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High-Speed Rail IDEA Program

FIBER OPTICAL SENSORS FOR HIGH-SPEED RAIL APPLICATIONS

Final Report for High-Speed Rail IDEA Project 19

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EXECUTIVE SUMMARY

Laboratory experiments performed at the University of Illinois at Urbana-Champaign (UIUC) and field testing at the Transportation Technology Center (TTC) in Pueblo, Colorado have demonstrated that fiber-optic sensors can show good sensitivity to rail break and buckling events. Fiber-optic sensors have found wide usage in applications due to their high sensing performance and small size. Different types of fiber-optic sensors have been demonstrated for the measurement of properties such as temperature, pressure, vibration, and strain. Furthermore, with the advent of fiber-optic communication systems to support growing internet and data traffic, costs of fiber-optic components are continually decreasing. Research in fiber-optic sensors for railroad applications is a relatively new area and has progressed rapidly over the past five years.

A fiber-optic sensor system was installed on a section of rail in the high-tonnage loop at the Facility for Accelerated Service Testing (FAST) with trains running at 40 mph. Track circuit and strain gage systems were also used for comparison. On March 26, 1999, the fiber optic-system recorded the occurrence of a rail break. The rail was not inspected at this time, and trains continued to run over the test rail. On March 29, 1999, the track circuit and strain gage systems signaled the occurrence of a broken rail. Upon inspection, a weld crack of about 1 inch was observed in the test rail. These results are significant because: (1) rail break detection using the fiber-optic sensor was demonstrated in the field and (2) for this test case, the fiber-optic system detected the occurrence of the broken rail before the track circuit and strain gage systems.

During the field testing for rail break detection at TTC, the detected laser signal through the rail-bonded fiber sensor showed perturbations as the train traveled multiple times over the section of rail with the fiber sensor as shown in Fig. 1. This indicated that the presence and speed of the train presence might be detectable using fiber-optic sensors. We investigated this concept under this IDEA project using two types of fiber-optic sensors, point sensors and distributed sensors, and two types of detection systems, a continuous-wave system and a pulsed optical time domain reflectometry (OTDR) system. Laboratory testing and field results indicate that the point sensor and continuous-wave system will provide the most sensitivity to train presence and speed detection. The fiber-optic point sensors which were developed in our group have also been demonstrated in the lab for other applications such as weigh-in motion and the detection of flat spots on rail car wheels.

During the fiber installation for initial field testing, we found that manual placement and bonding of the fiber to the rail was difficult and time-consuming. Through the support of the AAR and TRB, we developed a fiber installation cart that automates the fiber placement and bonding process on the rail. An updated version of the fiber installation cart modified by TTCI has been developed (Fig. 2) and is capable of installing fiber at a rate of 10 ft. per minute.

In summary, fiber-optic sensors show promise for several railroad applications. They have been successfully demonstrated for rail break and buckling detection in both the laboratory and field settings. The fiber installation cart improves the practicality of field application. Laboratory testing has successfully demonstrated the possibility of using fiber-optic sensors for train presence and speed detection as well as weigh-in motion and wheel flat spot detection. Widespread use of this technology in the railway industry will require further research and development of a cost-effective application process, field diagnostic and maintenance procedures, and methods to protect the fiber form track maintenance operations. Currently-available epoxy for bonding the fiber to the rail must be applied within a narrow rail temperature range (e.g., 50 to 80 degrees F). Railroads have commented that, to be cost-effective, the application rate must be significantly increased beyond ten feet/minute, and the temperature range increased. An effective method of installing fiber over thermite welds must also be developed. Ballast dumping and plowing operations were found to significantly damage the fibers, so ways to protect the fiber need to be developed.

The specific accomplishments of this project were to:

- Determine which type of fiber is best suited for rail break detection, rail buckling detection, and train presence and speed detection.

- Determine the optimum fiber location on the rail.
- Identify promising methods for attachment and removal of fiber from the rail.
- Conduct field testing of fiber-optic sensors to determine their potential for rail break and track buckle detection.
- Design, develop, fabricate, and conduct preliminary laboratory tests of a prototype detection system for train presence and speed detection, including algorithms, sensors, and associated software.
- Conduct field testing of fiber-optic sensors for train presence and speed detection.

The promise of fiber optics for these applications demonstrated in this project should provide the incentive for the additional research and development to address the remaining issues, described above, to enable widespread implementation.

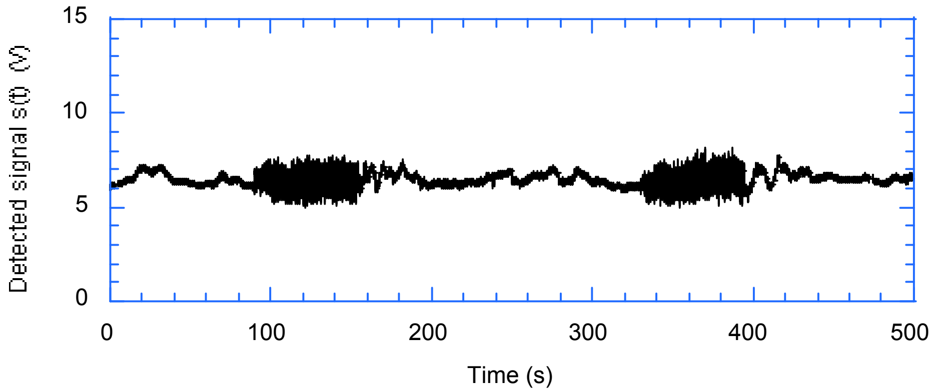


FIGURE 1 Detected laser signal through a rail-bonded fiber-optic sensor as a function of time. A train passing over the sensor section of rail creates perturbations in the signal.

FIGURE 2 Photograph of a current version of the fiber installation cart which includes a fiber application board, balance rig, and pneumatic pump for the epoxy applicator.

INTRODUCTION

Fiber-optic sensors have found wide usage in applications due to their high sensing performance and small size. Different types of fiber-optic sensors have been demonstrated for the measurement of properties such as temperature, pressure, vibration, and strain. Furthermore, with the advent of fiber-optic communication systems to support growing internet and data traffic, costs of fiber-optic components are continually decreasing. Research in fiber-optic sensors for railroad applications is a relatively new area and has progressed rapidly over the past five years.

Our research group at the University of Illinois has for several years been investigating the use of fiber-optic sensors to supplement track circuits for detection of broken rails in collaboration with the Association of American Railroads (AAR) *(1)*. The advantage of using fiber-optic sensors is that they overcome some of the limitations associated with track circuits and may also provide greater sensitivity to rail breaks. We have also developed fiber-optic sensors for several novel applications such as rail buckling detection, weigh-in motion, and wheel flat spot detection *(2)*. In this project, we have built upon our previous work with the AAR to further develop practical fiber-optic sensor systems, procedures, and equipment for more efficient installation on rails, and investigate rail break detection, track buckles, and train presence and speed detection using fiber-optic sensors.

IDEA PRODUCTS

I. FIBER INSTALLATION CART

The fiber installation cart allows for a reliable and efficient installation of optical fiber on rail. This will have a tremendous impact on our ability to apply fiber sensors to rail quickly and efficiently replace fiber sensors when necessary. The fiber installation cart consists of an application board which contains a fiber spool, tape spool, and epoxy applicator. The application board is attached to a cart apparatus where the wheels of the cart roll on the rail. After an initial setup procedure, the fiber installation cart is pushed along the rail and automatically installs and bonds the fiber sensor to the web of the rail with epoxy and tape. The current version of the fiber installation cart as shown in Fig. 3 performs well on rail. We propose to continue to develop the fiber installation cart to also work more smoothly around weld and rail joint areas to further decrease fiber installation time. We also propose to develop a real-time continuity check system for the fiber installation cart so that accidental fiber breaks can be detected and repaired quickly during the installation process.

II. FIBER SENSORS FOR RAIL BREAK AND BUCKLING DETECTION

We have developed several fiber sensors based on single-mode and multimode optical fibers with tape and epoxy for the detection of rail break and buckling. Software programs based on Labview have also been developed for data acquisition and analysis. A differential signal technique has also been developed for the signal processing to enhance the signal to noise ratio.

III. COMPLETE FIBER-OPTIC SENSOR SYSTEM

Development of a complete fiber-optic sensor system as shown in Fig. 4 is planned that will include the laser transmitter, fiber-optic sensor, photodetector receiver, and data acquisition components including a modem for wireless transmission, computer, and data storage and analysis software. This fiber-optic system will initially focus on rail break and track buckling detection. Future applications may include train presence and speed detection, weigh-in motion, and wheel flat spot detection. We will be able to implement a robust fiber-optic detection system at virtually any site and perform rail break and track buckling detection. Additional functions such as train presence and speed detection, weigh-in motion, and wheel flat spot detection can be added in the future.

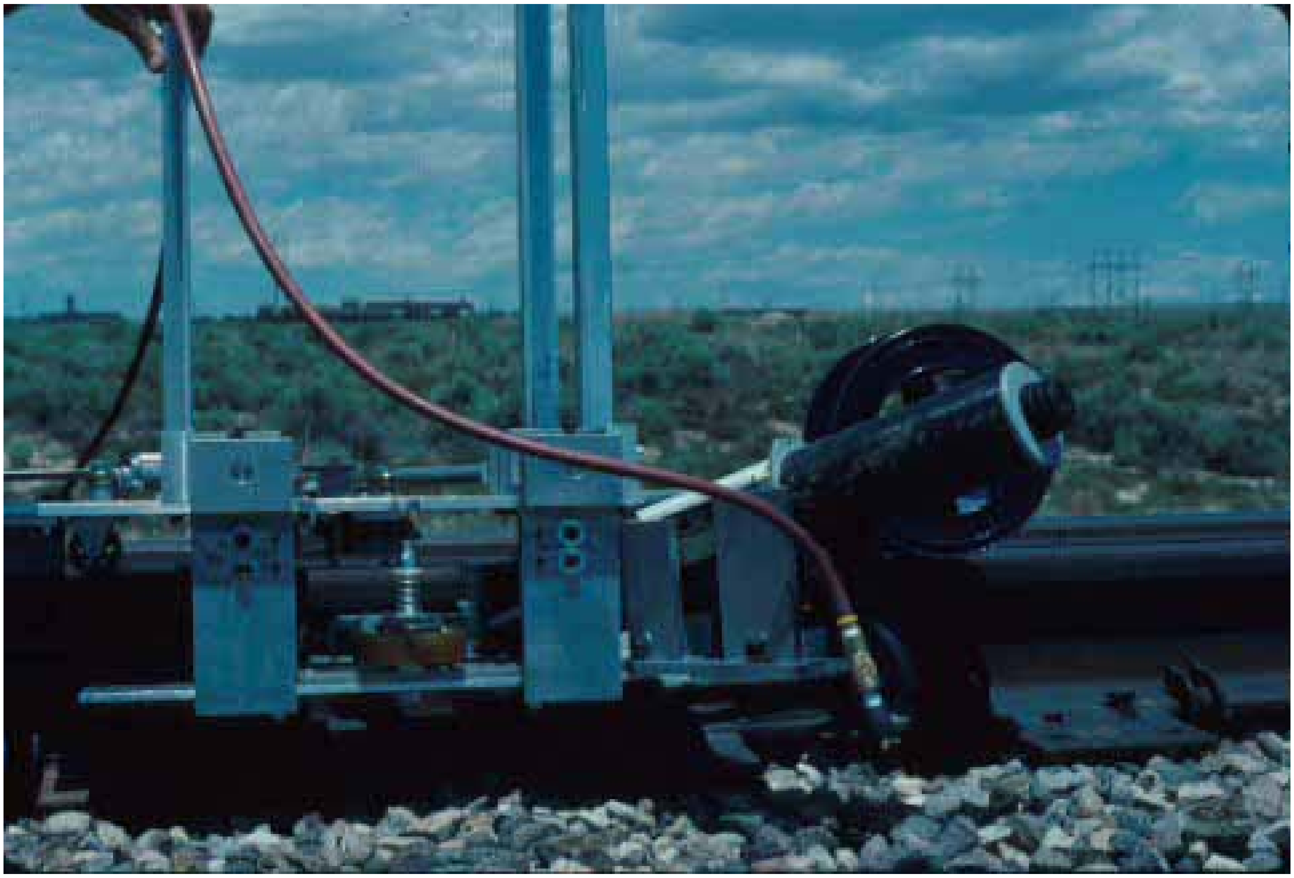


FIGURE 3 Photograph of the current version of the fiber installation cart during a field demonstration at TTC.

