IDEA

Innovations Deserving
Exploratory Analysis Programs

High-Speed Rail IDEA Program

Feasibility of Locomotive-Mounted Broken Rail Detection

Final Report for High-Speed Rail IDEA Project 38

Prepared by:
Steven Turner
Analogic Engineering, Inc.
Guernsey, WY

June 2004

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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

This investigation was performed as part of the High-Speed Rail IDEA program supports innovative methods and technology in support of the Federal Railroad Administration's (FRA) next-generation high-speed rail technology development program.

The High-Speed Rail IDEA program is one of four IDEA programs managed by TRB. The other IDEA programs are listed below.

- NCHRP Highway IDEA focuses on advances in the design, construction, safety, and maintenance of highway systems, is part of the National Cooperative Highway Research Program.
- Transit IDEA focuses on development and testing of innovative concepts and methods for improving transit practice. The Transit IDEA Program is part of the Transit Cooperative Research Program, a cooperative effort of the Federal Transit Administration (FTA), the Transportation Research Board (TRB) and the Transit Development Corporation, a nonprofit educational and research organization of the American Public Transportation Association. The program is funded by the FTA and is managed by TRB.
- Safety IDEA focuses on innovative approaches to improving motor carrier, railroad, and highway safety. The program is supported by the Federal Motor Carrier Safety Administration and the FRA.

Management of the four IDEA programs is integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation.

For information on the IDEA programs, contact the IDEA programs office by telephone (202-334-3310); by fax (202-334-3471); or on the Internet at http://www.trb.org/idea

IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

FEASIBILITY OF LOCOMOTIVE-MOUNTED BROKEN RAIL DETECTION

IDEA Program Final Report
For the Period September 1, 2002 Through October 15, 2003

Contract Number HSR-38

Prepared for
The IDEA Program
Transportation Research Board
National Research Council

Steven Turner

ANALOGIC ENGINEERING, INC.
PO Box 873, 320 W. Whalen St.
Guernsey, WY 82214

analogic@prairieweb.com

Revised
June 21, 2004

ACKNOWLEDGMENTS

I would like to thank the following people for their contribution to this project:

Consultants:
- John Hill, Independent Consultant
- Bob Kubichek (Also on Advisory Panel), University of Wyoming

HSR-IDEA Program Officer:
- Chuck Taylor, Transportation Research Board

Advisory Panel:
- Jeff Gordon, Department Of Transport, Volpe Center
- Bob Kubichek, University of Wyoming
- Bob McCown, Federal Railroad Administration
- Don Plotkin, Federal Railroad Administration
- Rich Reiff, Transportation Technology Center, Inc.

I am very grateful to the advisory panel members from the railroad administration and railroad research community for taking the time to participate, and the knowledge and experience that they contributed. I would also like to thank Chuck Taylor for guiding our company through the IDEA program, and allowing us the latitude to learn from this experience and be better prepared for any future projects. Finally, I very much appreciate the expert technical advice, guidance and encouragement provided by John Hill and Bob Kubichek.

ABSTRACT

This research examined the feasibility of applying Time Domain Reflectometry to the task of broken rail detection. The key innovation is to regard the track as a two-wire electrical transmission line, and then apply the same electrical pulse/echo technique that is commonly used to locate breaks and shorts in electrical cables. The aim of the proposed locomotive-mounted system is to allow each train to independently test the track ahead for broken rails and track occupation, up to a given detection range. This approach is designed to work in conjunction with Communication-Based Train Control to replace the present wayside signaling system and eliminate the associated per-mile maintenance costs. A theoretical framework for the proposed test system was developed to explore the likely benefits and problems, and a MATHCAD signal path model was developed to estimate the detection range. Anticipated problems that were considered included track-shunting structures such as turnouts; interoperability with the existing track circuits; RF safety and licensing issues; and the complex mechanical and electrical requirements for coupling signals between the train and the track. The signal path model incorporated factors such as the estimated transmission line characteristics of railroad tracks with wood or concrete ties and wet or dry ballast conditions; initial pulse characteristics; signal coupling losses to and from the rail; electrical reflection models for various configurations of broken rail or track occupation; and signal processing techniques that could be applied to recover highly attenuated echo signals. To estimate transmission line characteristics, previous European research on railroad track electrical properties was extrapolated to the required test frequencies. Railroad track was found to have a high attenuation rate because of ballast conductance, and the attenuation rate was predicted to increase significantly at the higher frequencies needed for pulse/echo testing. Even so, the model predicted that a range of one mile for wet ballast and two miles for dry ballast could be possible by using correlation processing to enhance the echo signals, and a variety of initial pulse characteristics to cover different segments of the required search range for various track conditions. The given range might be suitable for some train categories but not for others, depending on the full-service braking distance for each category of train. It is recommended that field measurements be made of the track attenuation rate over a broad range of frequencies for various U.S. track conditions. The aim would be to validate and fine-tune the model, and then reassess the predicted detection range compared to the safe stopping distance of each category of train.

KEY WORDS

Broken Rail Detection
Track Occupation
Time Domain Reflectometry (TDR)
Transmission Line
Communications-Based Train Control (CBTC)
Positive Train Control (PTC)

TABLE OF CONTENTS

EXECUTIVE SUMMARY **1**

1. INTRODUCTION **3**
- 1.1 PROBLEM STATEMENT 3
- 1.2 PROPOSED SOLUTION 3
- 1.3 POTENTIAL BENEFITS 4
- 1.4 ANTICIPATED PROBLEMS 5
- 1.5 RESEARCH GOALS 6

2. IDEA PRODUCT **7**
- 2.1 TRANSMISSION LINE MODELS AND RANGE PREDICTIONS 7
- 2.2 PROPOSED SYSTEM OUTLINE 9
  - 2.2.1 Driver Interface Unit 9
  - 2.2.2 Electronics Unit 10
  - 2.2.3 Rail Coupling Unit 11
- 2.3 POTENTIAL FEATURES, ADVANTAGES AND BENIFITS 14
- 2.4 OTHER POSSIBLE APPLICATIONS 16
  - 2.4.1 Work Crew Protection 16
  - 2.4.2 Advanced Grade Crossing Predictor 16
  - 2.4.3 Platform and Pedestrian Crossing Safety 16
  - 2.4.4 Commuter and Light Rail 16

3. CONCEPT AND INNOVATION **17**
- 3.1 BACKGROUND 17
- 3.2 METHOD SELECTION 17
- 3.3 COMPARISON TO OTHER ALTERNATIVES 18
- 3.4 RELATED TECHNOLOGIES 19
  - 3.4.1 Time Domain Reflectometry (TDR) 19
  - 3.4.2 RADAR Signal Processing 20
  - 3.4.3 Global Positioning System (GPS) 20

4. INVESTIGATION **21**
- 4.1 ORIGINAL RESEARCH TASKS 21
- 4.2 RESULTS 21
- 4.3 ADDITIONAL TASKS AND RESULTS 22
  - 4.3.1 Signal Loss at Bonded Joints 23
  - 4.3.2 RF Exposure 23
  - 4.3.3 RF Licensing 25
  - 4.3.4 Interaction with Existing Track Circuits 25

5. PLANS FOR IMPLEMENTATION **27**

6. CONCLUSIONS **28**

7. INVESTIGATOR AND CONSULTANT PROFILES **29**
- 7.1 PRINCIPLE INVESTIGATOR - STEVEN TURNER 29
- 7.2 CONSULTANT - DR. JOHN HILL 29
- 7.3 CONSULTANT - DR. ROBERT KUBICHEK 29

8. REFERENCES **30**

EXECUTIVE SUMMARY

Railroads presently use a wayside system of track circuits and signal lights to detect broken rails and manage traffic separation. Communications-Based Train Control (CBTC) is an alternative method of traffic regulation that does not require track circuits, but CBTC alone can not provide broken rail detection. A cost-effective alternative for detecting broken rails would allow railroads that adopt CBTC to eliminate track circuit-based signaling and the associated per-mile maintenance costs. Therefore, the Committees for Railroad Track Structure System Design and Rail Transit System Design have each released Research Problem Statements calling for alternative methods of broken rail detection. This research examined Time Domain Reflectometry (TDR) as the basis for a locomotive-mounted broken rail detection system that would avoid introducing any new per-mile costs.

TDR works on the principle that when an electrical signal traveling along a transmission line encounters a deviation from the characteristic impedance, some (or all) of the signal will be reflected according to the degree of impedance mismatch. This principal is employed in instruments that are used to locate faults in transmission lines such as underground telephone cables. If a cable is damaged, there is nearly always an associated local change in the transmission line impedance. To locate the damage, a TDR instrument is connected to one end of the cable, electrical pulses are sent into the cable, and any signals reflected back to the instrument are detected and displayed. These echo signals have a time delay that is proportional to the distance to the fault, and the shape of the echo identifies the type of reflector. Specifically, an open-circuit will reflect the original pulse shape while a short-circuit will reflect an inverted pulse shape. The detection range of a TDR instrument can be many miles, and is mostly determined by the shape and energy of the initial transmitted pulse, the rate of signal attenuation along the cable (to the reflector and back), and the sensitivity of the receiver. To summarize, a TDR instrument connected to one end of a transmission line can determine the type and location of any significant impedance variation along the cable, including open or short circuits, by transmitting an electrical pulse and then measuring the time delay and the shape of any returning echo.

The key innovation of this research is to apply the same test method to the task of broken rail detection by treating the two rails and track bed as an open two-wire transmission line. The concept is that the lead locomotive of every train would be equipped with a TDR-based system to search the track ahead for open circuits caused by broken rails. In addition, a track occupation would also be detectable as a short circuit reflector, and be distinguishable from a broken rail by the inverted shape of the echo. Thus, with little dependence on external equipment, the proposed system would identify any broken rail or track occupation within the TDR detection range, calculate the distance ahead, and generate appropriate displays and warning alarms for the train crew.

The main objective of TRB IDEA contract HSR-38 was to determine if the concept was technically feasible, and if further research might be warranted. This was accomplished by determining the theoretical detection range and exploring the possible problems, advantages and disadvantages of the proposed system.

To be viable, the proposed system would need to provide a detection range greater than the stopping distance of the train, preferably using a "full service" rather than an emergency brake application. Therefore, the first major research task was to create a MATHCAD model for predicting the TDR detection range. The model included possible initial pulse characteristics, the total signal path attenuation, possible receiver characteristics, and the benefits of signal correlation methods such as those used in RADAR systems to recover and identify very low-level received signals. The railroad track attenuation rate, relative to test pulse frequency, was estimated by consultant Dr. John Hill by extrapolating from previously published research, and included the effect of various track conditions such as rail weight, tie type (concrete or wood) and ballast conductance (wet and dry). Options were included in the signal path portion of the model to allow for the calculated reflection coefficient for either a track occupation or a broken rail, as well as coupling models for transferring the electrical signals between the train and the track. The completed mathematical model estimated detection range for broken rails and track occupation for various track conditions and for given parameters such as the pulse frequency, pulse duration, transmitter power, test repetition rate, signal correlation period, and train speed.

The second major research task was to consider the anticipated problems of implementing a locomotive-mounted TDR system. Some problems related to the fact that railroad track is an inconsistent transmission line. The high attenuation rate is very dependent on the track bed conductance, which varies with location and season. This conductance also contributes to a complex transmission line impedance that causes the attenuation rate to be frequency-dependant. The electrical effects of track structures such as rail joints, bridges and turnouts were also

considered. Another problem was devising a method of coupling signals to and from the track that would not be affected by the local electrical shunt of the train itself. Finally, factors were considered that might reduce range by limiting the maximum allowable initial pulse energy. These included the RF radiation hazard, FCC licensing requirements, practicality and cost of high-power transmitters, and interactions with the existing track circuits.

The third major task was to determine the potential advantages and disadvantages of the proposed system. For this task, a system overview was developed that included the possible system/subsystem component layout as well as the expected functional requirements of the key subsystems. The purpose of the system description was to provide insight into how a final system might be implemented; help anticipate other potential problems; suggest how information might be presented to the train crew; and identify possible advantages and disadvantages compared to existing track circuits as well as other suggested methods of broken rail detection.

