		#
1315	# 4 20 MPH		#
1323	# 5 20 MPH		#
1330	# 6 40 MPH		#
1335	# 7 40 MPH		#
1339	# RED SIGNAL. BROKEN RAIL SEC 32 TIE [illegible] BEGIN REPAIR. BAD RAIL.		#

Figure 27. Test Events Log for Rail Gap Testing Run 5143

Figure 28. Rail Gap Testing DAS System Alarms

2.4 DAS System Observations during Testing

A number of observations were made over the course of the project. These observations took place during the setup of the DAS systems, calibration periods, and testing. Observations that have been noted occurred on one or more of the DAS systems.

- Calibration and GPS mapping errors contributed to early false alarms (fixed before trial period started)
- There were issues with tracking trains at lower speeds, which resulted in gaps of broken rail detection availability
- There were alarms caused by train acceleration and deceleration (observed during calibration periods, but believed to have been filtered out by the vendor during the trial)
- Some DAS systems only alarm once per event and other DAS systems alarm multiple times for the same event
- Location determination of train and broken rail alarms have a tolerance range of ±450 feet
- The test bed was only configured for single track territory, but testing during some periods of the trial on the RTT caused alarms on the HTL (these alarms were discarded because the test bed was setup for single track testing)
- Some vendor broken rail alarms that were not actual broken rails were more closely inspected at the vendors' request, and the following were found:

  - One alarm correlated with a section of rail that had a crushed head (rail was replaced before the next day of testing)
  - Another alarm correlated with a section of ties that had loose spikes (spikes were fixed before the next day of testing)
  - Another alarm was at a location with a lot of rail and tie pumping (track crew inspected area and determined additional tamping was needed)
- During FAST operations the crew on the ground can detect the rail break before the train moves off of the signal block, meaning there is less than one train pass over the rail break.
  - When the break was found immediately by the crew, the DAS systems may not have gathered as much data for that break as it would with rail breaks in normal revenue service operations

3. Gap Analysis

This section summarizes the research completed to determine whether or not DAS systems can perform the functions of conventional track circuits. The following subsections give an overview of conventional track circuits and a comparison between track circuits and DAS systems for various use cases.

3.1 Track Circuit Background

Track circuits have been in use by North American railroads in one form or another since the late 1800s and have seen only one major design change in their nearly 150 years of use.

The first track circuit was demonstrated by its inventor, Dr. William Robinson, in 1870 [2]. The design consisted of trackside levers attached by wire to relays that would energize to activate an actuator that changed the aspect of a track signal when that lever was acted upon by the wheels of a passing train. As the train proceeded along its route, it would again encounter a lever that would reset the signal to its original state. This track circuit was known as an open circuit system as the circuit is open (turned off) in the absence of a train, and it is closed (turned on) when a train is present. The design was quickly adopted by the Philadelphia and Erie Railroad and installed at Kinzua, PA.

Upon further evaluation of his design, three major flaws were identified that could introduce dangerous operating conditions for the railroads:

1. A train has the potential to set the signal to a clear indication while still present upon a section of track. If that train were to stop, after setting the signal to clear, a following train would have no indication of the train ahead, making a train collision possible.
2. A train may enter the section of track at the opposite end, or from a siding, and not activate the block signal having not encountered one of the controlling levers. This again would lead to a false clear indication to trains making opposing movements.
3. In the event of a broken wire, the visual block signal system would fail in the clear position whether or not a train is occupying the block ahead, making train collisions possible.

It was determined that for any railroad signaling system to be effective, it had to be fail-safe. Fail-safe means that, in the event of a system failure (e.g., power outage or broken wire), the system will fail in a manner that leaves the system in its safest position. In the case of visual block signals, it is desirable to have the signal show the most restrictive indication.