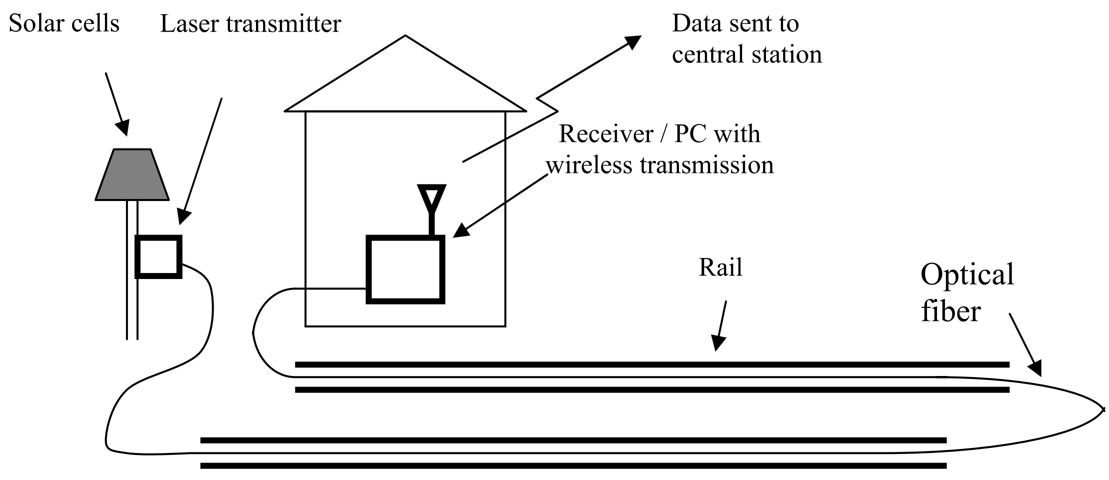


FIGURE 4 Schematic of a complete fiber-optic sensor system which includes the laser transmitter, fiber-optic sensor, photodetector receiver, and data acquisition components including a modem for wireless transmission, computer, and data storage and analysis software.

CONCEPT AND INNOVATION

I. NOVEL APPLICATION OF FIBER-OPTIC SENSORS FOR RAILROAD APPLICATIONS

A. Rail Break Detection

Detection of broken rails is a high priority in the railroad community. Broken rails can cause service disruptions, affect system reliability, and have the potential to cause serious accidents. Current track circuit technology relies on the electrical conductivity of the rail to monitor for rail breaks. If a rail break occurs over tie plates or in the presence of salt-ionic substances, for example, the conductivity may not be disrupted and the break not detected. Track circuit operation can be also disrupted by lightning strikes. Furthermore, track circuits are not available in dark territory. Fiber-optic sensor technology is a relatively new way to perform rail break detection and can be used to supplement track circuits to decrease the number of undetected rail breaks. Fiber-optic sensors can offer high-sensitivity performance and their small size (< 1mm diameter) allows them to be unobtrusively bonded to rail. The fiber is placed on rail in a position where it is least likely to be damaged by maintenance-of-way equipment. Using the fiber installation cart, the fiber-optic sensor is bonded to rail as shown in Fig. 5. Light produced from a laser is coupled into the fiber sensor which acts as a channel for the laser light signal. This signal is monitored using a photodetector as a function of time. If a rail breaks, the fiber also breaks and light transmission decreases dramatically. After the rail break is detected, an optical time domain reflectometry (OTDR) unit, which acts as an optical radar for fiber breaks, is used to detect the location of the fiber and rail break to within a few meters accuracy over several kilometers. Finding the precise location of detected rail breaks quickly in this way is difficult using track circuit technology.

B. Rail Buckling Detection

Detection of rail buckling is similar to rail break detection. As a rail buckles, the bonded fiber also bends and as a result, an amount of light proportional to the bending escapes the fiber. The amount of buckling in the rail can therefore be monitored by measuring the amount of attenuation in the detected light signal. As shown in Fig. 6, the precise time of buckling events can also be clearly resolved using this technique by monitoring the differential, or change in the light signal as a function of time. The fiber-optic sensor approach has a distinct advantage over alternative methods such as strain gages because they are small in size and can be applied over much larger sections of rail.

Field test results for rail buckling detection were also obtained. A bulldozer was used to physically buckle a section of rail with a bonded fiber-optic sensor. As shown in top plot of Fig. 7, a stringpot was used to measure the physical displacement of the rail and a strain gage was also attached but not used. At t = 247 seconds, the rail was buckled about 15 inches by the bulldozer, and small fluctuations in the fiber-optic signal can be observed. In the bottom plot of Fig. 7, the differential signal, or change in signal, is shown. The fluctuations in the differential signal clearly correspond to the occurrence of the rail buckling.

C. Train Presence and Speed Detection

A critical safety issue is correct timing for crossing gates at railroad highway grade crossings. If the warning signals and crossing gates are activated too soon, impatient motorists may try to cross in spite of them which may result in a train-car collision. If the system is activated too late, again a serious accident may occur. Consequently, the timing of grade crossing warning activation is critical. On rail lines with a mix of traffic speeds such as slow freight trains and fast passenger trains, the need for train-speed dependent warning systems is particularly important.

Train presence and speed detection can also be performed by measuring how the light signal passing through the rail-bonded fiber sensor is affected by a train passing over the rail. As shown in the top plot of Fig. 8, the light transmission through a fiber sensor was monitored during a field test at the Transportation Technology Center (TTC) in Pueblo, CO while a train periodically passed over a section of fiber-bonded rail. The presence of the train is clearly observed in the significant perturbations in the light signal as a function of time. The presence of the train is more clearly seen in the differential signal which illustrates the change in signal in the bottom plot of Fig. 8. By conducting research on novel fiber sensors and laser detection systems, we have tested several methods by which train presence and speed detection could be performed.

These methods include the use of distributed-type and point-type fiber sensors and continuous-wave (CW) and pulsed optical time domain reflectometry (OTDR) detection systems. The distributed-type sensor is the same type of sensor

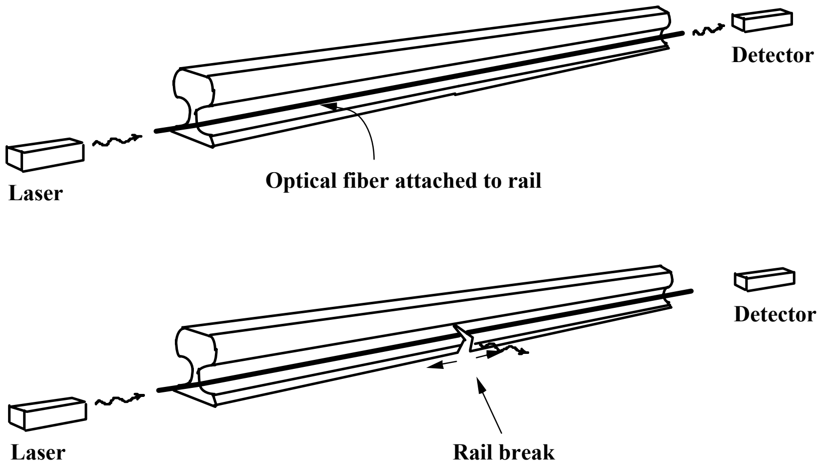


FIGURE 5 Concept of rail break detection. During a rail break, the fiber bonded to the rail also breaks and light transmission through the fiber decreases dramatically.

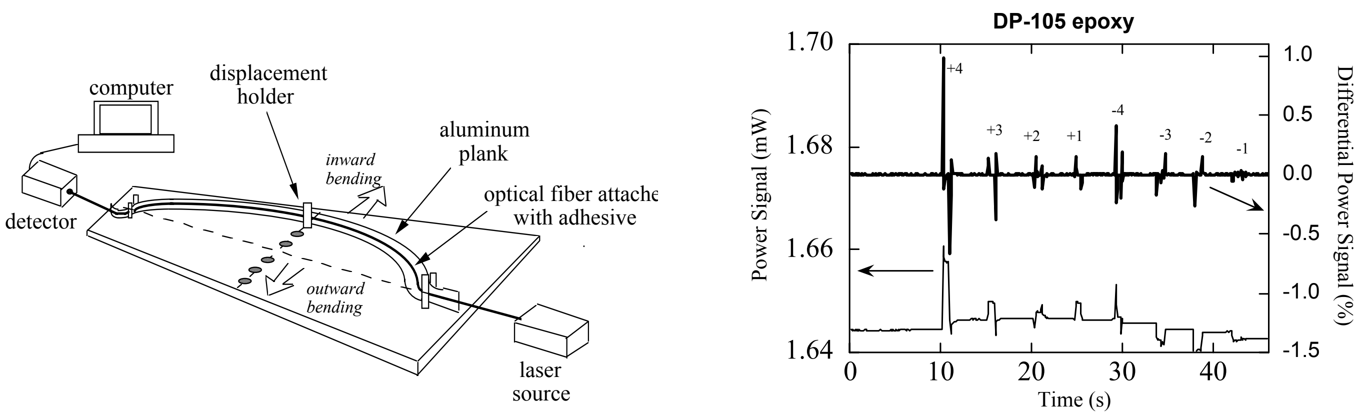


FIGURE 6 Rail buckling experimental setup and experimental data showing the measured power signal and differential signal for various inch displacements as a function of time.

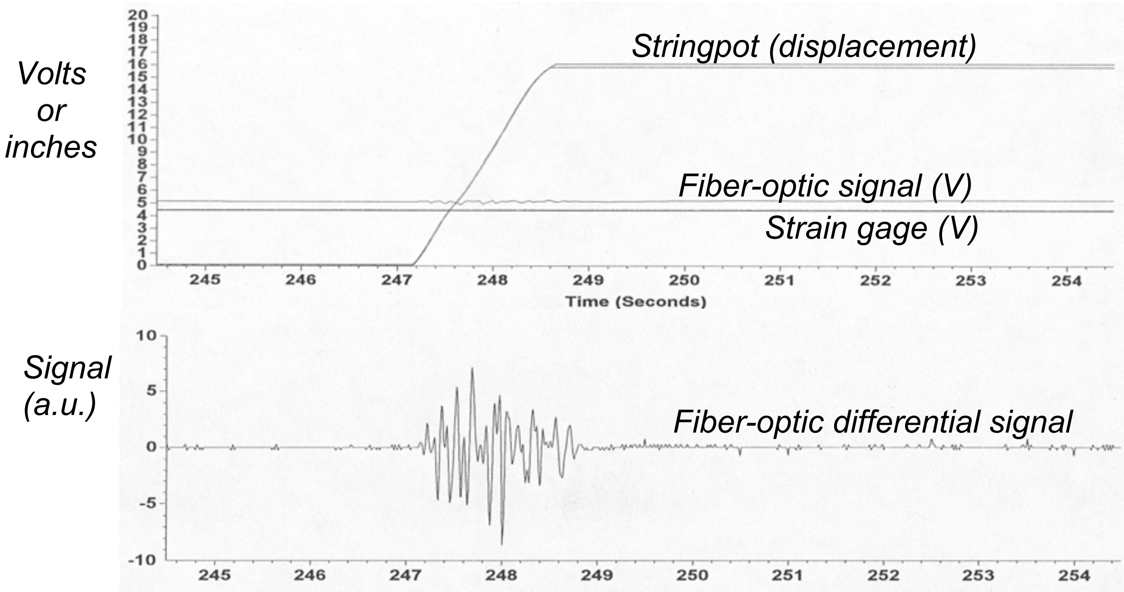


FIGURE 7 Field test data for rail buckling. The stringpot shows the physical displacement of the rail due to a bulldozer. During the buckle, the fiber-optic signal is perturbed as shown in the differential signal.