The resulting MATHCAD model predicted a detection range of approximately 1 to 2 miles depending on the track conditions such as ballast moisture content. Since the track attenuation rate increases with frequency, low-frequency pulses are necessary to achieve the maximum range. On the other hand, the pulse frequency can not be too low since the duration of the initial pulse has to be limited to avoid overlap between the trailing edge of the generated pulse and the leading edge of the returning echo. Rather than a single compromise frequency, it was found that a spread of pulse frequencies from 50 kHz to 500 kHz might be necessary to cover different segments of the range, i.e., lower frequencies for long range reflectors and higher frequencies for nearby reflectors. To achieve maximum range, a transmit power of 10 kW at 50 kHz for up to 60 uS was considered (approximately a 1000 V peak rail-to-rail signal), but the relationship between power and range was found to be logarithmic such that a 100 W pulse (100 V) would achieve 90% of the 10 kW pulse range, and a 1 W pulse (10 V) would achieve 80% of this range. This suggests that transmitter power could be reduced to meet safety and compatibility requirements without a dramatic loss of range. It should be noted that the MATHCAD models were based on extrapolations from track measurements performed at much lower frequencies, and it is recommended that field tests be performed to confirm the predicted track transmission line properties. This is important because the predicted range may or may not be suitable based on the braking distance for each category of train (freight, heavy-haulage, light rail, passenger, etc.). Field tests would determine if the actual detection range is equal to, more than or less than predicted, and allow an assessment of how useful this range would be for each type of train.

To couple signals to and from the track, an inductive coupling method was proposed that would incorporate the leading axle shunt as part of the coupling circuit. This solution would require a coil or a pair of coils, one for each rail, held above the rails at a reasonably constant height and alignment. To achieve this, two possible mechanical approaches are suggested: using the leading axle as a reference by attaching the coil support to the traction motor or axle bearings; or a gauge reference guide wheel system similar to those used by some track maintenance vehicles. In either case, considerable safety and mechanical design issues would need to be resolved.

Based on MATHCAD modeling, the TDR method was predicted to have many of the same shortcomings as the present track circuit method, i.e., partial breaks, breaks under compression and breaks on tie plates would not be detected if there was no significant loss of electrical continuity. It was also found that due to the increased resistance at each joint, the detection range on tracks with properly bonded joints (every 39 ft) would be reduced, but only slightly (about 1% to 2%) compared to CWR. Insulated Joints (IJs) would behave like broken rails and limit the test range, but it may be possible to add bypass filters tuned to the TDR frequency to continue testing past the IJ. Turnouts and other track structures that shunt the track would also limit test range unless modified. Two methods are suggested for transferring the initial pulse and returning echo signals past a turnout. A passive approach would use IJs to electrically isolate the shunt and cables with electrical relays to provide electrical continuity to match the track alignment. The alternative would use an active repeater system with coils to receive and retransmit signals around the shunt so that no IJs would be needed.

This report details the possible advantages of a TDR-based system. As an adjunct to CBTC, the proposed locomotive-mounted system could allow for the elimination of track circuits. Other advantages could include providing continuous, real-time monitoring of the track ahead directly to the train crew without depending on external equipment, signals or communications systems that might delay critical warning information. Locomotive mounting would provide a local power source and a well-controlled operating environment plus the added security and safety of not relying on exposed wayside equipment. In support of CBTC, the proposed system could provide a backup for collision-avoidance in the event of a CBTC error or communications failure, and also detect unexpected track occupations such as isolated freight cars.

1. INTRODUCTION

1.1 PROBLEM STATEMENT

The Transportation Research Board (TRB) has identified the need for an alternative method of broken rail detection to help encourage the adoption of Communications-Based Train Control (CBTC). This need is described in the Committee Research Problem Statements of the Committee on Railroad Track Structure System Design (A2M01) (*1*), and the Committee on Rail Transit System Design (A2M04) (*2*). To summarize, many railroads employ track circuit-based signaling systems that display track status information to train drivers, and provide two important safety functions: a primary function of avoiding collisions and providing basic traffic flow regulation by warning of other traffic ahead in the next few blocks of track; and a secondary function of avoiding derailments by warning of broken rails ahead in the next few blocks. As U.S. railroads improve operating efficiency and cope with increased traffic density and diversification on major rail corridors, the fixed block boundaries and limited vocabulary (go, prepare to stop, stop) of the present signaling system have become major limitations. Communications-Based Train Control is a proposed solution that would use data communications channels to connect each train to a centralized traffic control facility. GPS speed and location data would be gathered from each train. All traffic would be continuously analyzed and individual target speeds would be assigned to each train to maintain safe separation, optimize traffic flow, and minimize the need for heavy braking or acceleration.

As a replacement for the primary function of the present signaling system, CBTC is expected to improve railroad efficiency by providing flexible and precise traffic control, but CBTC is not able to provide the secondary function of broken rail detection. If a cost-effective method to cover this deficiency were available, railroads that implement CBTC would have the option of removing track circuit-based signaling altogether to eliminate a significant component of per-mile maintenance costs and simplify the railroad infrastructure. Therefore, the TRB is seeking a viable method of broken rail detection that could work in conjunction with CBTC to provide a complete replacement for the present signaling system; thus providing additional financial incentive and safety reassurance to railroads that are considering changing over to CBTC.

Clearly, any viable alternative must be more cost-effective than retaining the present signaling system for the sole purpose of detecting broken rails. Maintenance costs per-mile may not be significantly reduced if the alternative method requires new wayside infrastructure that introduces a new set of maintenance problems and costs. Similarly, the replacement method should avoid adding to the cost of normal track maintenance tasks. If any of the common track maintenance operations such as ballast, tie or rail replacement, track realignment, or repairing rail defects become more difficult, or if track maintenance equipment has to be modified, the overall financial incentive is reduced. This implies that the replacement broken rail detection system should be highly compatible with existing track construction and maintenance procedures. Finally, any replacement system must be at least as accurate and reliable at identifying broken rails as the present method.

1.2 PROPOSED SOLUTION

This report describes an electromagnetic pulse/echo method that was devised in consideration of the above requirements. The key innovation is to view the track structure as a two-wire parallel transmission line, and then apply a technique known as Time Domain Reflectometry (TDR). The principle of TDR is that if a signal is traveling along a transmission line and it encounters a deviation from the characteristic impedance, some of the signal is reflected (100% in the case of a complete open or short circuit). TDR-based transmission line analyzers are often used to locate damage and circuit failures in transmission lines such as power and communication cables. A test pulse is injected into the transmission line, and any reflected signals are then measured and analyzed. The type and degree of circuit interruption is estimated from the phase and amplitude of the reflected signal, and the pulse-echo time delay is used to calculate the distance to the reflector. A relevant feature of TDR cable testers is that testing is performed from one end of the cable with the transmitter and receiver contained in a single unit at the same location. If the same TDR principle can be successfully applied to broken rail detection, this might allow a fully self-contained broken rail detection system to be placed on the lead locomotive of each train, thus reducing the dependence on wayside infrastructure.

Since detection would be based on the same principle that is used by existing track circuits (i.e., detecting differences in electrical properties between normal rails and broken rails), the proposed system should be compatible with existing railroad construction. Apart from the modifications to track-shunting structures such as turnouts and diamond crossings (detailed in this section), no changes in track design, construction methods, maintenance equipment or rail repair procedures would be needed. This is important because the benefits of eliminating the present signaling system would be reduced if new equipment was added along the track that required any significant amount of maintenance, or if other aspects of track maintenance became more difficult or expensive. Although new equipment is being proposed, these costs would be per-train rather than per-mile, and far fewer systems would be required than the present number of track circuit controllers. Furthermore, any maintenance that might be required could be centralized and performed at existing locomotive workshops by the same technicians that service other locomotive control systems and future CBTC systems. To summarize, the proposed method addresses the specific problem described in the Committee Research Problem Statements, in a way that might lead to significant cost savings without compromising on present performance.

Beyond meeting these basic requirements, the proposed method may offer specific new advantages. Some of these advantages arise from placing the system in the locomotive. For example, reliability should be improved because the locomotive would provide dependable power and better protection from environmental extremes than the present wayside equipment boxes. Also, warning messages would be directly available to the crew so that immediate action could be taken, rather than depending on external visual or radio communications that might have some risk of delaying or losing the message. Other advantages would arise from knowing the exact distance to the reflector rather than just to within a signaling block. Knowing the available stopping distance could encourage the optimum safe driver response, and pinpointing the break location could also reduce track repair time. Finally, track occupation detection was not a requirement of the Committee Research Problem Statements since CBTC is intended to provide the replacement for this function of track circuits. However, the ability of the proposed method to detect and determine the distance to a track occupation would provide useful additional benefits. This could provide a backup in the case of a CBTC system failure, and protect against unusual track occupations such as isolated or runaway freight cars that would not be registered by the CBTC system.

Track structures that shunt the track such as turnouts and diamond crossings would truncate the test range until the train passed beyond the structure. To overcome this limitation, two methods were devised to allow the initial outgoing pulse and the returning echo signals to bypass these structures. One method would be to use cables to continue the electrical path around the shunt with IJs on each rail to electrically isolate the structure itself. In the case of turnouts, electrical switches operated by the track switching mechanism could be used to match the electrical continuity of the rails to the mechanical alignment of the track so that the train would “see” past the turnout onto the correct track. For diamond crossings, cables crossing under the tracks could provide the proper electrical continuity of each pair of rails. In this case, it might be useful to electrically link the two tracks so that a train approaching or across the intersection would shunt all four rails to indicate an occupation of both tracks.

An alternative method would avoid the need for any IJs by using fixed inductive coils on each track connected to the shunting structure. The operating principle would be the same as the locomotive coupling coils that operate near the shunt caused by the leading axle, except that these coils would be permanently fixed to the inside base of the rail. The main disadvantage of this method is that an active system would be required at each turnout to receive and re-transmit the signals around the shunt. Even so, the additional “per-turnout” costs and maintenance requirements may still be justifiable if this allows the elimination of “per-mile” track circuit costs.

1.3 POTENTIAL BENIFITS

- *Locomotive-Mounted*
  Since TDR is based on detecting and measuring reflected signals, the signal source and receiver can be at the same location. This could allow a system to be operated from the lead locomotive of a moving train. Resulting benefits would include: reduced wayside infrastructure; centralized installation and maintenance; warning information directly available to the train crew without depending on external communications or displays; equipment located in a cleaner, regulated and secure environment; and fewer systems required (i.e., railroads generally have fewer trains than blocks of track).

- *Measures Distance to Reflector*
  The pulse-echo time delay would be proportional to the distance to the reflector, so the exact location could be provided rather than just “somewhere in the signal block”. This might allow increased traffic density by overcoming the present “two block” spacing limitation, and could also reduce repair delays.

- *Comparable Detection Performance and Reasonable Compatibility with Existing Track Construction*
  Some proposed alternatives for broken rail detection would require major changes in track construction and maintenance procedures. Some alternatives could be overly sensitive to normal track components such as welds. The proposed TDR method would identify broken rails by detecting the local change in electrical conductivity, i.e., the same underlying principle as track circuits. This similarity is expected to provide comparable accuracy in identifying broken rails. Common track features such as welds, boltholes and properly bonded joints should not produce false-positive indications or significantly limit the test range, and the proposed system should be compatible with existing track designs and construction methods, defect repair procedures, track maintenance procedures, and track maintenance equipment.

- *Protection Beyond Turnouts and Other Track-Shunting Structures*
  By incorporating the modifications to turnouts and other track-shunting structures that are suggested in this report, the proposed system could provide additional reassurance to the train crew that the turnout was correctly aligned, and that the track up to and beyond the turnout was intact and unoccupied. For a train approaching the turnout, a broken rail or track occupation ahead on the selected track would be detected while the state of the unselected track (e.g., a siding occupied by a waiting train) would be properly ignored. A turnout set against an approaching train would be identified appropriately as a broken rail that would signal the train crew to stop before the turnout.