The second first track circuit design shared many similarities to his first. Both utilized electrical current generated by a battery to power relays that activated actuators controlling the signal aspect displayed. However, this new system was set up to utilize the rail itself as a conductor of electrical current. This required sections of track, known as blocks, to be electrically isolated or insulated from one another by using insulated joints at each end of the block. At one end of the block, a battery was connected to the rails with each of its terminals attached to opposite rails. On the opposite end of the block, a relay was connected with its magnet terminals similarly attached to opposite rails. In the absence of a train, the electrical current would flow from one battery terminal, down a rail, energize the relay at the opposite end, pass through the relay to the opposite rail, returning to the battery thereby closing the circuit and energizing the clear signal.

When a train entered the block controlled by the track circuit, the wheels and axles of the train electrically connected one rail to the next, as they are sufficiently conductive to allow an electrical current to pass through them. This diversion of the track circuit's electrical current was sufficient to redirect current flow away from the relay at the opposite end, de-energizing its magnet. When de-energized, the relay would switch the signal aspect from clear to stop. This is known as a closed circuit system, as the circuit is closed (turned on) in the absence of a train, and it is opened (turned off) when a train is present. Further, this design satisfied the criteria of a fail-safe system as in the event of a failure in the circuit (e.g., power failure, broken wire, or potentially a broken rail), the visual block signal would automatically display its most restrictive indication.

The closed circuit track circuit design, patented in 1872 and first implemented in mainline railroad service in 1872, remains to this day the foundation on which all railroad signaling systems are designed.

The primary function of a track circuit is to indicate the presence of a train within a defined section of track known as a block. However, the physical presence of a train is not the only means by which a track circuit may show a block as occupied.

Due to the functional characteristics of the track circuit's closed circuit design, the track circuit can be used as an indicator of other potential risks associated with the track structure. One such risk is a broken rail. In the event of a broken rail within a block, and assuming the rail breaks in such a manner that the two sections of rail separate sufficiently to no longer be in contact, the track circuit will show the block as occupied.

This track circuit concept is still the underlying system to modern signaling systems. Signaling systems use information from the track circuit and communicate with adjacent signal blocks, typically by a coded message through the rail, to create a signaled block system that can give engineers advance warnings for approaching stops or track diversions. The next few sections cover some use cases with explanation of how track circuits and DAS systems operate. Recommendation for use of supplementary technologies or improvement to DAS systems are made for use cases where a DAS system cannot currently operate at the same level as track circuits.

3.2 Use Cases

TTCI worked with the Advisory Group to develop typical use cases for a fiber optic DAS Broken Rail Detection system.

3.2.1 Broken Rail – Single Track Territory

For this section, only indications from the systems pertaining to broken rails in single track territory are considered.

The design of track circuits is such that if the rail breaks and there is enough electrical separation between the rail, the track circuit will indicate a stop at the entrance into that block, protecting the train from the broken rail. A track circuit will not indicate where within the block a broken rail is located, just that there is a rail break somewhere within that entire block. Track circuits do have a few limitations that will result in giving a clear signal into a block that has a broken rail. If the rail break does not electrically break the circuit, the track circuit will still indicate a clear into the block. There are also dead sections within a track circuit where certain features are jumpered electrically to eliminate track circuit failures due to joint connections. If a rail break occurs between jumpered sections, a track circuit will still indicate a clear into the block. Due to the fail-safe nature of track circuits, there can be a stop into a block where no rail break is present. If the track circuit connection to the rail is broken, power to the track circuit is interrupted, and/or signal jumpers are broken within the track circuit, the block will show a stop even though there are no rail breaks within the circuit. To clear a track circuit block that has a stop due to a broken rail or other issue, the rail needs to be replaced or the issue needs to be fixed. As soon as the rail or issue is repaired and the circuit is electrically closed, the track circuit will indicate a clear into the block.