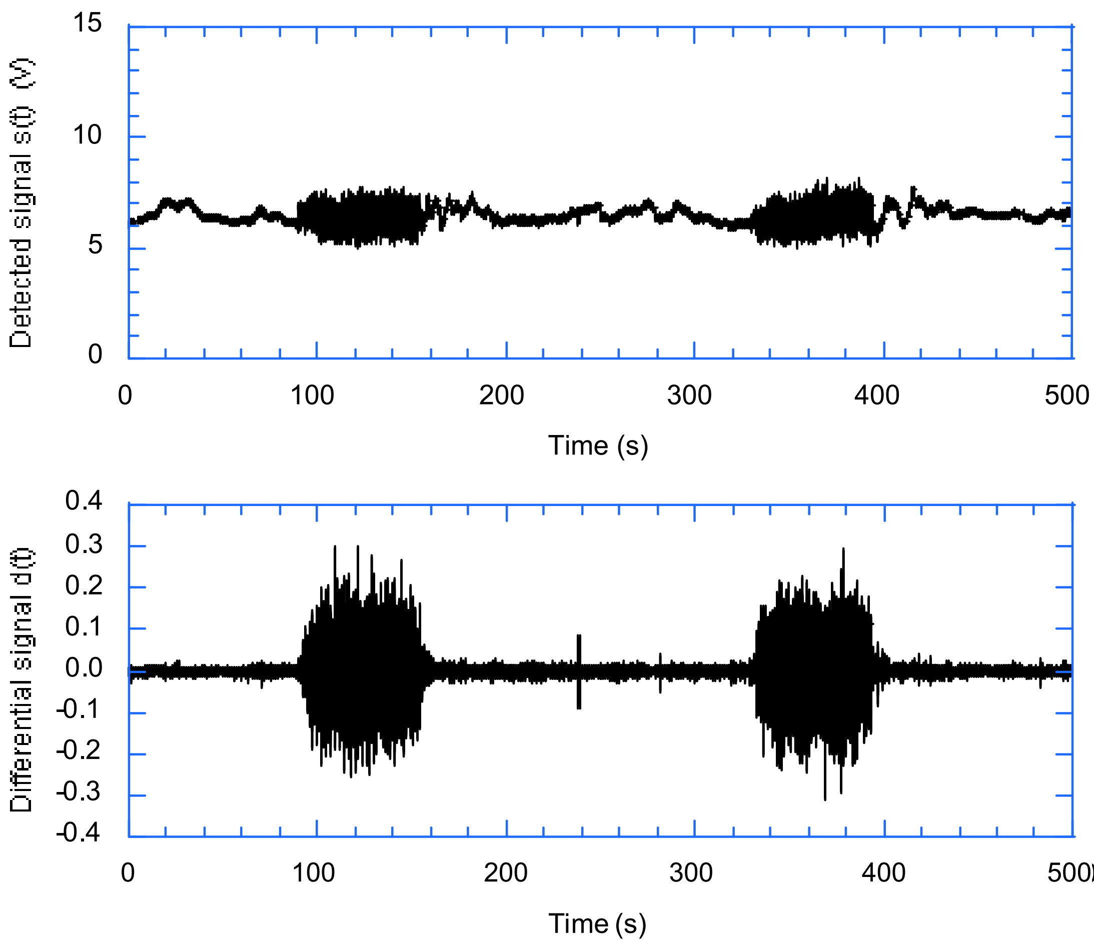


FIGURE 8 Field test data showing the showing train presence detection.

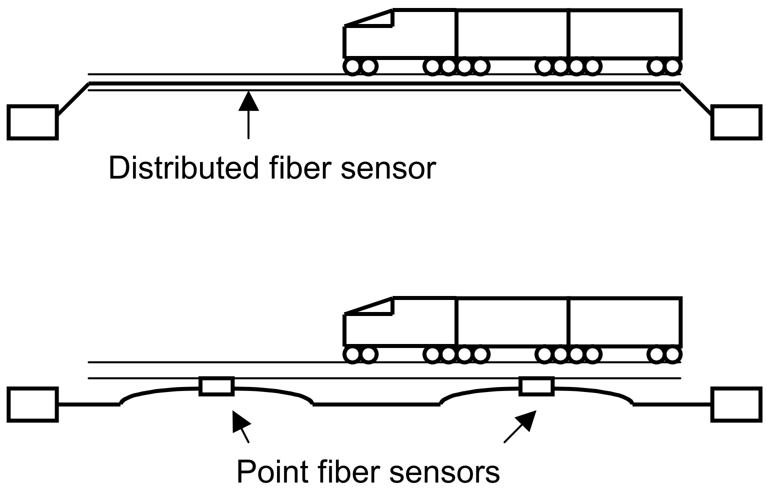


FIGURE 9 Schematic of the distributed fiber sensor and point fiber sensors. The distributed fiber sensor operates over the entire length of the rail while the point fiber sensors operate at discrete points along the rail.

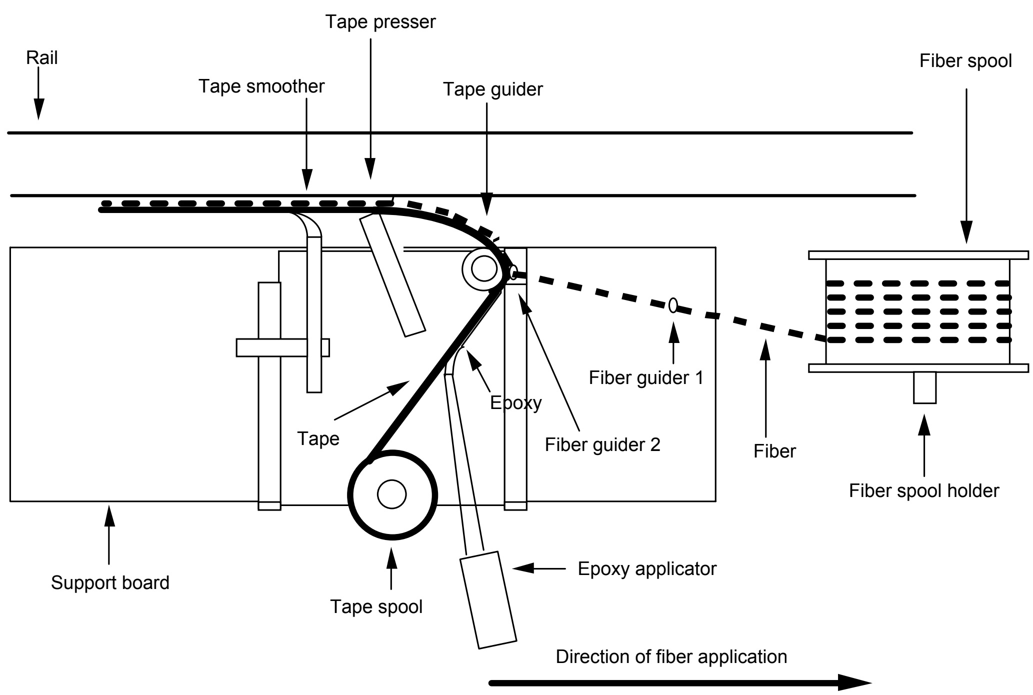


FIGURE 10 Top-view schematic of the application board of the fiber installation cart during fiber installation. As the board moves down the rail, fiber and tape is released from their respective spools and a thin bead of epoxy is applied to the tape. The fiber, epoxy, and tape are then pressed to the rail and the epoxy cures over the fiber sensor inside the tape.

used for rail break and buckling detection which is bonded to rail. The point-type sensor however is not bonded to the rail and measures the force on the rail at a discrete point. Both types of sensors are illustrated in Fig. 9.

The two types of detection systems which we investigated are the CW and OTDR detection systems. The CW system is the same which is used for rail break detection where light from a laser is coupled into the fiber sensor, the output is measured using a photodetector, and the transmitted light power is measured. In the OTDR system, a transmitter section sends a train of laser pulses down the optical fiber. For each discrete distance down the fiber from the OTDR, the photodetector/receiver detects the returned light power in a time-gated manner corresponding to the distance and refractive index in the fiber, thereby mapping out the detected power as a function of distance in the optical fiber. The OTDR is typically used to detect losses and breaks in optical fiber telecommunication channels over long distances (>100 km) from one remote location.

We considered four different configurations for train presence and speed detection using combinations of the fiber sensors and detection systems. In our investigation, we performed laboratory testing of each configuration and evaluated the performance of each. In general, these configurations have various tradeoffs. Point-type sensors offer greater sensitivity while distributed-type sensors can give information about the entire length of the rail. The CW system is easier to operate and has good sensitivity while the OTDR system can give more precise information as a function of distance along the rail.

II. IMPLEMENTATION OF FIBER-OPTIC SENSORS

In the course of conducting research on fiber-optic sensors for railroad applications, we have addressed a number of practical engineering issues associated with fiber sensor installation. This has led to a number of innovative solutions for challenges concerning fiber attachment. We have combined the ease of tape application with the bonding strength of epoxy by developing a hybrid tape-epoxy bonding method for fiber sensors as shown in Fig. 10. In this method, a bead of epoxy is applied to the center of a length of tape and the fiber sensor is pressed lengthwise into the epoxy. Then, the tape, epoxy, and fiber sensor are pressed into the rail. The tape serves to allow the epoxy to cure and harden around the fiber sensor and makes positioning of the fiber sensor on the rail possible. We have implemented this technique in an automated manner by developing a fiber installation cart which rolls along the head of the rail and includes a spool of fiber and tape and an epoxy applicator. The current version of the fiber installation cart allows for installation rates of 10 feet per minute, making fiber installation more practical and reliable.

INVESTIGATION

There were two major goals of this project: practical fiber installation and rail break and track buckle detection. Practical fiber installation is of critical importance in making fiber-optics a feasible technology for railroad applications. In the first field tests of fiber-optic sensors at the Transportation Technology Center (TTC) in Pueblo, CO, a fiber installation of a few hundred feet was unreliable and took several hours. In this project, our goal was to make fiber installation a reliable and efficient procedure. Our second major goal was to investigate the use of fiber-optic sensors for train presence and speed detection in addition to their use for rail break and buckling detection. The specific goals of this project are summarized as:

- Determine which type of fiber is best suited for rail break detection, rail buckling detection, and train presence and speed detection.
- Determine the optimum fiber location on the rail.
- Identify the most promising methods for attachment and removal of fiber from the rail.
- Conduct field testing of fiber-optic sensors to determine their potential for rail break and track buckle detection.

- Design, develop, fabricate, and conduct preliminary laboratory tests of a prototype detection system for train presence and speed detection, including algorithms, sensors, and associated software.
- Conduct field testing of fiber-optic sensors for train presence and speed detection.

I. DETERMINATION OF TYPE OF OPTICAL FIBER FOR SENSORS

Optical fiber is a cylindrical waveguide consisting of two parts: an inner core region and an outer cladding region which has a lower refractive index than the core. Light travels through optical fiber by total internal reflection in the core. For our applications, we considered three types of optical fiber which differ in material composition and core/cladding dimensions and compared the sensor performance and cost in Table 1.