- *Detects Track Occupation*
  Track shunts would also cause a reflection, but with a signal phase distinguishable from broken rails, so any track occupation ahead could also be located and identified. This would provide redundancy for avoiding collisions with other CBTC registered traffic. More significantly, this would provide protection against unusual track occupations such as isolated freight cars that would be “invisible” to CBTC.

1.4 ANTICIPATED PROBLEMS

- *Detection Range*
  The ideal detection range would provide adequate time for the train to safely stop using, at most, a “full service” brake application, plus an allowance for crew reaction time. Factors affecting braking distance include the train speed, weight and braking system, track conditions such as grade and rail surface conditions, and additional considerations such as passenger safety. A detection range of two miles was thought to be a reasonable initial benchmark. For certain conditions, such as a heavy-haulage train on a steep downgrade, a greater range may be required.

- *Coupling Signals To and From the Track*
  TDR cable testers operate using a direct connection to the end of the transmission line cable to be tested. In this application, a direct connection would not be suitable because the train itself represents a short circuit across the track. An inductive coupling coil method is proposed to solve this problem, but it may be difficult to provide sufficient coupling efficiency, especially considering the mechanical clearances required for grade crossings, turnouts, etc., and the need to maintain consistent coil alignment with both rails while the train is moving.

- *Compatibility With Track Circuits*
  Although the proposed system was designed with the idea of working with CBTC to eventually replace signals and track circuits, both systems would likely have to coexist for some time. Compatibility would

depend on the transmit pulse power, duration and frequency required to achieve an adequate detection range. The proposed system would operate at higher frequencies than most track circuits, so in theory it could be possible to use passive filtering to isolate the systems. At higher pulse power, the breakdown voltage and overload voltage of track circuit controller inputs would need to be considered. Existing track circuits that use Insulated Joints (IJs) to define each block would limit the detection range unless each IJ was bypassed with a tuned circuit to allow the test pulse or echo signals to continue past the IJs.

- *Electrical Characteristics of Broken Rails and Bolted Joints*
  Like track circuits, the proposed method depends on measuring a change in rail conductivity to detect a broken rail. Therefore, many of the same limitations apply. In particular, a significant loss of electrical continuity would be required, so partial breaks, breaks on tie plates, and breaks under compression might not be detected. For similar reasons, bolted joints would still require bond wires to ensure a good electrical connection; otherwise they could generate a false broken rail indication which would truncate the test range. On jointed track with bond wires (every 39 ft), the detection range was predicted to be slightly reduced (1% to 2% less than CWR) due to the cumulative transmission loss at each bond wire.

- *Modifications to Turnouts and Diamond Crossings*
  The general aim of the proposed system is to reduce wayside infrastructure and the associated "per-mile" costs. However, track-shunting structures such as turnouts and diamond crossings would need modifications and/or additional equipment to prevent the track shunt from limiting the test range.

- *Train Crew and Rail Worker RF Safety, and FCC Licensing Requirements*
  The transmit power required to achieve an adequate range may present problems with RF radiation exposure limits and FCC licensing requirements. Fortunately, the very long wavelengths of the RF frequencies that are being considered means that the RF energy is not readily absorbed by objects the size of human beings. The licensing requirements have not been thoroughly determined since the exact frequencies and transmitter power requirements should first be determined through field-testing (using very low-power RF pulses). If and when the actual track behavior is known, the exact relationship between the initial pulse power, the pulse frequency, and the resulting range can be specified.

1.5 RESEARCH GOALS

- *Determine Theoretical Validity, Model and Predict Transmission Line Behavior, and Predict Range*
  Review literature and search US Patents. Compile and analyze all available rail and track electrical data, extrapolate for widest possible range of pulse frequencies and track conditions, and generate a mathematical model of transmission line behavior. Estimate optimum pulse frequency, pulse timing, and other basic design parameters and system requirements. Extend model to include all signal path components and requirements. Estimate range for various track conditions including wet or dry ballast.

- *Establish General Design Requirements for a Practical System Implementation*
  Develop system design parameters and a general system outline. For each key component, determine in general terms if and how to meet the design requirements. Attempt to anticipate potential "show stoppers" and look for possible solutions. Examine related technologies such as low-frequency atmospheric RADAR and select useful processing methods and device types. Based on equipment used in related fields, determine practical equipment limitations on transmit pulse power and receiver sensitivity. Determine if and how a system might be practically implemented at a reasonable cost.

- *Determine Potential Advantages and Disadvantages of the Proposed System*
  Based on the theoretical model and the system outline from the first two research goals, determine the possible advantages and disadvantages of the proposed system compared to existing track circuits and to other known alternatives for broken rail detection.

2. IDEA PRODUCT

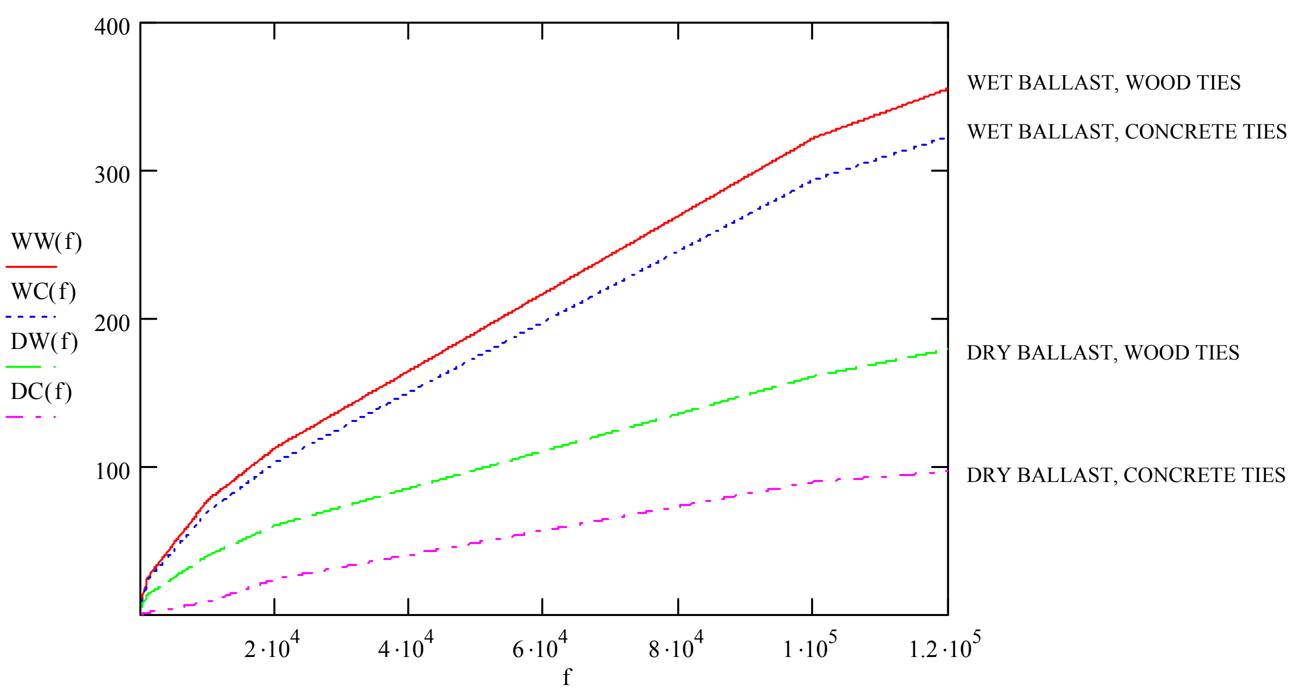
2.1 TRANSMISSION LINE MODELS AND RANGE PREDICTIONS

The major task of this research was to determine if the idea of applying Time Domain Reflectometry to the task of broken rail detection was feasible. This was accomplished by developing a set of MATHCAD models to estimate the behavior of a differential electrical pulse with a given frequency and duration traveling along the railroad track and being reflected from a simulated broken rail or track shunt. The main aim was to predict the detection range to determine if the warning distance provided might be adequate. Ideally, the warning distance should be greater than the "full service" braking distance of the train, plus some additional time to allow for crew reaction. Braking distances vary depending on such factors as the type of train (freight, heavy-haulage, passenger, empty, loaded, etc.), the train speed, and the track grade. In discussions with the advisory panel, it was suggested that a two-mile detection range was a reasonable initial benchmark, but that a lower range might be adequate for some types of train.

The most significant factor in determining range is the attenuation rate of a signal traveling along the track. The maximum possible range is determined by the distance at which the initial pulse is so attenuated, traveling to the reflector and back, that it can no longer be reliably detected. Apart from attenuation rate, the other factors that must be considered are the initial pulse energy; the signal coupling efficiency to and from the track; the reflection coefficient of the target; the sensitivity of the receiver; and the extent to which the received signal can be improved by "processing gain". Processing gain would be achieved by first correlating the received signal to the original pulse, and then correlating these results over thousands of pulse/echo test cycles. All of these factors were incorporated into the MATHCAD models.

The track electrical parameter data used in the transmission line models was mostly based on previous research performed or supervised by Dr. John Hill. During initial literature searches, Dr. Hill's work in this field was found to represent the most significant and comprehensive analysis of the electrical properties of railroad track at various frequencies. Dr. Hill was contacted to discuss this project and agreed to act as a consultant. A report provided by Dr Hill (*3*) summarized the results of previous research and provided estimates for electrical properties over the frequencies anticipated for the task of broken rail detection. The following graph depicts the estimated round-trip attenuation rate (i.e., to the reflector and back) in decibels per mile for frequencies up to 120 kHz and for various combinations of ballast condition and tie type.

FIGURE 1 Predicted Round-trip Signal Attenuation (dB/Mile) Versus Frequency (Hz).



It should be noted that only limited measurements were available for higher test frequencies, and the extrapolated data should be tested and corrected as necessary by field measurements over a broad range of test frequencies. In other words, the range predictions in this research are best estimates based on the available data, and actual detection range may be more or less depending on actual track behavior over various frequencies and track conditions. It should also be noted that the measurements used were mostly from European railroads, and that typical ballast conditions such as moisture content may vary for the United States, and even from region to region.

Another key parameter of track behavior is the propagation velocity factor. This is the speed at which an electrical signal of a given frequency travels along the track, relative to the speed of light. The significance of this parameter is that for pulse/echo based systems, the duration of the initial pulse is generally limited so that the trailing edge of the outgoing pulse does not overlap with the leading edge of the returning echo, i.e., the transmitter and receiver are not operating simultaneously. Therefore, the maximum possible pulse duration is limited by the time required for the initial pulse to travel to and from the nearest possible reflector. This in turn restricts the frequency and number of cycles in the transmit pulse. Pulse duration is also one of the factors, along with transmitter power, that determines the initial pulse energy. In Dr. Hill's previous research, it was found that the velocity factor of railroad track is typically much lower than most transmission-line cables. This is basically due to the less-than-ideal insulation property of the ballast that emphasizes the series inductance of the rails so that the track has a residual inductive component to its impedance. The low velocity factor is actually a benefit since this would permit a longer initial pulse that can employ lower frequencies and have greater energy.

Many factors were found to interact in the completed MATHCAD models. For example, greater signal correlation time increased the processing gain and therefore extended the range. On the other hand, increasing the correlation time too much meant that a speeding train would move closer to the target during the processing time and therefore decrease the effective range. A correlation time of 4 seconds was found to be a reasonable compromise for train speeds up to 80 MPH, and 2 seconds for train speeds up to 160 MPH.

Another significant interaction was between the pulse frequency and the usable range. A low pulse frequency might extend the maximum detection range by virtue of the reduced attenuation rate at lower frequencies, but low pulse frequencies generally increased the pulse duration so that the minimum detection range was also increased. For nearby reflectors, short-duration high-frequency pulses were required but the higher attenuation rate limited the maximum range. Rather than select a single compromise pulse frequency, it was determined that a spread of test frequencies would be better to cover both nearby and distant reflectors. The proposed system would step through different pulse configurations searching for a reflector. The following table provides an example set of pulse parameters for covering different range segments with various track conditions.