DAS systems have the potential to detect rail breaks that produce a significant amount of acoustic energy as a train moves over the break. As seen in the DAS rail break trial, there are rail breaks that DAS systems currently miss either due to low acoustic energy or located around features that cause acoustic signatures that interfere with the capability to detect the broken rail. A DAS system also requires the presence and active tracking of a train to detect broken rails and current systems showed some issues of train tracking at lower speeds, which means there may be gaps in their ability to detect rail breaks at slow speeds. Future enhancements need to be made to DAS systems to improve the success rate of broken rail detection and the tracking of trains at lower speeds. Data from the trial also showed that other acoustic signatures from the train moving down the track resulted in the DAS system flagging broken rails when there were none.

DAS systems will report a GPS location for the broken rail alarm that will narrow down the location of the break, as compared to track circuit blocks. An inspector may need to inspect an area around the reported GPS location, because of reporting tolerance by the systems, but the inspector may not need to inspect the whole section monitored by the DAS system. If there is an alarm for a rail that is broken and subsequently fixed, or if the alarm was a false alarm, there needs to be some mechanism to clear the alarm at the DAS system. Currently, this is a manual process. This can result in an unsafe condition if the system alarms to a true broken rail, but the inspector misses the break and clears it from the system. In this case, the rail would still be broken and at least one train would be allowed into a clear block before the broken rail would be flagged again.

DAS system recovery from power outage or other system failures would also need to be addressed. Unlike track circuits, when DAS systems recover from a power outage or other system failure, they have no way of checking the rail for continuity until the system tracks a train across the block. This may require the train to operate at restricted speed over areas where broken rail detection is provided by a DAS system that has lost power or failed, until a train passes or some other solution that can verify the area is clear of broken rails.

3.2.2 Occupancy – Single Track Territory

For this section, only occupancy indications from the systems for single track territory are considered.

Track circuits will show a block occupied when a train or equipment enters the block and shunts the track. The track circuit will continue showing the block occupied until the train exits the block and the circuit is closed again. If a train or equipment enters a block but does not shunt the track, the block may still give a clear indication. If there is a track circuit to rail connection issue, equipment failure, and/or power outage, the block will indicate as occupied. Once the issue is corrected, the track circuit will again be able to tell if the block is clear or not.

DAS systems can track a train along the track and show blocks occupied, with some known issues at lower speeds. DAS systems will need to improve train tracking for all speeds to make sure track occupancy works reliably. DAS systems would also need to show that different types of track equipment can be tracked at all speeds when on the rails and that traffic operating on parallel roads or access roads do not show up as occupied track. A buffer may need to be built around the reported train location to make sure the reported occupancy is correct, due to current accuracy of DAS system location determination.

If there are equipment or power issues with the DAS systems, the track will show occupied, but unlike track circuits, once the issue is resolved, the DAS system will not have any indication of whether the track is occupied or not.

Another occupancy scenario of concern, although unlikely, is one in which the DAS system is tracking a train that comes to a stop, then one car is disconnected from the consist and the train continues down the track. With current location determination of the train, there could be a chance the DAS system clears the track occupancy with the car sitting on the track. Wheel sensors could be used with the DAS systems to eliminate some of these concerns by counting the cars in and out of areas, as well as knowing if the train has entered an area past the wheel sensor or not.

3.2.3 Occupancy – Multi-Track Territory

For this section, only occupancy indications from the systems for multi-track territory are considered. It is also noted that limitations from single track territory are still valid for multi-track territories.

In multi-track territory, track circuits operate the same way as in single track territory and will distinguish which track the train is occupying. Track circuits will also indicate whether or not a train is within clearance limits of adjacent tracks and will update block occupancy as necessary. If multiple trains are operating on parallel tracks, track circuits will show occupancy of the blocks each train is operating on.

DAS, as a stand-alone system, has the potential to track a train across multi-track territory but will not be able to definitively determine which track the train is located on. Monitoring switch positions or strategically placing wheel sensors and integrating this information with a DAS system could allow for the system to track a train through multi-track territory and report track occupancy accurately. Wheel sensors may also be needed at clearance points of tracks to be used with the DAS system to make sure occupancy for blocks is updated when a train enters or passes the clearance point. With wheel sensors and/or monitoring of switch positions, DAS systems have the potential to track multiple trains on parallel tracks, but testing of the location determination of each train would need to be conducted to see if acoustic signatures interfere with the ability to reliably track the trains.