Type of optical fiber	Performance	Cost
Conventional glass fiber	Very low attenuation (<1dB/km@1.55mm)	$0.10 per meter
Polarization-maintaining glass fiber	Sensitive measurement, complex setup	Several times higher than conv. glass
Plastic fiber	Very high attenuation	Lower than conv. glass

TABLE 1 Comparison of conventional glass fiber, polarization-maintaining fiber, and plastic fiber.

The high cost of polarization-maintaining fiber and the high attenuation in plastic fiber make these unsuitable for the railroad applications we are considering. Conventional glass fiber has the best combination of low attenuation and low cost due to its use in telecommunications and is therefore used in all of our sensor designs. The fiber used is Corning SMF-28 (singlemode fiber) and CFC6 (multimode fiber). The specifications for each are listed in Appendix A.

II. DETERMINATION OF FIBER LOCATION ON RAIL

The optimum location for installing fiber in rail was found to be on the vertical portion of the web directly under the head as shown in Fig. 11. This location avoids rail fasteners at the base, maintenance-of-way equipment, and rail markings on the center of the web. This location also avoids damage from the drilled holes for rail joints.

III. IDENTIFICATION OF FIBER INSTALLATION AND REMOVAL TECHNIQUES

The general approach to an automated fiber installation procedure was to develop a cart which would spool out fiber and attach the fiber it to the rail with an adhesive as the cart traveled down the rail. The optical fiber is released from a spool as the cart moves along the rail. At the same time, a strip of tape is released from a tape spool and a bead of epoxy is applied to the center of the tape. The fiber is guided toward the center of the tape, and the fiber, epoxy, and tape are then pressed to the rail. The epoxy eventually cures over the optical fiber and the tape holds the fiber and epoxy in place during the curing process. A prototype version of the fiber installation cart was demonstrated on an Illinois Central railroad line in Champaign, IL (Fig. 12(a)).

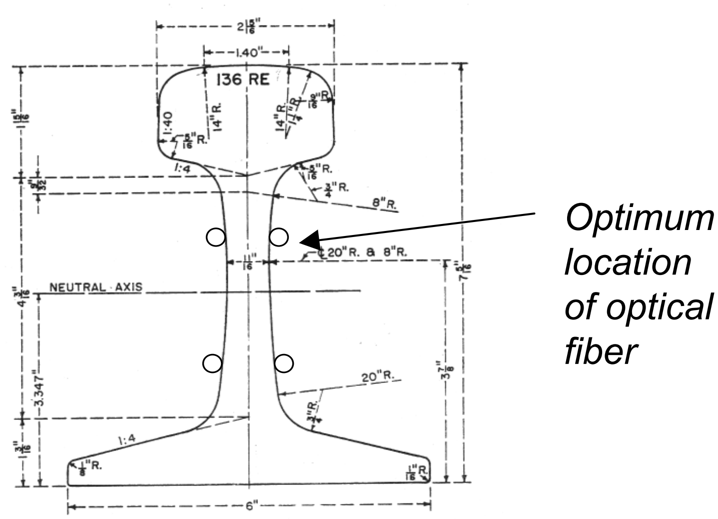


FIGURE 11 Schematic of the front cross-section of a rail. The optimum location for optical fiber installation was determined to be on the upper part of web just under the head.

Our group delivered the fiber installation cart to AAR at TTC and we trained AAR personnel on how to use the fiber installation cart. The AAR recently made some modifications to the fiber installation cart including a pneumatic epoxy applicator which replaced the manual applicator, a balance rig, and a wire brush cleaner for pre-cleaning of the rail. The most recent version of the fiber installation cart is shown in Fig. 12(b) during a demonstration at TTC. At present, the fiber installation cart is capable of installing fiber over straight rail at a rate of 10 feet per minute. A procedure for faster fiber installation over welds is currently being developed at TTC.

IV. TRAIN PRESENCE AND SPEED DETECTION USING FIBER-OPTIC SENSORS

In this work, we investigated two different types of fiber-optic sensors for train presence and speed detection. The first type was a distributed fiber sensor. This sensor consists of a fiber sensor bonded continuously along the rail in the same manner as for rail break and buckling detection. Train presence and speed is detected by measuring the perturbations in the signal due to train-induced rail vibrations. The second type of sensor investigated was a point fiber sensor system. This system consists of two fiber sensors located at discrete locations under the rail. When the train travels over the sensors, light escapes from the fiber sensors due to microbending effects in the fiber and this light loss is proportional to the train weight. A comparison of these sensors is shown in Table 2.

Fiber sensor Type	Fabrication and installation	Sensitivity	Additional features
Distributed sensor	Simpler **(+)**	Lower	Could be combined with rail break and buckling detection functions **(++)**
Point sensor	More difficult	Very high **(+)**	Could be combined with weigh-in motion and wheel flat spot detection functions **(+)**

TABLE 2 Comparison of the Distributed and Point Fiber Sensors.

In addition to the two types of sensors, two types of detection systems were also investigated for train presence and speed detection. The first type is a continuous-wave (CW) detection system consisting of a laser and photodetector which measures the light power transmission through the fiber sensor as a function of time. The second system is a pulsed optical time domain reflectometry (OTDR) system which acts as an optical radar system and measures the losses in fiber as a function of distance. A comparison of these detection systems is given in Table 3.

Detection system Type	Sensitivity	Sampling time	Additional features
CW system	Higher power **(+)**	Faster **(+)**	With point sensors, staightforward train presence and speed detection **(+)**
Pulsed OTDR system	Lower power	Slower	With distr.sensors, could monitor train speed and presence continuously **(++)**

TABLE 3 Comparison of the Continuous-Wave and Optical Time Domain Reflectometry Systems.

The point fiber sensors should have a higher sensitivity and faster sampling time, but the distributed fiber sensor is attractive because it could also be used in conjunction with rail break and buckling functions. The CW detection system generally has a faster sampling time than the pulsed OTDR system but the OTDR system could possibly provide more precise train presence and speed information.

We first investigated the high-risk high-reward combination using the distributed fiber sensor and the pulsed OTDR system with laboratory and field testing. We then performed laboratory testing for the point sensor configurations that offer higher sensitivity to train presence.

A. Distributed-Type Sensor – OTDR Detection System Results

The standard type of OTDR system consists of a pulsed laser transmitter source and a time-gated photodetector receiver. The laser transmitter section sends a repeated series of light pulses down a length of connected optical fiber. As these pulses travel down the fiber, small impurities in the fiber cause a fraction of the light pulses to be reflected back toward the OTDR system. The receiver in the OTDR system detects these reflections in a time-gated manner corresponding to the round-trip distance of the backscattered light at a specific location in the fiber and the refractive index of the fiber. The OTDR system then combines the information from the receiver at different time-gating periods and displays the backreflected power as a function of distance. If there is loss in a specific section of fiber, less reflected power will be returned to the OTDR and this shows up in the OTDR output signal. The OTDR is traditionally used to detect losses and breaks in optical fiber telecommunication channels over long distances (>100 km) from one remote location. The specific model of OTDR used in the laboratory experiments is the Tektronix TFS2020, and the specifications are listed in Appendix B.

As shown in Fig. 13, an initial OTDR data scan is taken and the distance where enhanced fluctuations begin to appear in the scan due to train presence is marked using a digital signal processing algorithm. A second scan is then taken and a second distance is marked (closer to the OTDR system). By calculating the time between scans and the difference between marked distances, the train speed is calculated. In this case, the scan time is fixed and the OTDR measures the marked distances in successive scans.

Simulating a distributed perturbation force such as a train over a long distance of fiber sensor is difficult to perform in a laboratory setting. Therefore, in order to get an approximate evaluation of the distributed fiber sensor – OTDR detection system, we simulated the train by employing a point perturbation source which applied loss to the fiber at a low frequency. A novel spring fiber sensor shown in Fig. 14 was developed to act as the point perturbation source. The spring fiber sensor consisted of a jacketed optical fiber which was attached to a noncompressed steel spring at a specific initial bend radius. When the spring was compressed a certain distance, the optical fiber bend radius would decrease, producing a specific amount of optical transmission loss in the fiber. As shown in Table 4, the spring fiber sensor was able to provide perturbation losses ranging from 0.5 dB to 2 dB with good repeatability.

Sensor #	Noncomp./Comp. fiber bend radius (mm)	Insertion loss (dB)	Loss in compression state (dB)	Standard deviation (%)
1	1.55 / 1.20	1.2	2.1	4.3
2	1.75 / 1.40	1.8	1.1	7.6
3	1.75 / 1.35	0.5	0.5	6.1
4	1.75 / 1.30	0.6	0.3	12.9

TABLE 4 Properties of Several Types of Spring Fiber Sensors.

The experimental setup shown in Fig. 15 was used to evaluate the performance of the system. The OTDR system was connected to one 2.2-m spool of fiber, then to the perturbation source, then to a second 2.2-km spool of fiber. A reference scan without perturbations is shown in Fig. 16(a). Points A, B, and C labeled in Fig. 16(a) represent the connector loss at the OTDR, the connector loss at the spring sensor, and the end of the second fiber spool. A scan with a 2-dB perturbation applied at a 1 Hz frequency is shown in Fig. 16(b), and the perturbations can be clearly observed in the scan. We found that in this experiment, the OTDR scans indicated that point perturbations of greater than 1 dB at a frequency of 1 Hz were detectable.

To further investigate the approach of using distributed fiber sensors and the OTDR detection system for train presence and speed detection, we conducted field testing at TTC in October 2000. A model (ANDO AQ7225B) was used that is similar to OTDR model used in laboratory experiments (Tektronix TFS2020) except that it had a more flexible computer interface. The specifications for the ANDO AQ7225B are listed in Appendix C. The data acquisition program was written in HP Basic and allowed for a sampling rate of 3 seconds per scan.

As shown in Fig. 17, the OTDR unit and PC used for data acquisition was housed in a bungalow. Jacketed fiber was connected to the OTDR unit, routed underground to the rail, and connected to the bonded distributed bare fiber sensor using a mechanical splice. The distributed fiber sensor was 600 ft. in length and was terminated in a flat cleave. Trains were run over the rail-bonded fiber sensor at speeds ranging from 10 to 40 mph.

We found that in field testing, the signal perturbations in the fiber due to the train were too small to be detected with the OTDR unit. This is attributed to relatively low sensitivity of the distributed sensor and the averaging scheme used by the OTDR unit. Another field test was conducted using a vibrational point sensor in an effort increase the sensitivity of the system. As shown in Fig. 18, the variance of the OTDR signal over five OTDR scans is significantly larger at the location of the vibrational point sensor for the case when the train is running over the fiber sensor.

(a)

(b)

FIGURE 12 (a) Photograph of graduate students Alan Hsu and Erik Young demonstrating a prototype version of the fiber installation cart on an Illinois Central line near Champaign, IL. (b) Photograph of the current version of the fiber installation cart at field demonstration at TTC.

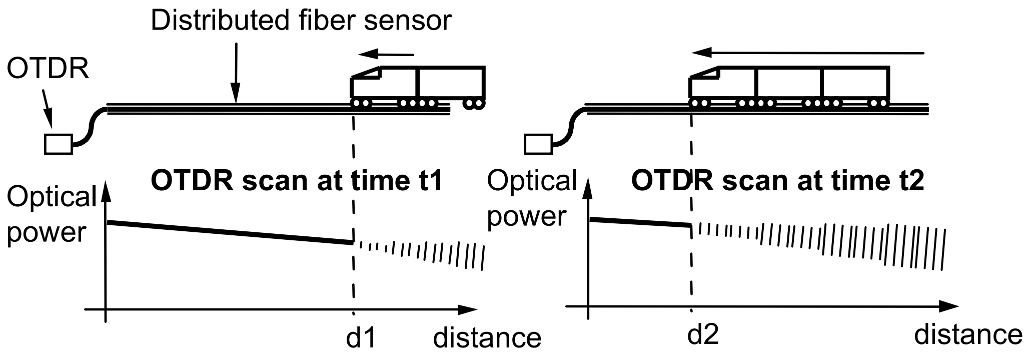


FIGURE 13 Concept of train presence and speed detection using the distributed sensor – OTDR detection system.