Pulse Parameters [1]				Range Segment (Miles) for Ballast Moisture/Tie Type [2]			
Frequency	Power	Duration	Test Rate	Wet/Wood	Wet/Concrete	Dry/Wood	Dry/Concrete [3]
50 kHz	10 kW	20 uS	5 kHz	0.52 - 1.00	0.52 - 1.10	0.66 - 1.99	0.38 - 3.38
50 kHz	100 W	20 uS	5 kHz	0.52 - 0.90	0.52 - 0.99	0.66 - 1.78	0.38 - 3.38
100 kHz	100 W	10 uS	10 kHz	0.40 - 0.53	0.49 - 0.58	0.49 - 1.09	0.18 - 1.61
125 kHz	100 W	8 uS	40 kHz	0.33 - 0.45	0.42 - 0.50	0.41 - 0.93	0.15 - 0.31
-----	-----	-----	-----	-----	-----	-----	-----
300 kHz	100 W	3.33 uS	80 kHz	0.18 - 0.24	0.24 - 0.27	0.21 - 0.49	0.08 - 0.20

(1) Other parameters: Train Speed = 80 MPH, Correlation Time = 4 Seconds, Receiver Sensitivity (10dB S/N) = 5 uV.

(2) In general, the lower range limit is determined by pulse frequency (controls propagation velocity) and pulse duration. Upper range limit is mostly determined by pulse frequency (controls attenuation rate) and pulse power.

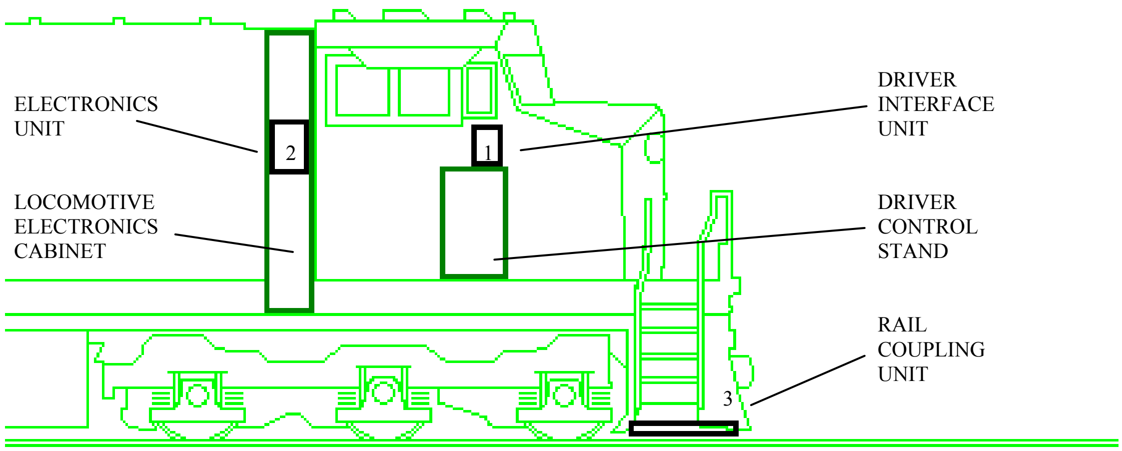
(3) In this case, the range is being limited by the test rate, i.e., a lower test rate would increase the upper range limit.

TABLE 1 Predicted Range Segments Versus Pulse Parameters and Track Conditions.

2.2 PROPOSED SYSTEM OUTLINE

Another major research task was to create a general system outline describing how the proposed system might be implemented. This is intended to provide insight into the concept behind this research, as well as a framework for comparing the proposed system to other alternatives in terms of possible advantages and disadvantages, particularly as a locomotive-mounted broken rail detection system as opposed to wayside-based alternatives. The proposed system would probably consist of three subsystem units, all contained on the lead locomotive of the train and positioned as indicated on the following diagram:

FIGURE 2 Proposed Location of Key Components.



1. *Driver Interface Unit*
   Display and control panel located on or near the driver control stand in the locomotive cab. Includes a flat panel display depicting a visual representation of track conditions ahead, and text information such as the classification, distance, location and speed of any identified reflectors; warning and alarm messages; and system status. Also includes audible alarm indicators and the operator control keypad for selecting the operating mode and performing initial system setup.

2. *Electronics Unit*
   Main equipment rack located in or near the locomotive control electronics cabinet, or possibly with the CBTC equipment if a separate area is designated. Contains the majority of system electronics modules and components in a rack-mount enclosure protected against dust, vibration and temperature extremes.

3. *Rail Coupling Unit*
   Inductive loop consisting of a wire coil on a mechanical support frame located just above the rails between the first axle and the front of the locomotive. Provides electromagnetic coupling of signals to and from the track.

2.2.1 Driver Interface Unit

The components of the driver interface would be the display screen, visual and audible alarms, and the operator keypad. The fully sealed operator keypad would be mostly used to initiate self-test startup functions, input general settings and select operating mode. The system would be designed to be as automated as possible so that little or no user input would be required once the train is underway.

The purpose of the visual and audible alarm indicators would be to ensure that the crew is aware of any abnormal or emergency situation. A range of alert cues would indicate the urgency according to the risk of derailment or collision. The risk level would be continuously assessed based on several factors such as the distance to the broken rail or track occupation, safety rules instituted by the FRA and railroads (such as minimum required separation distances for various types of traffic), the speed and braking capacity of the train, and the train crew=s response or lack of response to earlier warnings. Careful consideration would be given to working in conjunction with the existing locomotive displays, alarms and emergency systems to avoid operator overload, confusion and misinterpretation. One possibility that could be investigated is to use voice-warning messages, similar to collision and low-altitude voice-warning systems used in some aircraft.

When a hazard is first detected, it might be useful to require that a crewmember acknowledge the audible alarm by pressing a button. This would indicate that the crew has been alerted to the visual alarm messages on the display, and further audible alarms might be more distracting than useful. If the initial audible alarm is not acknowledged, the alarm could automatically repeat with increasing urgency to indicate the level of risk. For critical alarms such as an immanent collision or possible derailment, failure to acknowledge the alarm or take appropriate action in a timely fashion could automatically initiate a full-service brake application.

During normal operations, the display screen would be the most prominent feature of the driver interface. The screen would be based on a plasma or LCD flat panel display that could automatically adjust for optimum brightness and contrast under all lighting conditions. If necessary, additional displays could be provided at multiple locations so that the information is clearly visible from all key positions within the cab. The main area of the display would be a “moving map” of the track ahead to give visual indications of any rail failure or track occupation. The image would be similar to modern digital RADAR displays that use color symbols, icons and text overlays to present clear and precise information, except that in this case only a one-dimensional vertical line would be needed to represent the track ahead. As the system identifies a signal reflector, a limited amount of critical text information such as the location and distance ahead could be “tagged” to the reflector icon using a format similar to some RADAR displays. In the case of a track occupation, the speed and direction of the reflector could also be given. If desired, the display could also include additional information such as ETA (estimated time of arrival based on current speed and breaking or acceleration rates), or recommended actions (suggested brake application, etc.) to avoid an accident. Other detailed text information and system status information would be provided as necessary in other areas of the display.

If the system was linked with a central database of known track structures (possibly via the CBTC data link), other useful location and status information for turnouts, bridges, grade crossings, etc. could be mapped onto the same display. Linking with CBTC would also allow known CBTC track occupations to be displayed and compared to detected occupations on the track. Any discrepancies would generate an alarm to warn of an unexpected or unusual track occupation. For example, a “broken” train ahead could be identified if the speed of the track occupation ahead (the last axle of the last car) was slowing down relative to the CBTC position and speed of the preceding train=s locomotive.

The overall premise of the display would be that even if there was little or no outside visibility, the train crew could still be made aware of the relative position, distance and status of the track structures ahead, as well as any detected hazards. The moving map would provide a scale representation of the track ahead with graphic icons to convey the relative locations and status of track features, other trains or track equipment identified by CBTC, and any signal reflections caused by broken rails or unexpected track occupation. If a hazardous situation was detected, alarms would be generated and the icon representing the hazard would be clearly identified by flashing and/or color changes. The objective would be to provide the crew with a clear, unambiguous display that provides useful information during normal operations and maximum situational awareness in emergencies.

2.2.2 Electronics Unit

The electronics unit would be based on the 19 inch rack mount standard or other modular standard, whichever is most compatible with existing locomotive control systems and/or the planned CBTC electronics. The unit would consist of modules that would perform the following functions:

- Main control processor (system test and monitor, overall operation, coordinate all other modules)
- Timing control processor (pulse-echo sequence timing)
- Transmit pulse generator (digital to analog converter)
- Computer-controlled high-power transmit amplifier
- Transmit/receive switch
- Coupling coil matching
- Low-noise receiver preamplifier
- Computer-controlled receive amplifier
- Signal digitizer (analog to digital converter)
- Signal processor (signal correlation, reflector identification, etc.)
- System interface (for driver panel, CBTC, train speed sensor, emergency breaking, etc.)

An important part of designing the proposed system would be to combine the required functions into the optimum number of modules that would provide maximum reliability and allow easy troubleshooting and module replacement if necessary. Previous Analogic Engineering, Inc. projects that involved electronic systems for the railroad environment have taught that module interconnections should be kept simple and robust to avoid problems with heat, vibration and dust. Also, it might be preferable to mount some components of the transmitter, receiver or transmit/receive switch closer to the rail-coupling unit. This could be necessary if the high-power RF pulses interfere with other sensitive electronics within the locomotive cab, or if other systems such as locomotive power controllers interfere with the receiver. Placing some modules near the rail coupling unit could avoid routing very high-power or very low-power signals over long cables, either of which could accentuate problems with cables, connectors, interference, noise and ground loops.

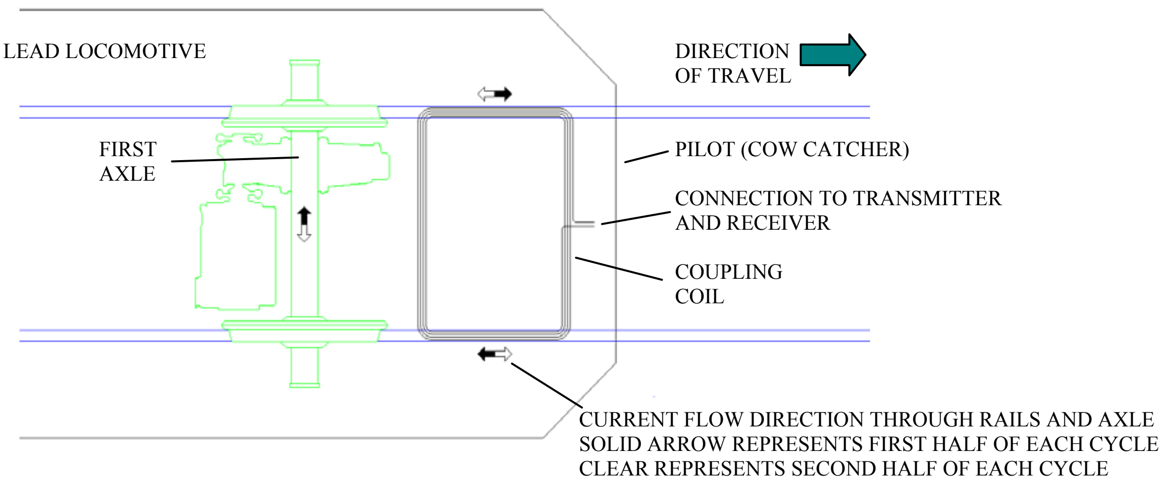
The electronics unit would contain many embedded processors to perform specific tasks such as timing control, low level signal processing, pattern recognition, alarm generation, operator interface and display management, and overall system operation. All software would be written and tested to standards that ensure reliable operation. The system would include self-testing, auto-calibration, and automatic adaptation to varying conditions such as ballast leakage resistance, so that operator intervention would not be needed during normal operation. Transmit pulse power, pulse frequencies and receiver gain would be automatically selected or adjusted to reliably achieve the specified range using the minimum transmit power. Inputs from other locomotive control systems could be used to modify system operation for particular circumstances. For example, an operating mode could be selected where range was linked to train speed so that low-speed yard maneuvers would use a much lower transmit pulse energy, but still cover the shorter braking distance of the train. If the locomotive was stopped for refueling, etc., the system could be automatically or manually disabled. By using the locomotive GPS information, the system could also adapt, according to particular locations or regions, to avoid interference to or from other low-frequency radio systems such as atmospheric RADAR or navigation beacons that operate in the same general frequency range.