3.2.4 Broken Rail – Multi-Track Territory

For this section, only indications from the systems pertaining to broken rails in multi-track territory are considered. It is also noted that limitations from single track territory are still valid for multi-track territories.

In multi-track territory, track circuits operate the same way as in single track territory and will distinguish which track a broken rail is on. If there are multiple broken rails on adjacent tracks, track circuits will indicate stop for the blocks on each track.

DAS, as a stand-alone system, has the potential to monitor for broken rails as a train moves down the track, but will not be able to flag a specific track for broken rail alarms. Monitoring switch positions or strategically placing wheel sensors and integrating this information with a DAS system could allow for the system to track a train through multi-track territory and report broken rail alarms on the correct track. With this integration in place, DAS systems have the potential to track multiple trains on parallel tracks and monitor for broken rails, but testing of broken rail detection capabilities with multiple trains operating in the same area would need to be conducted to see if acoustic signatures interfere with the ability to detect broken rails and select the correct track the broken rail is on.

3.2.5 Additional DAS System Capabilities

In addition to track occupancy and broken rail detection, DAS systems have the potential to provide additional functionality. DAS systems can potentially use the acoustic signatures of the track and train to monitor trains within a block or approaching grade crossings, monitor track structure, operate as slide fence protection, provide high wheel impact detection, and/or trespassing detection.

4. Conclusion

A baseline evaluation of DAS broken rail detection capabilities was conducted on three fiber optic DAS systems. Raw data from the testing was recorded and saved, and is available for the vendors to use for playback while making improvements on their systems. The evaluation conducted by TTCI showed that improvements need to be made to the broken rail detection accuracy, as well as the false positive rate, before the technology would be acceptable for revenue service operation. Testing and observations also identified other areas of improvement to DAS systems, such as improved train tracking at lower speeds, improved handling of train acceleration and deceleration, and improved configuration or system response to track structures that cause higher acoustic energy events like switches, frogs, and crossings.

The comparison between DAS systems and conventional track circuits also identified areas of concern for DAS systems, such as track discrimination, precise train location, system recovery from a shutdown, power outage, or other system failure, performance with other train types and track equipment, and detection capabilities with multiple trains operating on parallel tracks.

It is recommended that the next steps of DAS system testing be conducted in single track territory or dark track territory with emphasis on improving broken rail detection accuracy and reducing the false positive rate. This will also provide testing on other train types at varying speeds. The vendors should also pick a location that can highlight some of the additional capabilities of DAS systems, such as train tracking through blocks or approaching grade crossings, high impact wheel detection, and/or track structure monitoring.

5. References

1. Holcomb, M., and Mauger, D. (2013, October). "*Feasibility Study of Fiber-Optic Technology for Broken Rail Detection*." Technical Report, DOT/FRA/ORD-13/44, Washington, DC: Federal Railroad Administration.
2. American Railway Association. (1922). "The Invention of the Track Circuit: The history of Dr. William Robinson's invention of the track circuit, the fundamental unit which made possible our present automatic block signaling and interlocking systems." New York, NY: Signal Section of American Railway Association.

Appendix

Technical Transportation Center, Inc. (2018). Appendix A. TTCI DAS Rail Break Trial Results and Analysis Report, and Appendix B. Compilation of FAST Logs. Federal Railroad Administration: Washington, DC.

Abbreviations and Acronyms

Abbreviations	**Acronyms**
DAS	Distributed Acoustic Sensing
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
GMT	Greenwich Mean Time
GPS	Global Positioning System
OTDR	Optical Time Domain Reflectometer
HTL	High Tonnage Loop
RTT	Railroad Test Track
SQL	Structured Query Language
TCR	Test Conditioning Run
TTC	Transportation Technology Center (site owned by Federal Railroad Administration)
TTCI	Transportation Technology Center, Inc. (wholly owned AAR subsidiary)