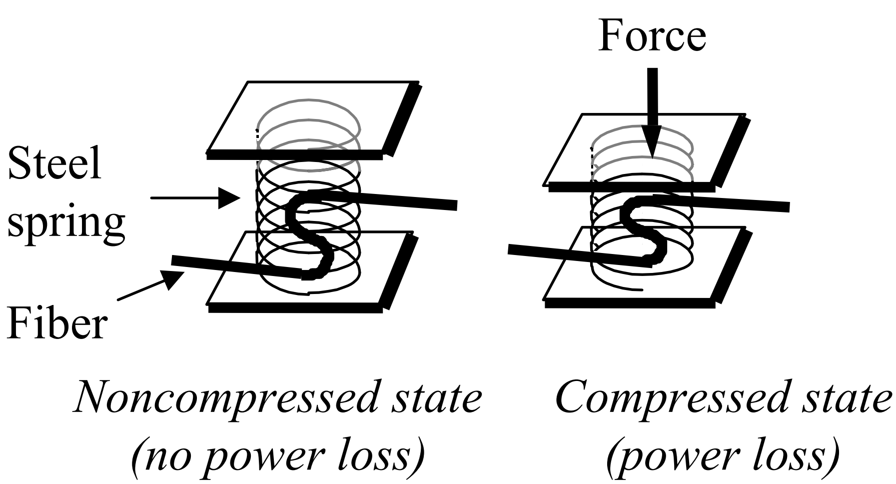


FIGURE 14 Schematic of the spring fiber sensor used as a point perturbation source for train simulations.

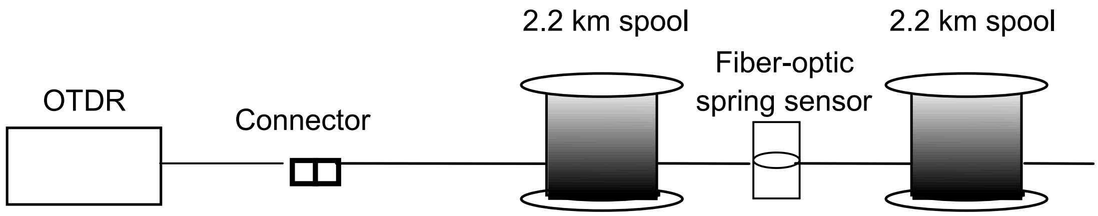


FIGURE 15 Experimental setup for evaluating the distributed fiber sensor – OTDR detection system.

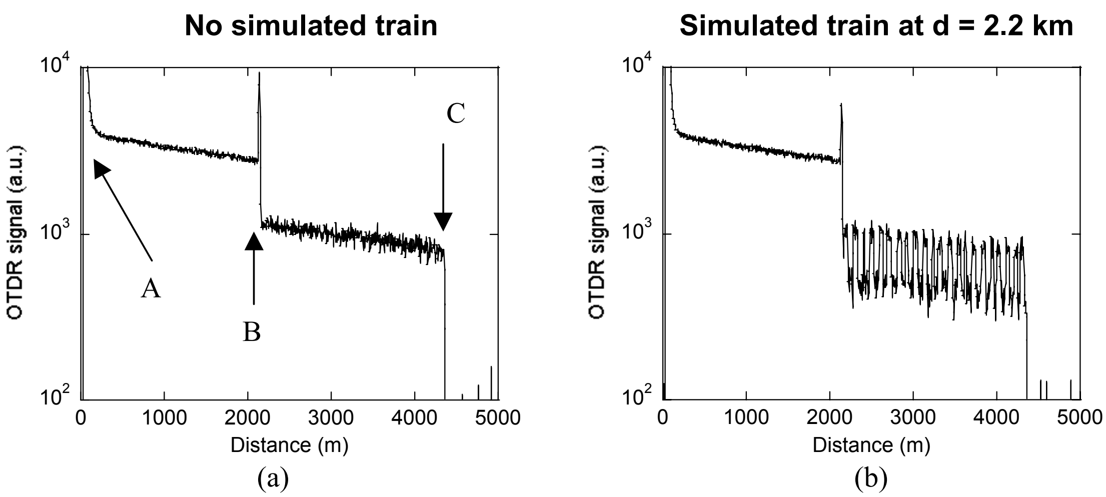


FIGURE 16 (a) Reference OTDR scan without perturbations. (b) OTDR scan with perturbations at d=2.2km.

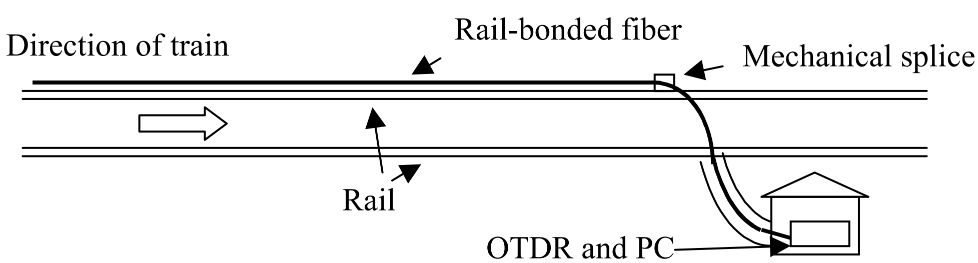


FIGURE 17 Experimental setup for field testing at TTC.

B. Point Fiber Sensor Laboratory Results

Point fiber sensor-based systems were investigated for train presence detection in laboratory experiments. Our group has developed point fiber sensors for various railroad applications such as weigh-in motion and wheel flat spot detection. The point fiber sensor as illustrated in Fig. 19 consists of a transmission fiber and microbending fiber wrapped together and embedded in epoxy between two aluminum plates. As force is applied to the plates, the entwined transmission fiber bends further which results in light loss. As shown in

Fig. 20, the point fiber sensor demonstrated linear repeatable sensing performance from 0 to 25 tons of loading force.

For train presence detection, two point fiber sensors were used at two different locations as shown in Fig. 21. We used the point fiber sensors with both the CW detection system and the pulsed OTDR system. In our simulations, when no train is present, there is no load applied to either Sensor#1 or Sensor#2. When a train conceptually arrives at Sensor #1, a load is applied to Sensor#1. As the train continues, the train also travels over Sensor #2 and a load is applied to both Sensor#1 and Sensor#2. We then compare the sensor response for the three cases to determine how well each case is distinguished from each other.

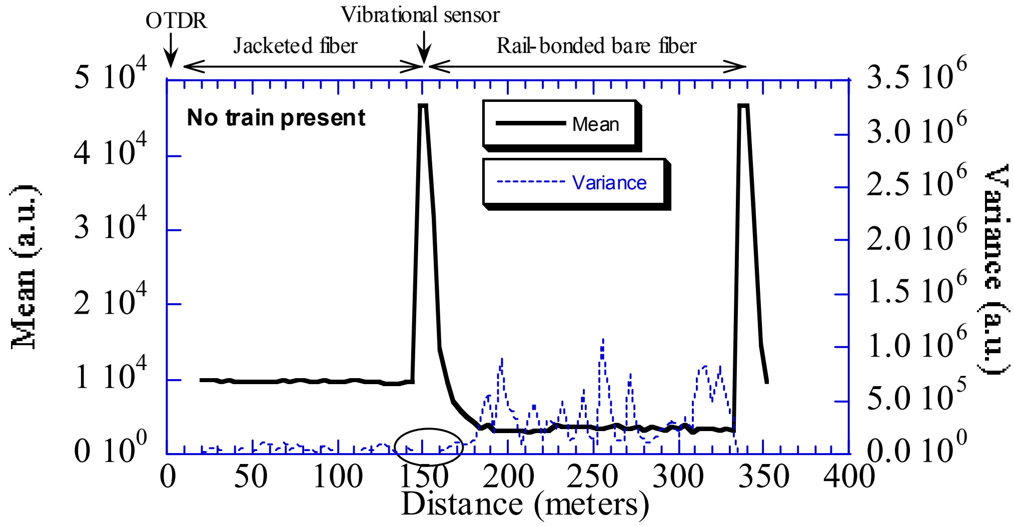
The results for the OTDR detection system are shown in Fig. 22(a) for a load of 20 tons. The load-on-Sensor#1 case shows a significant drop in signal after the Sensor#1 location compared to the no-load case. The load-on-Sensor#1-and-Sensor#2 case shows a signal decrease after the Sensor#2 location and an even larger drop after Sensor#2 as expected. The cumulative difference in signal between the load cases and the no load case is shown in Fig. 22(b) as a function of load force. We can see that the difference in signal increases with increasing load weight as expected, and that the two load cases are clearly distinguishable. This shows that from a signal-to-noise perspective, the point fiber sensor – OTDR detection system configuration should be effective for train presence detection.

The results for the CW detection system are shown in Fig. 23(a) for a varying load pattern ranging from 5 to 20 tons for Sensor #1 only. The light transmission signal clearly follows the load pattern. The differential signal which calculates the percent change in power in a given time interval is also plotted in Fig. 23(a) and clearly shows the transitions between load and no-load. This was also done for the load-on-Sensor#1-and-Sensor#2 case and showed the same trend. In Fig. 23(b) the difference in signal between two load cases and the no load case is plotted as a function of load. Like the OTDR system, the CW detection system shows good signal-to-noise characteristics between the no load case and the two load cases for loads between 5 and 20 tons.

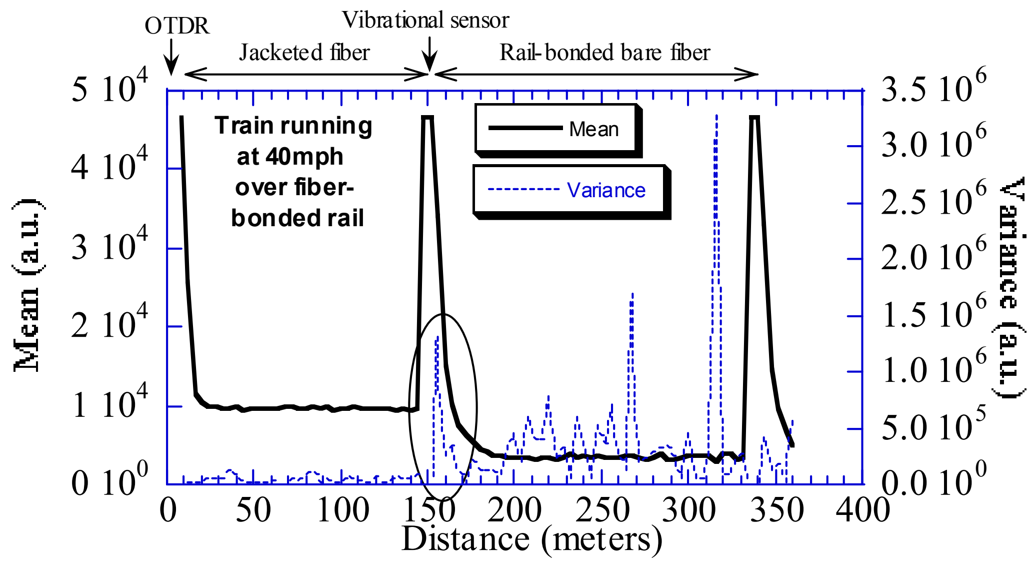
In summary, lab and field testing on train presence and speed detection systems using distributed sensors has been conducted. The CW system showed clear train presence while the OTDR system signal was too weak to detect train presence due to the low sensitivities of the distributed sensor and OTDR to train-induced rail vibrations. Lab results for point-sensor-based systems show promise in train presence and speed detection. Laboratory results show clear detection for loads ranging from 5 to 25 tons for both CW and OTDR systems. Additional field testing should be conducted to verify lab results. The major findings about which combination of optical sensor type and detection scheme work best for train presence and speed detection are summarized below in Table 5.