2.2.3 Rail Coupling Unit

Signal coupling between the locomotive and the two rails would be accomplished using a rail coupling unit mounted underneath the front of the lead locomotive, between the first axle and the pilot (cow catcher). The rail-coupling unit would consist of an inductive coupling coil mounted on a mechanical support frame positioned close to the rails, and signals would be transferred to and from the rails using magnetic induction. This method of coupling is necessary because of the low RF frequencies that would be required to achieve maximum range, and the local electrical shunts created by the train axles. The ties and ballast that separate the rails are less than ideal electrical insulators, and the transmission line analysis indicates that the track has a large attenuation rate that increases with frequency (see Figure 1). Optimum range would be achieved using a low-frequency RF test pulse between 50 kHz and 120 kHz. Even though the transmission line velocity factor for the track is only around 0.2 (i.e., a propagation velocity around 20% of the speed of light), these signals would still have very long wavelengths compared to the size of the train. This means that the track impedance at the train and for some distance ahead would be dominated by the low-impedance shunt effect of the train itself. In terms of a transmission line, the train would represent a region of minimum voltage (a voltage null), and any differential voltage source connected across the rails or any arriving differential voltage signal would be effectively shorted out. This would rule out any coupling unit that was based on a direct voltage connection such as conductive brushes, rollers or wheels insulated from the rest of the vehicle (although non-shunting track vehicles could use this approach). The alternative is to transmit and receive differential currents in the rails to take advantage of the fact that the train would also represent a region of maximum current on the transmission line (a current peak). Again, directly connecting a low-impedance driver across rails ahead of the first axle would not work since any transmitted current pulse would just circulate locally through the first axle. Since it is impossible to avoid the shunt effect of this axle, the proposed solution is to use an inductive coupling method so that this axle would become an integral part of the coupling circuit by completing the current path.

The general layout of the rail-coupling unit is indicated on the following diagram:

FIGURE 3 Location of Rail Coupling Unit.



Referring to Figure 3, it can be seen that the first axle and the two rails from the axle to the front of the coupling coil form a 3/4 turn electrical loop (or "stub"). This loop would act as one side of an impedance matching transformer, and the windings of the coupling coil would act as the other side. Transformer coupling would occur in the two regions of mutual inductance where the sides of the coupling coil overlap with the left and right rails. Consequently, the size, shape and location of windings of the coupling coil would have to be designed to provide maximum mutual inductance in these areas. The number of windings would be adjusted to achieve the best possible match between the impedance of the track and the impedance of the transmitter/ receiver. The net result would be that the first axle together with the two rails from the axle to the front of the coupling coil would act as a signal source during transmit and a signal load during receive. This signal source and load would, in effect, be connected to one end of the transmission line consisting of the two rails that extend ahead of the coupling coil.

Figure 3 also indicates the current polarity in the rail and first axle. This shows that the direction of the current would be reversed on the left and right rails (i.e., the transmitted and received signals are differential), and that the first train axle would be used to provide the path to complete the circuit. If the first axle behaved as an ideal shunt, it is clear that any differential currents in the rails would take the preferred zero resistance path through the axle, so differential signal currents traveling along the rails could not continue past that point. Therefore, all transmitted pulse energy coupled into the rails would propagate forward from the train. This means that the coupling unit would be directional, which is very useful since the rest of the train axles would not be "visible" to the system, and only reflectors ahead of the train could have any effect. For returning echo signals, any energy that is not transferred from the rails to the coupling coil would be reflected forward again. This raises the possibility of multi-path echoes that could be misinterpreted as distant phantom copies of local reflectors. The first phantom reflection would appear at twice the distance and seem to be moving at twice the relative speed of the real reflector. This problem also occurs in RADAR and ultrasonic testing, and methods of recognizing and filtering these anomalies have already been developed that would be applied in the proposed system.

Note: The above assumption about the first axle acting as an ideal shunt is not critical. In practice, the axle, wheel and rail/wheel interface would always have some resistance, but any current that continued past the first axle would immediately encounter the second axle, and so on. Since these signals would be considerably reduced at each axle, any reflections from subsequent axles would be highly attenuated (in both directions of travel) and they should be insignificant by the time they return to the coupling coil. Also, at low RF pulse frequencies very little phase shift would occur over these short distances, so any reflections would mostly reinforce the initial differential signal current. From a transmission line point of view, the axles of the locomotive are separated by very small fractions of a wavelength, and would appear to be substantially in parallel.

To achieve effective transfer of electrical energy between the coil windings and the rails, the two sides of the coupling coil that run along each rail would need to have significant mutual inductance with the respective rails. This would require that these sides are as long as possible and positioned as close as possible to the rail. Any vertical or transverse movement would cause variations in coupling efficiency or coupling balance from rail to rail. This would vary the signal levels and could reduce system performance. Although it should be possible to compensate for some amount of signal variation, it would be preferable to minimize the underlying mechanical variations. Therefore, the coil windings should always be centered over the track, and the distance between the windings and respective rails should be kept constant.

The mechanical design of the support frame would be critical for safe, reliable and consistent operation. On one hand, the coil windings would have to be supported at a constant, close position over the rails. On the other hand, the coil would have to be rugged enough or far enough away from the rail surface to survive possible impact sources such as mismatched joints. Every precaution would need to be taken to avoid interfering with other equipment at the front of the locomotive and in particular, nothing must ever be able to foul the leading wheels. To achieve all of these objectives, the coil, support frame, tow arm and any other associated mechanical structures would be designed to comply with a standard clearance profile that takes into account high ballast, road crossings, turnouts, tunnels, bridges, etc. The positions of other possible equipment under the front of the locomotive, such as sand dispenser nozzles, RADAR speed sensors, cab-signaling sensors, etc. would also be considered.

Methods would be examined to maintain the minimum practical distance between the rail and the coil, and limit vertical and horizontal movement relative to the top of the rail. One approach would be to simply attach to the most stable reference platform relative to the rail. The pilot (cowcatcher) is solidly attached to the locomotive body and conveniently located close to the rail at the very front of the locomotive. The back of the pilot usually consists of a flat vertical steel plate across the full width of the rail that would provide solid mounting for a frame or tow arm. The major problem with using the pilot would be that the locomotive body moves both vertically and horizontally relative to the rail profile. Some of the horizontal movement is due to the front truck rotating slightly on its center pivot to allow the locomotive to negotiate curves. Other horizontal movement is due to the small difference between the track gauge and the outside flange-to-flange distance that allows the front axle to hunt slightly from side to side (although the wheel tread taper tends to keep the axle centered). The vertical movement is mostly due to the suspension travel as the ends of each axle slide up and down in vertical guides against coil or air bag springs. Referencing off the front axle itself by building an extension forward from the motor casing or the axle bearing supports could eliminate most of the vertical and horizontal movement, leaving only the slight sideways hunting within the rail gauge gap.

Another method would be to provide separate guide wheels for the support frame. This method is successfully used in ultrasonic rail testing to “lock” the position of the transducers that run on the top of the rail to the position of the gauge corner. A similar approach is used on some other track machines, including some geometry cars that can operate at train speeds. The guide wheels are usually non-tapered and can be slightly pressured outward to follow any variations in gauge. The coil frame would be towed from the front to lift up and away from any unexpected track obstructions. An automatic lift system could be provided to rapidly retract the coil frame in the event that the frame or guide wheels strike an obstruction or become misaligned with the track. The coil frame would also be retracted if the locomotive were not in the lead position. Either approach would require extensive consultation with the FRA, railroads and locomotive manufacturers to ensure that safety requirements are satisfied, and might add significantly to the overall system cost. Therefore, a mechanical guidance system would only be considered if absolutely necessary.

2.3 POTENTIAL FEATURES, ADVANTAGES AND BENIFITS

The anticipated features, advantages and benefits of the proposed system are described in the following table:

Features	Advantages	Benefits
Self contained system mounted in lead locomotive. Control system, display and warning indicators located in locomotive cab and instrument bay, inductive track coupling loop mounted ahead of first axle.	No reliance on existing wayside signaling system, no replacement "per-mile" alternative wayside infrastructure.	In conjunction with CBTC, enables cost savings by eliminating the need to maintain wayside infrastructure. Provides additional financial incentive for adopting CBTC. Could be implemented without CBTC to provide independent rail break and track occupation detection. Simplifies conversion of present dark territory (requires CWR or the addition of rail bonds in jointed track, but no additional wayside infrastructure, power or communications network).
	Broken rail or track occupation warnings generated in the lead locomotive.	Improved train safety. Information directly available to train crew, even with loss of communications or low outside visibility (snow, heavy rain).
	Not dependent on relaying warning information from external equipment to train via radio system, cab signals or external signal lights. Reduced risk of delayed warnings or lost warnings. Real time display and alarms for train crew.	Higher reliability, no intermediate stages. More reaction time to avoid or minimize accidents. Information immediately available where it is most useful to allow prompt driver response (e.g., to a rail break under the previous train).
	Could provide emergency control input to train, such as speed control and/or braking.	Option for fast response, automated emergency system to avoid derailments and collisions.
	Control system housed in locomotive cab with other protected electronic systems. Utilizes onboard power supply.	Safer and more reliable than wayside equipment that is exposed to weather extremes and vandalism. Reduces need for large number of distributed wayside power sources.
	Fewer units (i.e., "per-locomotive" rather than "per-signal-block").	Could to be more cost-effective for both capital outlay and ongoing maintenance. Could improve reliability by having fewer points of possible failure.
	Allows centralized equipment servicing at existing locomotive facilities.	Installations and maintenance in good work environment. Centralized technical staff rather than many distributed field technicians.

Features	Advantages	Benefits
Detects track occupation as well as rail breaks.	Backup to CBTC. Also detects unusual track occupations such as detached or runaway freight cars.	Adds redundancy and protects against accidents involving track occupations not registered by CBTC.
Detects rail breaks by loss of rail electrical continuity and track occupation by rail-to-rail shunt. Avoids the use of acoustic transmission, strain gauges or fiber optic cable.	Essentially the same detection characteristics as existing signaling systems. Not affected by welds, rail repairs, bolted joints (with usual bond wires), boltholes, etc.	Compatible with all existing rail installation, maintenance and repair equipment and procedures. No special equipment re-installation or re-calibration required after rail installation or repair. Not susceptible to false alarms from common track features.
Uses Time Domain Reflectometry pulse/echo technique that provides distance to reflector and identifies break or occupation.	Allows speed/distance/time of arrival calculation. System could suggest or initiate optimum response. Locates rail break for repair crew.	Knowing the distance to the hazard could promote a safer outcome either for responding to a broken rail or unexpected track occupation. Faster repair, less down time.
Optional two-way communication link to locomotive CBTC system.	Access to precise GPS train location and speed. Access via CBTC to central database of known track features and reflector locations. Comparison and verification between any detected track occupation and the CBTC registered occupations (known train locations, etc.) Alarm messages relayed via CBTC to train control, other trains, etc.	Combining information from both systems provides additional useful data such as exact break location, time to location, etc. Differences indicate unexpected track occupations. Matches improve confidence and reliability for both systems by cross-verifying data. Any detected rail breaks and unexpected track occupations are immediately updated in CBTC to provide system-wide situation awareness.
By using Insulated Joints, electrical bypass cables and electrical switching operated in parallel with the turnout mechanism, electrical continuity could be made to correspond with track continuity.	Protection could extend beyond turnouts (and diamond crossings). A train approaching a turnout would "see" the state of the selected track ahead, ignoring the alternative track. Appropriate warnings would be given for an incorrectly set turnout (e.g. open rails at turnout, track occupied past turnout at passing track, rail terminates past turnout at backtrack).	Confidence under all circumstances, for all speeds, from main line to yard track, that a safe distance of track ahead is available (i.e., is free from breaks and not occupied).