	CW	OTDR
Distributed sensor	**Good train presence detection**	**Signal too weak for train presence detection**
Point sensor	**Good train presence detection; better precision speed sensor;** field tests needed	**Good train presence detection; lower precision speed sensor; field tests needed**

TABLE 5 Relative Merits of Sensor Type with Detection Scheme.



(a)



(b)

FIGURE 18 The mean and variance of five output scans for (a) no train present and (b) train travelling at 40 mph over the fiber sensors. The variance of the OTDR signal at the location of the vibrational point sensor, circled in each plot, is clearly higher for the train case.

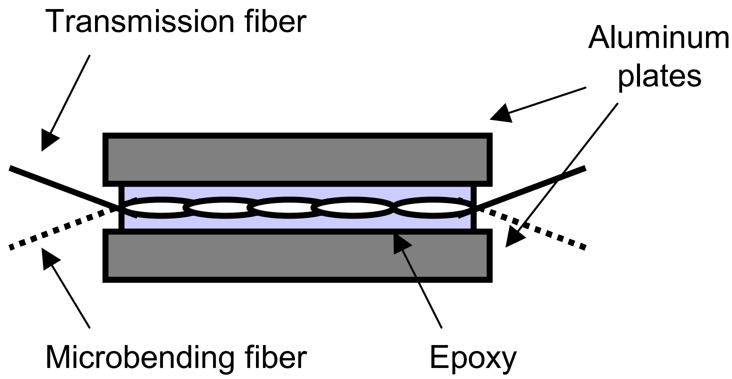


FIGURE 19 Schematic of the point fiber sensor which consists of a transmission fiber and a microbending fiber to increase sensitivity. Both fibers are encased in epoxy between aluminum plates on which force is applied for measurement.

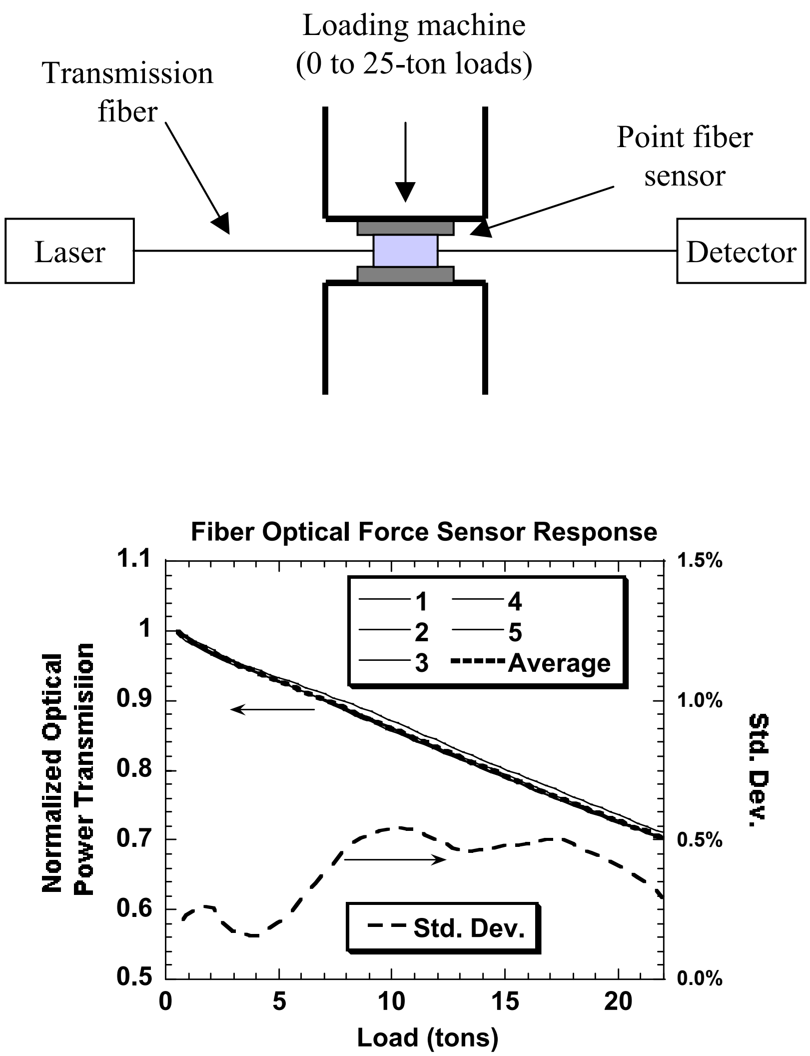


FIGURE 20 Experimental setup for characterizing the point fiber sensor and results. The sensor shows a linear response as a function of load and good repeatability with a standard deviation of less than 1%.

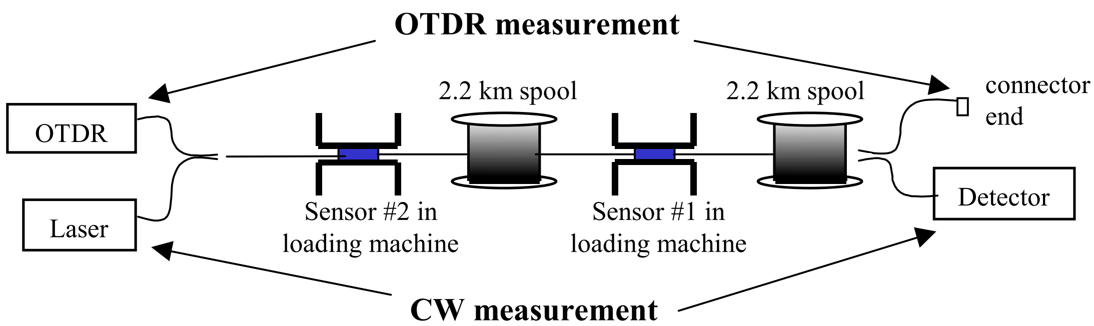


FIGURE 21 Experimental setup for train presence simulations using point fiber sensors and either the OTDR detection system or the CW detection system.

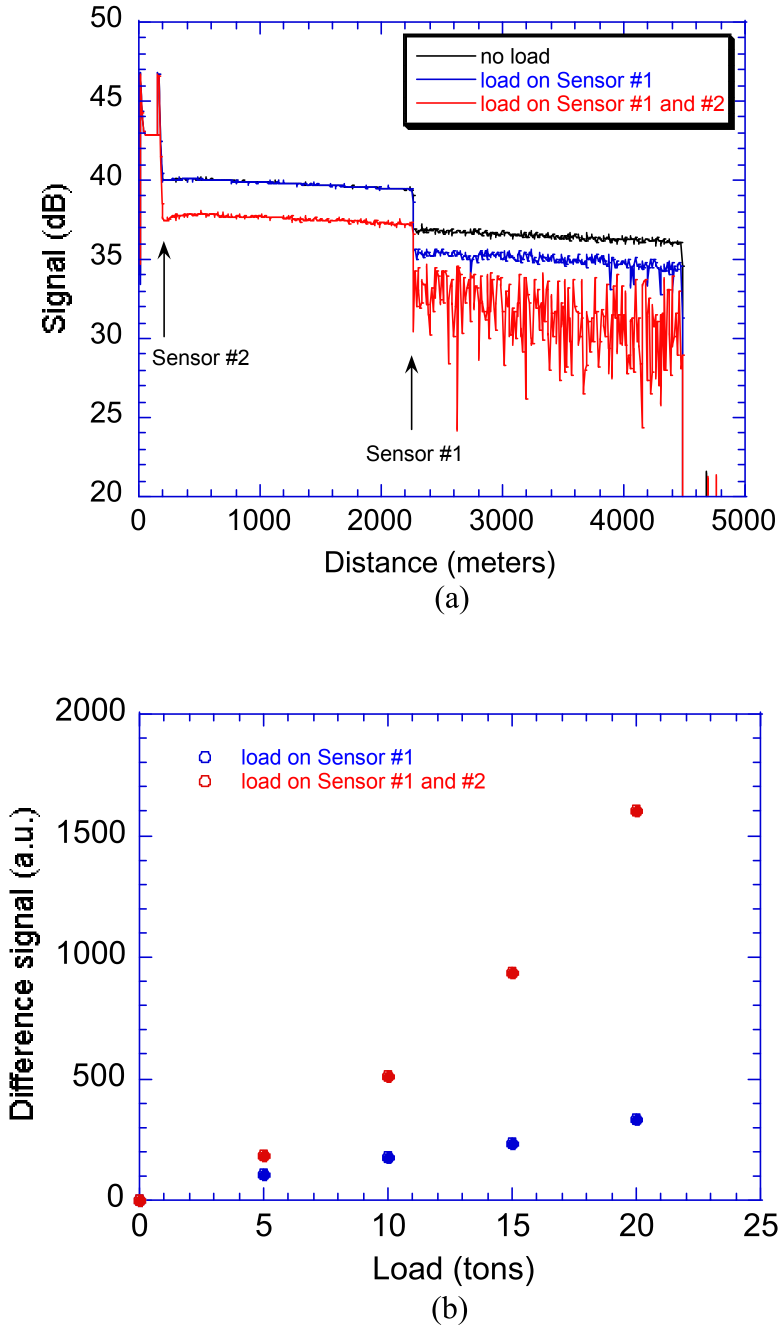
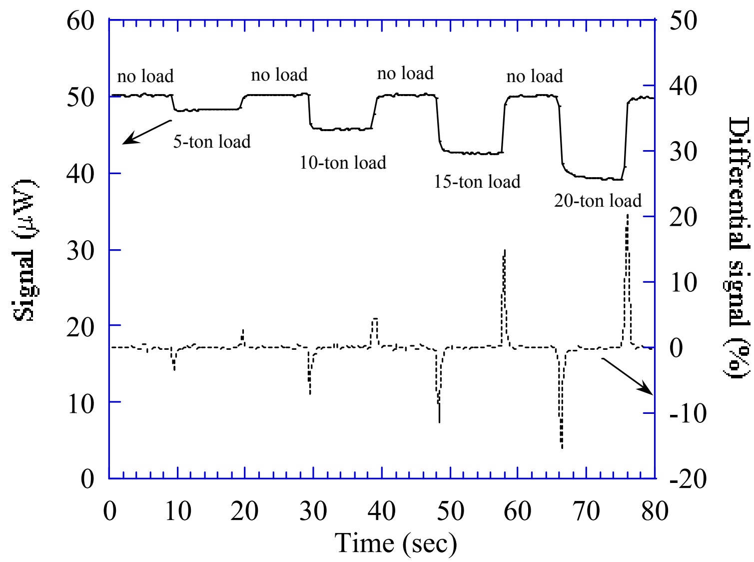
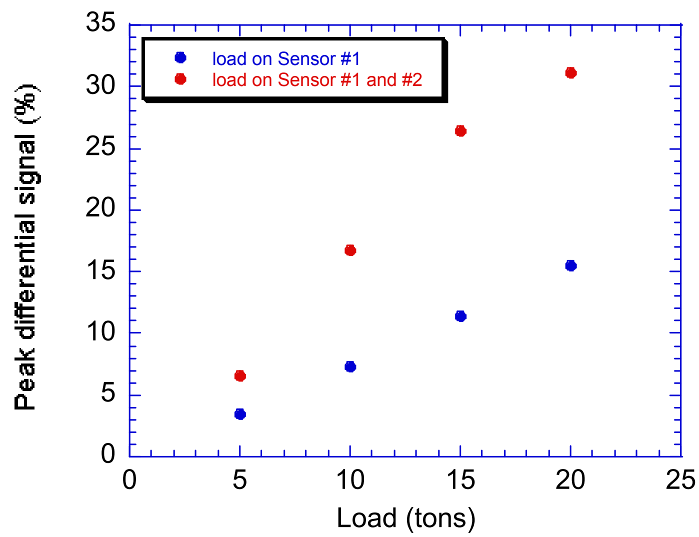


FIGURE 22 (a) OTDR scans for the no-load case, load-on-Sensor#1 case, and load-on-Sensor#1-and-Sensor#2 case. (b) Difference signal for the two load cases as a function of load.