TABLE 2 Features, Advantages and Benefits.

2.4 OTHER POSSIBLE APPLICATIONS

Accurately measuring the speed and distance of an approaching train could be useful in many applications, notably since the TDR approach would tolerate a much higher shunt resistance without indicating a "loss of shunt".

2.4.1 Work Crew Protection

A portable unit could provide a train arrival warning system for rail gangs, based on the measuring the speed and distance of approaching trains. The battery-powered unit would sit beside the track and attach with jumper cable clamps to the base of each rail. The cable to the far rail would run under the near rail so that the attachment could remain in place as traffic passes over. Optional features could include solar panels and a "vibrating pager" transmitter for noisy environments. Specific alarms could be sounded based on the time remaining to clear the track. Other alarms would be given to indicate fault conditions such as a low battery or a poor connection to the track. An "acknowledge" button on the unit could be used to terminate the escalating alarm sequence and verify that the work crew was clear. Another option would be for the unit to present an intermittent or partial track shunt to indicate the work crew location to the approaching train (fitted with the detection system described in this report), and also indicate whether the crew had acknowledged the alarm and was clear of the track. As an alternative to acting only as a passive shunt reflector, the unit could be an active transponder that would insert additional identification or status data into the return signal. A further option would be to replace one leg of the normal pulse/echo path through the track with an alternative path such as a direct radio broadcast to the approaching train. This would be similar to the technique used by aircraft RADAR transponders. An active transponder would double the effective range by halving the track attenuation path.

2.4.2 Advanced Grade Crossing Predictor

Existing grade crossing predictors measure the rate of change in resistance of the loop formed by the rails and the approaching train. This method is not entirely accurate and timing errors have been cited as contributing to at least one grade crossing accident. Sufficient warning time is critical, especially as high-speed passenger trains are introduced, but if crossing gates close too early for slow moving trains, road drivers have been known to become impatient and circumvent the barrier. A TDR-based sensor could determine the exact speed and distance of an approaching train so that the arrival time could be precisely calculated. Warning lights and road barriers would be operated with consistent warning times, whatever the speed of the train. The proposed sensor would not require a particularly low shunt resistance, and could be made failsafe by placing a passive partial shunt reflector at some distance from the crossing, and releasing the gate circuit if the reference reflector is not continuously detected.

2.4.3 Platform and Pedestrian Crossing Safety

Another type of fixed site application would be a train-warning indicator for passenger platforms and pedestrian crossings. For the pedestrian crossing application, walk/don=t walk lights, audible alarms and even barrier gates could be operated in a similar fashion to the grade crossing application. At platforms, a progressive voice message warning could be given to stand back from the edge of the platform, with additional emphasis if the train is continuing through at a high speed.

2.4.4 Commuter and Light Rail

As an alternative to signaling systems or CBTC, a low-power system on each train could provide broken rail detection and collision avoidance up to a range of one mile or so. Inductive loops could be designed to couple signals in and out of the rail even for light trains that don=t always provide a reliable track shunt.

3. CONCEPT AND INNOVATION

3.1 BACKGROUND

Train drivers need to be warned if the track ahead is either damaged or occupied by another train, because otherwise the danger may not be seen in time to stop. Existing warning systems work by dividing the track into multiple "blocks" about 1 to 2 miles long with a set of status lights known as "signals" at the entrance to each block. The signals act somewhat like traffic lights, and give the train driver a visual warning if the next block or the block after are not safe to enter, i.e., whether to immediately stop or prepare to stop because there is a broken rail or track occupation ahead in the next block or two.

To operate the signals, each block uses an electrical system known as a "track circuit" to determine the safety status of the block and automatically display the appropriate warning lights or "signal aspect". Track circuits take advantage of the fact that railroad track consists of two electrically conducting steel rails held at a constant separation by regular cross ties, usually made of wood or concrete, that provide a reasonable degree of electrical insulation. At block boundaries, IJs are used in each rail to electrically isolate each block. A continuous voltage (DC, AC or pulsed) is applied across the rails at one end of each block, and the amount of voltage arriving at the other end is measured. A track occupation anywhere in the block will short out or "shunt" the voltage between the rails, and a mechanical failure of the steel in either rail will usually interrupt current flow along the rail. In either case, the loss of voltage through the track circuit indicates that the block is not safe to enter, and signal aspects are set that warn the driver to stop the train before it reaches the block.

The present system successfully maintains safe train spacing and has prevented many collisions and broken rail train derailments. However, an extensive and complex wayside infrastructure is required, and ongoing maintenance is expensive. Also, the block-by-block basis for detecting hazards and issuing warnings does not promote finely graduated speed control to optimize fuel efficiency or brake wear, or allow traffic spacing to be adjusted and optimized for different types of traffic.

To solve these problems, the railroad industry is expected to eventually adopt Communications-Based Train Control (CBTC). Using a two way communications link, a centralized control facility will continuously receive the GPS location and speed data from each train and then transmit back any required speed adjustments. By coordinating all traffic, CBTC is expected to optimize traffic flow, improve railroad efficiency, and safely increase traffic density by allowing flexible spacing based on the speed, braking distance and risk associated with each type of train (passenger train, freight train, chemical transport, loaded coal train, empty coal train, etc.).

Despite these many advantages, CBTC does not provide broken rail detection, and the continued cost of maintaining the existing signaling system just to provide this function limits the economic incentive to adopt CBTC. Therefore, the railroad industry is seeking an alternative broken rail detection method that would work in conjunction with CBTC to eliminate the need for track circuits, signals and all other associated wayside infrastructure and costs.

3.2 METHOD SELECTION

Several alternative technologies for broken rail detection were examined. Since track circuits operate on a simple principle that has been optimized over many decades, it is likely that any alternative based on a "per mile" wayside infrastructure would not reduce the "per mile" maintenance costs or have a lower initial cost compared to track circuits. Alternative wayside systems would still require a distributed power supply and some method of communicating warnings to the train crew. However, if the replacement system could operate from each train, maintenance tasks could be centralized and costs might be reduced since fewer systems would be required. Also, the electronics could be better protected within the locomotive cab, electrical power would be readily available, and the warning information would be immediately presented to the crew without depending on external communications or visual signals. Eliminating warning delays is particularly significant since CBTC would probably decrease separation for some types of traffic, and rail failures sometimes occur under a preceding train.

For a detection system to be fully independent and self-contained on each train, the system must be both the source and detector of some form of Ailluminating@ wave that will be reflected by the typical broken rail. Two candidates, acoustic waves (including ultrasonic) and Radio Frequency (RF) electromagnetic waves, were examined in detail. The main advantage of acoustic waves would be that some types of rail failure could provide an acoustic reflection even if the electrical continuity of the rail were maintained. Examples include jagged or non-vertical breaks with points of contact across the gap; breaks with the rail under compression; and breaks resting on a conductive tie plate. Even a partial break or an imminent break such as large head defect might be detectable. The disadvantages of acoustic waves would include the limited range due to acoustic dampening by the anchors, ties and track bed, and the inability to test past poor or intermittent acoustic conductors such as joints and other track structures. Also, many false-positive indications would be produced by normal track features such as joints, temporary rail repairs and other common track structures, and possibly also from boltholes, bond wire holes, some types of weld, and the numerous, small internal defects in the rail steel that are generally benign. The limited range, lack of "visibility" beyond joints, and amount of false-positive "clutter" would probably render an acoustic pulse/echo system ineffective for use as the exclusive or primary protection against broken rails.

In contrast, a system using electromagnetic waves should be no better or no worse than existing track circuits at detecting broken rails and ignoring benign track anomalies, because detection would still be based on the interruption of electrical continuity at the broken rail. Some types of rail break would continue to be difficult to detect, but common track features such as bonded joints, temporary repairs, welds and boltholes would not cause false-positive alarms. Since detection would rely on the same basic electrical properties of rails, track beds, breaks and occupation as the present system, no major changes in track construction or maintenance would be required. In particular, no new skills, procedures, special or modified equipment, etc. would be needed for rail repairs or rail replacement. The essential difference between the proposed method and existing track circuits is that detection would be based on the reflection of pulsed electrical signals that would be both generated and received at each locomotive, rather than the interruption of continuous electrical signals that are generated and received at two separate fixed track locations using wayside equipment. To summarize, a locomotive-mounted pulse/echo test system has the potential to solve the problem of dependence on wayside equipment; maintain compatibility with existing track design and construction methods and present repair and maintenance procedures; and provide similar detection accuracy as track circuits by depending on the same principle of electrical continuity.

3.3 COMPARISON TO OTHER ALTERNATIVES

Many technologies have been and are being investigated by other researchers to warn train drivers of broken rails. Some of these technologies were presented at the "Expanded Workshop on Rail Defect and Broken Rail Detection" (*4*) held by the Association of American Railroads (AAR) in 1997. This included "Broken Rail & Buckled Rail Using Fiber Optics" (*4a*), "Broken Rail Detection Using Remote Sensing: Air Coupled Transducers and Laser Generation of Ultrasound" (*4b*), "Broken Rail Detection Using Laser Scanning Devices" (*4c*), and "Broken Rail Detection without Track Circuits MTA - New York City Transit - A Proposal", a method for electrified systems only based on measuring the current distribution balance in the rail return path (*4d*). Other technologies that have been researched under Federal grants include IDEA Award #HSR-18 "An Investigation into the Use of Buried Fiber-Optic Filament to Detect Trains and Broken Rail" (*5*), and SBIR DOT Award #37834 "Guided Wave Ultrasonic Detection of Broken Rail" (*6*). The results of a Transportation Technology Center, Inc. (TTCI) field assessment of two systems are presented in "Broken Rail Detection" (*7*). A US Patent titled "Railway Signal System" (*8*) was also found to be relevant. An alternative wayside system using guided acoustic waves is being investigated under IDEA Award #HSR-42, but results have not yet been publicly released.

Broken rails or immanent breaks can be detected as the train passes over them using a number of different sensors. Sensor technologies include optical recognition using high-definition cameras or laser technology; EMAT, laser or air-coupled ultrasonic detection of breaks or large head defects (including pulse/echo and Doppler detection methods); and magnetic methods such as eddy current and flux leakage. In evaluating all of the possible technologies, the primary consideration should be ensuring the safety of the train crew and passengers by averting train derailments. Therefore, sensor technologies that can only detect breaks close to the train are considered less useful since they do not provide any advance warning for the crew. However, these technologies could be useful as secondary detection methods to detect partial or immanent failures for following trains. For example, a system could be deployed on the last car or helper locomotive to detect failures occurring under the train.

One approach to providing advance warning is to use fixed wayside equipment (like the present signaling system). Two examples of alternative wayside-based systems, fiber-optic filaments bonded to the rail and distributed rail stress measurement sensors, were extensively tested at TTCI (*7*). Another example would be the guided acoustic wave method being investigated in HSR-42. In the author's opinion, these methods may be useful in particular circumstances but would face several problems as a general replacement for track circuits. Firstly, existing track circuits are based on a very simple principle that has been used for over a hundred years. It seems unlikely that any replacement wayside technology could be more cost-effective per mile to install and maintain (although the fiber-optic filament method and stress measurement method might provide additional functionality by predicting heat buckles). Secondly, if anything is added to the track that necessitates special rail handling, new procedures or equipment modifications for track maintenance and repair, the cost of these changes must also be considered. For example, the fiber-optic filament is very delicate and difficult to repair in the field, so any rail repairs would require additional time, equipment and skills. The stress sensors are battery powered and require wayside data collection sites along the track. Some of these proposed systems would be prone to damage during any re-ballasting, tamping or tie replacement operation, and some would need to be reinstalled after a re-rail operation. (Note: Elsewhere in this report, suggestions are given to allow the proposed system to test beyond shunting track structures such as turnouts. The fiber-optic filament method might be ideal for protecting the turnout itself.)

In general, any wayside system will suffer many of the same disadvantages as present track circuits and signaling systems, such as depending on remote power and/or communications, and operating in a harsh mechanical environment exposed to weather extremes, dust, grease, chemicals, mud, etc. Distributed wayside systems also have an increased risk of accidental damage or vandalism, and specialist technicians may still be required throughout the railroad territories, even just for occasional repairs and maintenance. Finally, wayside equipment must still relay warning information to the train crew, and any delay or possible loss of communications could be fatal. Since CBTC will allow reduced separation for some trains, a broken rail that is created under a preceding train will need to be quickly detected and the crew of the following train immediately informed.

For all of these reasons, a locomotive-mounted system that could test ahead to provide a sufficient advance warning might be a better solution. Apart from the electromagnetic pulse/echo method described in this report, the only other technology that might provide this feature would be pulse/echo guided acoustic waves. As mentioned in the previous section, acoustic waves could provide some benefits such as detecting additional types of immanent, partial or complete breaks that are not detected by track circuits because electrical continuity is maintained. Unfortunately, this advantage is outweighed by problems such as limited range due to the accumulated acoustic damping of each tie plate; not being able to reliably test beyond common structures such as joints; and susceptibility to false-positive indications from benign track features such as bolt holes, various types of weld, and small internal defects.

A feature of the proposed electrical pulse-echo reflectometry approach compared to other proposed methods of broken rail detection is that the basis for detection is the same as track circuits, that is, the loss of electrical continuity at the broken rail. It is predicted that the detection performance would be similar (i.e., most breaks would be correctly identified and other track artifacts would be correctly ignored), and the main aim of eliminating wayside equipment could be achieved.

3.4 RELATED TECHNOLOGIES

3.4.1 Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) is used to detect and locate breaks and short circuits in long communication and power distribution cables, and is particularly relevant to the proposed method of broken rail detection. TDR relies on detecting the reflection caused by any changes in the characteristic impedance of the cable (e.g., a break, short or kink). The location of the reflector is calculated by establishing the velocity of electromagnetic wave propagation in the cable, and then calculating the distance to the reflector by measuring the time delay between the transmitted pulse and received echo. For cable tests, a TDR unit is directly connected to the cable and a step or impulse voltage or current is applied. For the purpose of broken rail detection, a pulse (tone burst) of RF energy would be coupled into and from the rail using an inductive coupling coil.

Every transmission line has an associated characteristic impedance that is determined by the physical cross-section and the electrical properties of the conducting and insulating materials used in its construction. An electrical fault in the transmission line will cause a local deviation from the characteristic impedance. Any signal arriving at the fault will have some of the signal energy reflected with the remainder continuing on. The proportion of energy reflected is determined by the degree of impedance mismatch. A complete short circuit or a complete open circuit represents the maximum possible mismatch and causes a 100% reflection. The phase of the reflected signal identifies whether the fault is a higher or lower impedance than the characteristic value. The time delay between transmitting and receiving the pulse is used to calculate the distance to the fault for a given propagation velocity.

For broken rail detection, the two rails would act as the transmission line. The electrical discontinuity usually associated with a broken rail would represent an open circuit transmission line fault. For occupied rail detection, the axles and wheels of the preceding train would act as a short circuit or shunt between the two rails. When either of these conditions is encountered, a pulse sent from the lead locomotive of the train would be reflected back to the train. As long as the signal was not too attenuated (traveling to and from the reflector), it would then be received and analyzed. The phase of the reflection would identify either a broken rail (higher impedance) or occupied track (lower impedance), and the time delay would give the reflector distance.

3.4.2 RADAR Signal Processing

In many ways, the proposed method of broken rail detection could be described as a guided electromagnetic wave RADAR system for trains. RADAR uses pulse/echo or continuous transmission of radio frequency energy into the atmosphere to determine the direction and distance to radio-reflective surfaces. For the proposed system, the two rails would represent the transmission medium instead of the atmosphere, so the signal would be confined to a single path and no direction information would be provided. In many other aspects, the technologies are closely related and a large amount of RADAR theory and signal processing methods would be applicable to the proposed system. Examples of useful techniques include:

- Coded transmit pulses with a correlating receiver to provide processing gain and help reject noise and interference. Like RADAR, different codes for each system would allow multiple systems to operate independently if the test ranges overlapped. Many code modulation schemes are available from RADAR theory and practice. For the proposed system, a simple approach would be to select the phase of each transmit pulse based on a Pseudo-Noise (PN) sequence.
- Time Variable Gain (TVG) and/or Distance Amplitude Correction (DAC) to compensate for the additional path loss for a more distant reflector. In the simplest approach, gain could be increased over each receive cycle to compensate for a constant attenuation rate along the track. A better approach would be to "map" the impedance variations along the track, such as a grade crossings covered with road salt or an area of contaminated ballast, and then detect variations from the expected signal patterns based on GPS location. RADAR systems often include similar processing methods to ignore expected signals ("clutter").
- Signal processing methods that determine and compensate for the relative movement of the reflector while performing test-to-test correlation.

3.4.3 Global Positioning System (GPS)

Global Positioning System (GPS) signal processing technology provides another excellent example of using signal correlation and the resulting processing gain to recover signals that are far below noise level. GPS technology also demonstrates the precise timing and location accuracy that could potentially be achieved. All this takes place while compensating for the complicated three dimensional relative movements between the GPS receiver and the set of satellites being monitored. In the case of this proposal, the spatial compensation task is greatly simplified to a one dimensional problem of a moving train traveling on a fixed path at a measurable speed toward the target which would also be confined to the path of the rail.

4. INVESTIGATION

4.1 ORIGINAL RESEARCH TASKS

The objective of this Type 1 Concept Exploration investigation was to establish the theoretical feasibility of the TDR approach based on an analysis of the rail transmission line parameters at various RF pulse frequencies. The ties and ballast between the rails provide less than perfect electrical insulation, so the track behaves as a lossy transmission line. The rate of signal loss along the track is the main factor that determines the reflector distance for which the returning signals become too small to detect. Therefore, the most important research task was to estimate the track transmission line attenuation rate against all other variables. The factors that were examined included: the electrical properties of the ballast and ties for various types of track; the initial test pulse frequency, power and duration; signal coupling losses (train to track and track to train); reflection coefficients for typical rail breaks and track occupation; receiver sensitivity; test repetition rate; and techniques of signal processing to provide processing gain to recover the highly attenuated signals. Since many of these variables interact, a mathematical model incorporating all parameters was created using MATHCAD to allow many different variations to be tested and optimized for maximum range.

For any pulse/echo system, maximum possible range is determined by the signal attenuation rate of the transmission medium, and the maximum acceptable round-trip signal loss. There is essentially a signal-to-noise ratio "budget" that is the difference between the maximum signal that can be generated and the minimum reflected signal that can be received, recovered, and reliably recognized. Other signal losses along the way such as transducer and/or coupling inefficiency, and target reflection coefficient, all have to be deducted. On the plus side, signal processing can provide "processing gain" to improve signal-to-noise based on correlating within each pulse/echo test cycle (i.e., between the transmitted and received waveforms), and between a sequence of test cycles (with suitable allowance for the relative movement over time between source, reflector and receiver). Therefore, the overall aim of the MATHCAD model was to simulate the entire signal path, from the transmitter to the receiver output, to estimate the probability of recognizing a reflector at a given range, and to optimize range for various track conditions by adjusting pulse frequency, power, duration and test repetition rate. The research also included a search of US Patents and published research for similar or related methods of testing rail.

4.2 RESULTS

From the literature and patent reviews, it appears that the proposed method is a novel solution. US patents that related to maintaining rail vehicle separation, detecting obstructions and detecting broken rails were reviewed to determine any overlap with the proposed method. There are many patents that indicate the use of RADAR and related pulse/echo signal timing techniques to maintain vehicle separation or detect hazards ahead of the train. Many relate to detecting obstructions only, and are not be applicable to detecting broken rails. Most patents do not suggest using the existing rails alone as the signal transmission medium. One patent describes using the rails as a cavity waveguide at UHF frequencies, rather than a two-wire open line system at lower frequencies. Others require additions to the rail system to propagate the signals. Of those patents that suggest using the rail pair alone as an electrical transmission medium, most are concerned with conventional "steady-state" signaling systems (i.e., not involving propagation timing), or communicating data along the rails.

Only one patent, 1,517,549, Dec. 1924, (*8*) was found to have a significant degree of overlap in both objectives and operating principal. This patent describes using the rails as a transmission line at low frequencies (50 kHz) to locate broken rails and track occupation. The significant difference is that detection is based on measuring changes in impedance due to standing waves caused by signal reflection. Considering the technology available at the time, this was a reasonable approach, but this method does not provide direct information on the distance to the reflector since no timing information is produced.

During initial research, it was discovered that nearly all the useful information on the electrical parameters and transmission line properties of railroad tracks was attributed to one particular researcher and his associates. Dr. R. J. Hill, now an independent consultant and researcher in Bath, England, was contacted to discuss the proposed method. Dr. Hill was very interested in this project and subsequently agreed to act as consultant. His consultant's report is available on request, and provides a thorough summary of the information that has been published on the electrical properties of railroad track.

The investigation revealed that the properties of the track as an electrical transmission line are mostly determined by the values of the ballast shunt resistance and capacitance, and typical values produce significant attenuation rates that are very frequency dependant. The MATHCAD model was used to explore the tradeoffs between initial pulse frequency, power and duration, various track conditions, signal processing gain and range. The main outcome was that no single combination of values for the initial pulse parameters provided the complete desired range. The proposed solution is to use a spread of pulses of varied frequency, duration and power to cover the range from a short distance ahead of the locomotive to the maximum possible range. At least three overlapping range segments would be employed, each with an optimized pulse frequency and pulse duration for the given segment. For the longest range, the pulse frequency would be reduced to decrease the signal attenuation rate, and the maximum pulse power would be required. For short-range testing, higher frequencies would be used, and lower transmit powers would be sufficient.

The results from the MATHCAD model indicate that for conditions ranging from wet to dry ballast, a distance of 1 to 2 miles could be tested ahead of the locomotive. To achieve this range, the initial RF pulses would need to be between 50 kHz and 500 kHz with a peak power from 100 W to 10 kW. This raised concerns during the Advisory Panel discussion regarding RF exposure levels for the locomotive crew and other railway personnel in and around the train, but further research revealed that human absorption rates are extremely low at these frequencies and that any exposure would be below the accepted guidelines (*9 - 17*). It was found that much less power would be required for shorter ranges, i.e., power requirements decrease exponentially with range. For example, a 100mW transmit pulse could be sufficient to test for breaks or occupation up to ¾ mile in wet ballast conditions and up to 1 ½ miles in dry ballast conditions (see Table 4 below).

During the investigation, various factors that impact the practical design of the system were determined. For example, competing factors affecting the selection of pulse frequency were examined, and a range of optimum frequencies for different distances and track conditions were determined. These choices, along with the need to account for the proximity of the train=s own axle shunts, affected the selection of the method of coupling signals to and from the rail, and a method was devised based on inductive coupling. A proposed system outline based on this and other design ideas is presented in section 2.2 - PROPOSED SYSTEM OUTLINE.

Other refinements of the original idea were developed during this research. For example, it would be essential to continue protection beyond turnouts, diamond crossings and other track-shunting structures. This could be achieved without any active circuitry by using IJs to isolate each rail and electrical cables to bypass the structure. For turnouts, electrical relays could be operated by the turnout mechanism so that the electrical continuity of the rail pair would correspond to the mechanically selected track. A broken rail or occupation on the track that the train was about to enter would be properly detected while the state of the other track (for example, a train waiting on the siding) would have no effect. An additional safety benefit would be that a train approaching along the unselected track would detect an open rail indicating that the turnout was set against it. The actual turnout would need to be protected by some non-electrical method such as a fiber-optic filament (*4a*).