(a)



(b)

FIGURE 23 (a) Detected power and differential signal for the load-on-Sensor#1 case for a varying load pattern ranging from 5 to 20 tons as a function of time. (b) Difference signal for the two load cases as a function of load.

PLANS FOR IMPLEMENTATION

As discussed previously, widespread use of this technology in the railway industry will require further efforts to develop a cost-effective application process, field diagnostic and maintenance procedures, and methods to protect the fiber form track maintenance operations. Development of a bonding agent, such as an epoxy, that can be used in a wider range of temperatures will be necessary. Currently-available epoxy for bonding the fiber to the rail must be applied within a rail temperature range of 50 to 80 degrees F. Railroads have commented that, to be cost-effective, the application rate must be significantly increased beyond ten feet/minute, and the temperature range increased. An effective method of installing fiber over thermite welds must also be developed. Ballast dumping and plowing operations were found to significantly damage the fibers, so ways to protect the fiber need to be developed.

Once these issues have been resolved, acomplete fiber-optic rail break detection system will need to be developed. This system includes the laser transmitter, fiber sensor, photodetector receiver, wireless modem for data transmission, and computer with data acquisition and analysis software. This system would initially focus on rail break detection but could be expanded to include other functions such as rail buckling detection, train presence and speed detection, weigh-in motion, and wheel flat spot detection.

Development of an improved fiber installation cart would also be necessary. It would include features for installation over welds and real-time fiber continuity checking during installation as shown in Fig 24. The goal would be to substantially decrease fiber installation time.

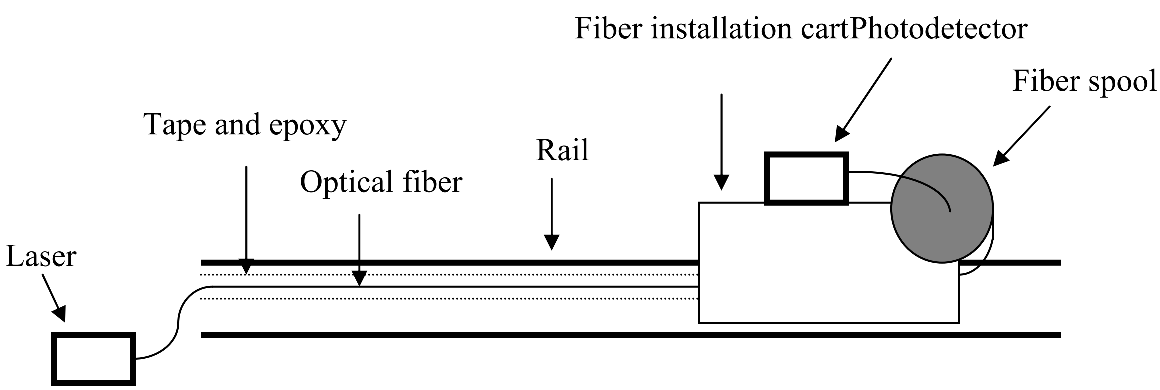


FIGURE 24 Schematic of the real-time fiber continuity check system for the fiber installation cart.

PUBLICATIONS

[1] A. Hsu, E. Young, S. L. Chuang, G. Liu, C. Barkan, R. Reiff, M. Schroeder, D. Williams, T. Johnson, "Fiber-optic sensor technology for railroad applications*," American Society for Nondestructive Testing 2000*, Birmingham, AL, March 2000. (Invited Talk)

APPENDIX A: Corning fiber specifications

Corning SMF-28 singlemode fiber (8.3-μm core)

Category	Specification
Effective Group Index of Refraction at:	
1310 nm	1.4675
1550 nm	1.4681
Spectral Attenuation at:	
850 nm	1.81 dB/km
1300 nm	0.35 dB/km
1310 nm	0.34 dB/km
1380 nm	0.55 dB/km
1550 nm	0.19 dB/km

Corning 62.5/125 CPC6 multimode fiber (62.5-μm core)

Category	Specification
Effective Group Index of Refraction at:	
1310 nm	1.496
1550 nm	1.487
Spectral Attenuation at:	
850 nm	2.72 dB/km
1300 nm	0.52 dB/km
1380 nm	0.92 dB/km
1550 nm	0.29 dB/km

APPENDIX B: Port specifications for the Tektronix TFS2020 OTDR

Universal Short Range Port

Category	Performance Requirement	Supplemental Information
Fault Measurement Range	≥ 7.5 dB	Up to 3 km @ 2.5 dB/km (singlemode fiber) Up to 1.3 km @ 3.5 dB/km (62.5-µm multimode fiber)
Distance Accuracy		
To Reflective Event	±2 m (6.56 ft.)	
To Non-Reflective Event	±2 m (6.56 ft.)	
Optical Output		
Wavelength	850 nm + 20 nm, -50 nm	
Peak Optical Power Output	≥ 30 mW	
Pulsewidths	10 ns ±20%, 50 ns ±10%	
Output Core Size	8 to 10 microns	

Long Range Port

Category	Performance Requirement	Supplemental Information
Fault Measurement Range	≥ 16 dB	≥ 40 km (~25 miles)
Distance Accuracy		
To Reflective Event	±5 m (16.4 ft.)	
To Non-Reflective Event	±5 m (16.4 ft.)	Entire dynamic range
Optical Output		
Wavelength	1300 nm ±25 nm	
Peak Optical Power Output	≥ 8.75 mW	
Pulsewidths	200 ns, 1 µs, 10 µs ±1%	
Output Core Size	8 to 10 microns	

APPENDIX C: Specifications for the ANDO AQ7225B OTDR

Dynamic Range	36/34 dB
Distance measurement accuracy	$\pm$(2m + $2.0\times10^{-5}\times$Measured distance (m))
Optical Output	
Wavelength	1310 ± 30 nm / 1550 ± 30 nm
Pulsewidths	0.02, 0.1, 0.4, 1, 4, 10 μs
Measuring fiber	10/125 μm singlemode fiber

APPENDIX D: Science Magazine, Newspaper, and Web Articles

Science Magazine Articles

M. D. Wheeler, “Fiber sensors ensure train safety,” *Photonics Spectra*, p. 32, May, 2001.

“Fibre-optic sensors light the way to improved train safety,” *Materials world*, vol. 9, no. 5, May, 2001.

Newspaper Articles

G. Kline, “Tracking flaws at light speed,” *The News-Gazette*, vol. 149, no. 232, p. A-2, Mar. 18, 2001.

J. E. Kloeppel, “Fiber-optic sensors detect damaged rails and faulty wheels,” *Inside Illinois*, vol. 20, no. 14, p. 4, Feb. 15, 2001.

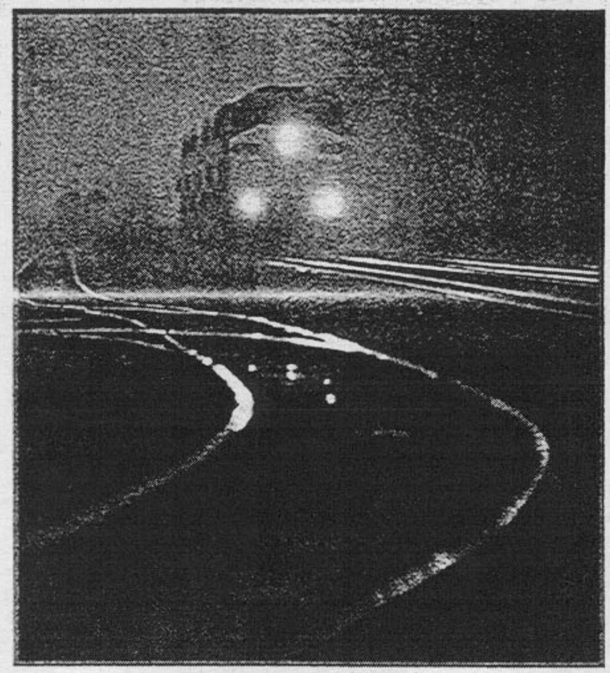
Web Articles

P. Fong, “Innovations”, *www.businessweek.com/index.html*, Mar. 5, 2001.

M. D. Wheeler, “Keeping trains on track: fiber optic sensors ensure train safety,” *www.photonicsspectra.com*, 2001.

http://www.sciencedaily.com/releases/2001/02/010205075953.htm (see attached)

Fiber Sensors Ensure Train Safety



Fiber optic sensors developed at the University of Illinois may prevent train derailments. The sensors monitor the weight of a passing train, defects in its wheels and stress resulting from a cracked or broken rail.

URBANA, Ill. — Fiber optic sensors may soon play a crucial role in preventing the derailment of freight and passenger trains. The sensors monitor the weight of a passing train, defects in its wheels and stress resulting from a cracked or broken rail.

Shun Lien Chuang of the University of Illinois and his research assistants Alan Hsu and Erik Young have developed a series of sensors based on fiber-coupled semiconductor lasers. Photodetectors record the transmission of the laser light through the fiber on a rail, and a computer identifies and records the location of changes or interruptions in optical transmission.

One sensor uses optical time-domain reflectometry to measure the signal loss in the fiber as a function of distance, using optical pulses to pinpoint the site of a broken rail. Another takes advantage of a "microbending" effect to measure the weight and force associated with a train's presence.

"The microbending effect is caused by the fact that a bent fiber will have part of the guided light leaking into the surrounding [area], therefore creating a decrease in optical transmission intensity," Chuang explained. Using a loading machine, the team calibrated the optical transmission coefficient as a function of the applied stress.

By introducing microbending into the fiber, the researchers can measure additional pressures, such as that of passing rail cars. This sensor has also proved effective in locating flat spots on wheels, because it measures the impact force between the wheel and rail.

American Railroads and the National Academy of Sciences, was begun after the association expressed interest in alternatives to the electronic systems currently in place on most railways. The team selected optical fiber sensors for their insulating properties, light weight, immunity to electromagnetic interference, and sensitivity to strain and stress, but there are additional benefits.

"A conventional track circuit depends on the electric current passing through the track," Chuang said. "In some cases, the rail track has only a crack instead of an open, broken gap, [and] the track circuit cannot pick up the broken rail signal since the conduction current path is not interrupted." Fiber sensors can pick up these smaller defects.

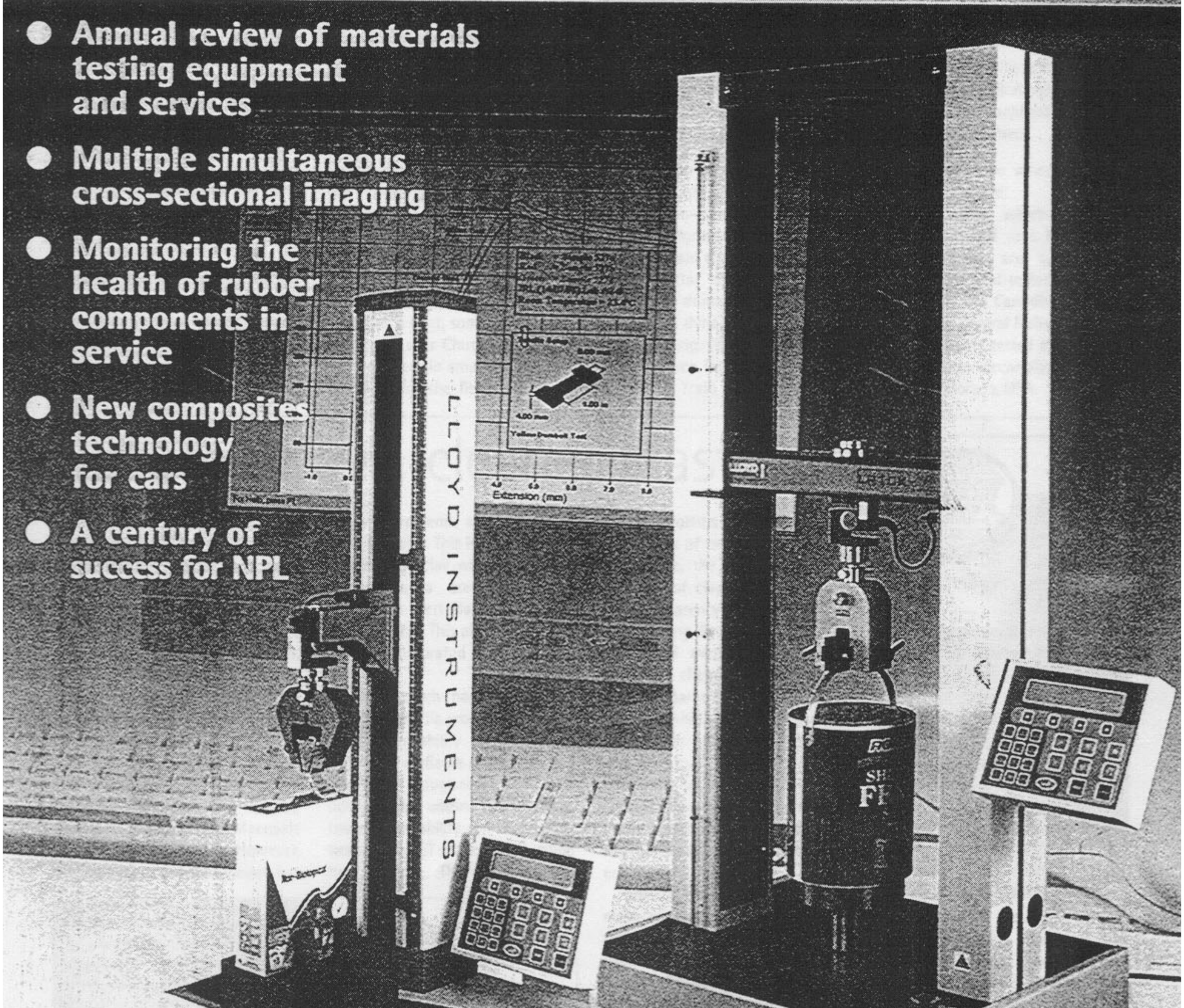
Some railroad companies have expressed interest in field-testing the fibers, and the research group hopes to make the sensors commercially

MATERIALS world

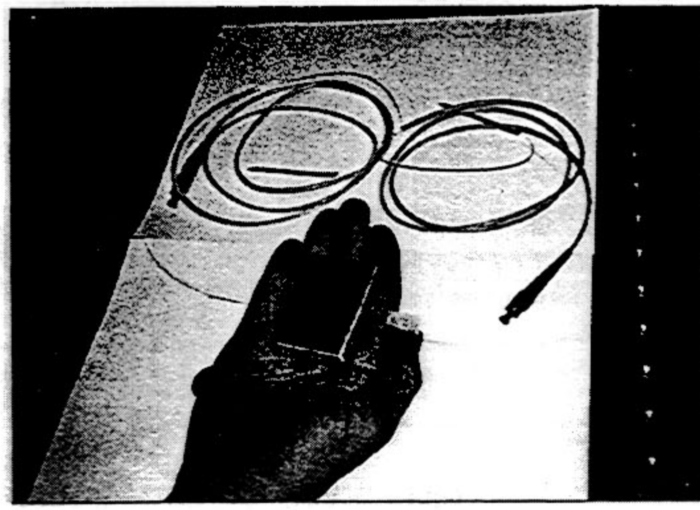
The Journal of the Institute of Materials

Volume 9 Number 5 May 2001

- Annual review of materials testing equipment and services
- Multiple simultaneous cross-sectional imaging
- Monitoring the health of rubber components in service
- New composites technology for cars
- A century of success for NPL



Fibre-optic sensors **light the way to improved train safety**



Fibre-optic sensors being developed at the University of Illinois could improve train safety by detecting flaws in rails and wheels. A number of different sensor designs are being developed for specific applications, which will help protect freight and passenger trains from derailment.

As the UK knows too well, broken rails can cause horrific train accidents with potential loss of life, injury or property damage. A number of reports published at the time of the Hatfield crash centred their criticism on broken rails, exacerbated by damaged wheels and poor testing. Researchers at the University of Illinois (UI) are fabricating fibre-optic sensors that can improve train safety by detecting flaws in rails and wheels.

Currently rail inspections in the UK are carried out using unsophisticated manual ultrasonic inspection techniques. The fibre-optic research being carried out by Shun-Lien Chuang, a UI Professor of Electrical and Computer Engineering, and his team, could provide an answer to the recommendation made to Railtrack by the Transportation Technology Centre Inc (TTCI) to implement modern digital testing techniques.

'Our sensors are based upon optical signal transmission through sensitive optical fibres that are firmly attached to the rails with epoxy and tape,' says Chuang. 'We use fibre-optics to sense an environmental change, such as the weight of a passing train or the strain created by a cracked, broken or buckled rail.'

A number of different sensor designs are being developed as part of the project sponsored by the Association of American Railroads and the Transportation Research Board at the National Academy of Science. In one design, the strain caused by the weight of a passing train is transferred to an attached fibre – the intensity of light emitted indicating the condition of the rail and the amount of induced strain. Another sensor design is based on the 'micro-bending' effect. 'Fibre-optics operate on total internal reflection, so when the fibre is bent, some of the light leaks out,' says Chuang. By introducing a certain amount of micro-bending into the fibre, additional pressure can be measured, including the weight of a passing train.

The palm-size sensor can also detect deformities, such as flat spots in train wheels. 'Wheels can develop flat spots in service, which can damage the rail due to the severe dynamic loads caused,' says Chuang. 'By measuring the impact force between wheel and rail as a train passes over the sensor, defective wheels can be readily identified.'

The sensors, which not only detect damaged rails but also a trains' position and speed, have already been field-tested in cooperation with the Canadian National and Illinois Central Railroad and are currently being tested at the AAR's Transportation Technology Centre in Pueblo, Colorado, USA.

Natural clays, cleaner plastics

A transmission electron microscopy (TEM) picture of a polypropylene/clay nano-composite. The black lines are the inorganic filler particles seen edge-on. The grey regions are the PP polymer. There is a coexistence of single filler layers dispersed in the organic matrix and filler particles bunched in parallel stacks. The inset is an atomistic view provided by computer modelling.

A Penn State researcher, Dr Evangelos Manias has developed an environmentally friendly and inexpensive plastic composite by adding small amounts of well-dispersed natural clays. The clays used are bentonites and montmorillonites, which are already used in paints to prevent dripping, in cosmetics to prevent shine and in pharmaceuticals. 'The clay can be added at the final stages of polymer processing without any change in the current industrial practices,' says Manias, Assistant Professor of Materials Science and Engineering. However, adding clay to polymer blends has its own problems, akin to mixing oil with water. This is dealt with by treating the clay with an organic surfactant, a compound that allows the inert clay to mix with the polymers. This allows the clays to be incorporated into the final product.

The research has shown that improved plastic properties, such as lower permeability to liquids and gases, higher flame retardancy and improved toughness, can be achieved by adding these clays. Lower permeability can make plastics such as PET suitable for bottling beer or wine. The clay-enhanced product protects the beverage from the effects of oxygen, while at the same time, the addition of small amounts of clays does not affect the transparency of the plastic.

Producing flame retardant plastics could eventually save lives. 'Currently, chemicals used to make plastics flame retardant contain bromine, which produces poisonous combustion gases when burned,' says Manias. 'Using clay is a green alternative to current practices and reduces flammability in a wide range of plastics.' As a result, it may have universal application as a general flame retardant.

'Natural clays are currently the most widely other used because they are the same clays already used in many products,' says Manias. 'However, synthetic clays, could provide a broad spectrum of enhanced plastics, Manias is also looking at polymer nanocomposites that contain platelets of metals and

A schematic of a polymer/clay nano-composite in an 'intercalated' form. The detail is from atomistic molecular simulations

Source: University Of Illinois At Urbana-Champaign (http://www.uiuc.edu/)

Date: Posted 2/7/2001

Fiber-Optic Sensors Detect Damaged Rails And Faulty Wheels

Champaign, IL -- Broken rails or damaged wheels can cause train accidents with potential loss of life, injury or property damage. Researchers at the University of Illinois are fabricating fiber-optic sensors that can improve train safety by detecting flaws in rails and wheels. "Our sensors are based upon optical signal transmission through sensitive optical fibers that are firmly attached to the rails with epoxy and tape," said Shun-Lien Chuang, a UI professor of electrical and computer engineering. "We use fiber optics to sense an environmental change – such as the weight of a passing train or the strain created by a cracked, broken or buckled rail."

In projects sponsored by the Association of American Railroads and the Transportation Research Board at the National Academy of Science, Chuang and his research assistants are developing different sensor designs for specific applications. The research on these sensors will help protect both freight and passenger trains from derailment, no matter what speed they are traveling.

In one sensor design, the weight of a passing train causes strain in the rail, which is transferred to the attached fiber. The intensity of light that is transmitted through the fiber will depend upon the condition of the rail and the amount of induced strain. In addition to detecting damaged rails, this sensor also can be used for detecting a train's position and speed.

"The device uses an optical time domain reflectometry system, which measures the signal loss in the optical fiber as a function of distance using a time-gated pulse detection technique," Chuang said. "A moving train creates perturbations in the fiber's optical transmission, so the system takes several scans and measures the distance to the perturbations in order to pinpoint the train's location and speed."

Another sensor design is based on the "micro-bending" effect. "Fiber optics operate on total internal reflection – so when the fiber is bent, some of the light leaks out," Chuang said. "We can calibrate the intensity of the optical transmission as a function of the applied bending pressure." By introducing a certain amount of micro bending into the fiber, the researchers can measure any additional pressure, including the weight of passing rail cars. The palm-sized sensor also offers a fast and cost-effective method to detect deformities – particularly flat spots – in rail-car wheels. "Wheels can develop flat spots in service, which can damage the rail due to the severe dynamic loads they cause," Chuang said. "By measuring the impact force between wheel and rail as a train passes over the sensor, defective wheels can be readily identified."

The telecommunications market has driven down the cost of optical fibers and lasers, making the fiber-optic sensors less expensive than conventional track circuitry or strain gauges, Chuang said. "Our sensors also can operate 24 hours a day unattended and are immune to electromagnetic interference." The sensors were field-tested locally in cooperation with the Canadian National Illinois Central Railroad. They are currently being tested at the AAR's Transportation Technology Center in Pueblo, Colo.

Note: This story has been adapted from a news release issued by University Of Illinois At Urbana-Champaign for journalists and other members of the public. If you wish to quote from any part of this story, please credit University Of Illinois At Urbana-Champaign as the original source. You may also wish to include the following link in any citation:
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