If IJs were not acceptable, an alternative would be to place a coupling coil on each track and use an active repeater system to receive incoming signals and retransmit them past the shunting structure. The coils would be fixed to the inside web or foot of each rail and operate on the same principle as the locomotive coupling coils.

4.3 ADDITIONAL TASKS AND RESULTS

In a discussion with Advisory Panel members, the following additional questions were raised:

- Would the pulse be more attenuated in jointed track (assuming normal bond wire connections)?
- Given the peak signal level of the transmit pulse required to achieve useful range (possibly up to 10 kW), what is the RF radiation hazard exposure in and around the train, along the rail, and in the vicinity of a rail break?
- Would the RF pulses damage or disrupt existing track circuits and overlay systems such as grade crossing predictors?

4.3.1 Signal Loss at Bonded Joints

A MATHCAD model was developed to estimate the additional signal attenuation due to bonded joints in jointed track. This model calculated the additional signal loss due to reflections at each joint caused by the local change in resistance. There could also be a slight change in rail inductance that would contribute to these reflections. At the pulse frequencies anticipated, the wavelengths are very large compared to the size of each joint, so the magnetic fields would be almost identical on either side of the joint. This suggests that the slight deviation in current path through the bond wire would have only minimal influence on the rail inductance, but the exact effect is difficult to predict. In any case, the resistance change would probably be the dominant influence on signal current through the joint. The capacitance and conductivity between the rails should not change significantly at the joint. This is because the entire joint would be at approximately the same voltage, regardless of the actual current path; the same surface area of each rail is in contact with the ties and ballast; and the physical shape and distance between the transmission line conductors at the joint is only slightly different relative to their separation. The model indicated that for joints on both rails every 39 ft, the detection range would decrease by no more than 2 percent compared to Continuously Welded Rail.

4.3.2 RF Exposure

A study was performed on the risk to railroad personal posed by the proposed high-power RF pulses. Several government agencies are involved in regulating RF exposure (*9 - 15*), and other organizations such as IEEE (*16*, *17*) and ANSI have contributed the underlying research and standards that determine safe operating limits. The most relevant information is summarized in the following table that lists exposure limits for uncontrolled environments (i.e., the general public and employees not trained or qualified to maintain and/or service RF equipment). These limits are based on the heating effect of RF fields within the human body, and the limited capacity of the human body to dissipate and regulate this additional heat source. There is also an added safety factor of 10 to ensure that any RF heating has no noticeable or subtle long-term effect.

Frequency Range (f)	Electric Field (E)	Magnetic Field (H)	Power Density (S) (E & H Fields)	Averaging Time (Tavg)	
(MHz)	(V/m)	(A/m)	(mW/cm^2)	(minutes) E^2	S or H^2
0.003 - 0.1	614	163	$(100, 10^6)$	6	6
0.1 - 1.34	614	16.3/f	$(100, 10^4/f^2)$	6	6
1.34 - 3.0	823.8/f	16.3/f	$(180/f^2, 10^4/f^2)$	$f^2/.3$	6
3.0 - 30	823.8/f	16.3/f	$(180/f^2, 10^4/f^2)$	30	6
30 - 100	27.5	$158.3/f^{1.668}$	$(0.2, 9.4 \times 10^5/f^{3.336})$	30	$.0636f^{1.337}$
100 - 300	27.5	0.0729	0.2	30	30
300 - 3000	-	-	f/1500	30	-
3000 - 15000	-	-	f/1500	90000/f	-
15000 - 300000	-	-	10	$616000/f^{1.2}$	-

TABLE 3 Maximum Permissible Limits for Uncontrolled Exposure.

The relevant exposure limit for the frequency range of interest (around 100 kHz or 0.1 MHz) is 100 mW/cm^2 averaged over a period of 6 minutes. The reason that the exposure limit is much higher at 100 kHz (compared to 0.2 mW/cm^2 at 30 MHz, for example) is that at this frequency the wavelength is much longer than the dimension of the human body, so the body makes a poor "antenna" and much less of the energy is absorbed. This is why it is possible to stand as close as 2 m to the base of a 100 kW, 1 MHz AM broadcast antenna tower without exceeding the exposure limits. This same distance from a 100 kW 100 MHz FM broadcast tower would expose the subject to 15 times the recommended limit. The fact that the body absorbs different amounts at different frequencies also explains the very low limits placed on many handheld radios and cell phones that operate at the higher VHF and UHF frequencies. For example, portable devices operating at 900 MHz within 5 cm of the human body require additional compliance testing if the transmit power exceeds 100 mW.

A MATHCAD worksheet was developed to calculate the possible exposure near a broken rail immediately ahead of the train, where the highest possible exposure might be encountered. The worksheet was based on the following assumptions:

- 100% of the transmitter power is coupled into the rail, and then all of this RF power is radiated from a broken rail immediately ahead of the locomotive.
- This power radiates upward and outward in a hemisphere originating near ground level.
- The industry standard estimate for the energy contribution due to ground reflection is applied. Therefore, the energy density in the aboveground hemisphere is 1.6 times the amount that would be expected if there was no ground and the energy could radiate outward in a complete sphere (i.e., 60 % reflected at ground plane, 40 % absorbed).
- The work crew is no closer than one meter from the rail break while the train is passing.
- The train crew is no closer than 1 meter and the effect of shielding due to metal floor and cab construction is ignored.
- The effect of operating in the RF near-zone is ignored.

At 2 meters, the estimated continuous transmit signal required to reach the specified safety limit is 31.4 kW. Repeating the calculation for a distance of 1 meter gives a permissible transmit power of 7.9 kW. Most of the assumptions leading to these figures are conservative. The coupling from the transmitter to the rail would actually be less than 100%, with some energy lost in the coupling system and some energy reflected back to the transmitter to be dissipated as heat. The broken rail would reflect energy rather than radiate it (although if close to the train, multiple reflections could occur between the break and the lead axle, and much of the energy might eventually be radiated). Finally, the metal cab would provide additional shielding for the train crew, especially at this low-frequency/long-wavelength where openings such as windows and doors would represent relatively small gaps in the shielding and therefore only minor signal leakage.

It is important to note that the limits for RF exposure at these frequencies are based on averages over a 6 minute period. One implication of this is that the duty cycle of the pulse is as important as the peak transmit power. For example, the transmitter will have a duty cycle from 20% to 50%. Therefore, the 7.9 kW average transmit power estimated above to be safe at 1 m could actually consist of pulses of 15.8 kW to 39.5 kW.

The other significant implication of averaging is that short-term exposure can occur at higher power densities if exposure time is limited. For example, a rail worker or a waiting passenger at a station standing very close to the track would only be close to the front of a passing locomotive for a short time. Since the power density varies inversely with the square of the distance between the source and the subject (i.e. the area of the expanding spherical surface), any significant exposure would only occur at smaller distances. Even if the train is moving slowly, the subject might only be in this critical range of 1 to 2 meters, for, say, 15 seconds. The allowable exposure for 15 seconds is 24 times (6 * 60 / 15 seconds) the limit averaged over 6 minutes. The exact figures would be obtained by integrating the varying exposure power density over a 6 minute period as the train passes the subject.

Similarly, the exposure of a rail repair worker working close to a rail break as a train is approaching would be averaged over the 6 minutes prior to the worker getting clear of the track for the train to pass. For most of this time, the train would be far enough away that the signal would be highly attenuated before reaching the break.

There would be a short time, depending on train speed and the safety margin for getting clear of the track, for which any significant exposure might occur as the train gets closer. For most reasonable combinations examined, the worker could be in the immediate vicinity of the break and still not receive any dangerous exposure sustained over the 6 minute period. It should be noted that at very close distances, different parts of the body would be exposed to different field levels. In these situations, the human body can tolerate higher exposures since the circulatory system can distribute heat away from the worst affected areas. For this reason, most exposure standards set higher limits for individually exposed body parts such as head, hands and feet.

4.3.3 RF Licensing

Based on this study, it is likely that the safety issue could be successfully managed, but there is still a licensing issue that would need to be addressed. It would not be possible to operate under FCC part 15 rules that govern unlicensed, low-power transmissions unless the reduced range would be adequate (for 100 mW ranges, see Table 4). Therefore, FCC licensing would be necessary to operate at the higher power levels that might be required. In the region of 100 kHz, international agreements provide reserved frequency bands for navigation, radio location and direction finding. Normally this applies to ship and aircraft navigation, but it seems reasonable that locomotives could also use these bands since the purpose is related to location finding (in this case, locating the broken rail rather than the train). Other frequencies in this region are available for atmospheric RADAR, which is based on a very similar pulse/echo technique and often uses much higher transmitter power. One complication for licensing may be that the transmitter is not fixed as in the case of these other applications.

It should be noted that in the proposed application, most of the transmitted signal would be dissipated along the track and very little would normally be radiated. The worst case for radiated RF would be using high-power pulses with a broken rail close to the train. As described in this report, the system would continuously scan the track ahead and automatically select pulses with lower power and higher frequencies for testing closer range segments. Optionally, the system could also include an RF receiver to monitor radiated signals. This would detect excessive radiation caused by a broken rail (and, as suggested by consultant Bob Kubichek, may provide an alternative signal timing mechanism for detecting and measuring the distance to a break). The RF receiver might also allow detection and correction of other system problems such as excessive mismatch between the coupling coil and the track. The exact pulse frequency, timing (test repetition rate), and coding (pulse phase sequence) could be varied depending on region (based on GPS location) and other received signals (frequency hopping) to minimize interference to any existing services and between different trains.

4.3.4 Interaction with Existing Track Circuits

The question of possible damage and interference to the existing track circuits was also examined. To achieve maximum range, a transmit pulse power up to 10 kW has been proposed. The efficiency of the coupling coil to the rail is estimated to be 50%, so approximately 5 kW would be transferred to the rail. Depending on the track conditions (that determine track impedance), this represents a pulse voltage in the order of 500 Vac between rails. This voltage level may pose the risk of damaging or at least inhibiting the operation of the existing track circuit equipment. On the suggestion of the advisory panel, the two signaling companies that supply the majority of equipment to U.S. railroads were contacted. Neither company was able to provide a definitive signal level that would or would not cause interference or damage (since there had never been a reason to test their equipment at these higher frequencies), but general information was provided on the protection circuitry used on most devices connected across the rails. These devices are typically rated to handle much larger voltages and currents than a single transmit pulse can produce, but are not necessarily rated to handle continuous pulses, even at lower voltages and currents.

In most cases, lightning protection is provided using three spark-gap arresters in a delta configuration between the two rails and a local ground. The two arresters from the rails to ground are typically high-voltage units that breakdown at 350-950 Vac, while the rail-to-rail arrester is typically a lower voltage unit that will breakdown at 50 to 100 Vac. The unit across the rails has a typical continuous operating voltage of 25 Vac. A similar delta network of three semiconductor devices (TransZorb, MOVs, or two series Zener diodes) is often used in parallel with the spark arresters to further limit any high-voltage spike. A final stage of protection is usually a filter circuit consisting of capacitors and inductors designed to attenuate noise and interference outside the frequency used by the track circuit (in particular, to reject the power line frequency of 60 Hz and the first few harmonics). The filter stage is sometimes part of the surge suppressor unit or a second separate unit, but is more often built directly into the track circuit controller.

From this information, it appears that a transmit power of 25 W would be within the normal operating range of the surge protection circuit, and a transmit power of 100 W might begin to cause breakdown of the spark arrester. Therefore, it may be necessary to limit the transmit power to 100 W or less to avoid equipment damage when the train is approaching an existing track circuit device (Note: With access to the locomotive GPS information, any necessary power adjustment could be performed automatically). The effect of reducing the transmit pulse power on the maximum detection range can be seen in Table 4 below.

There may also be a lower voltage level that would not damage existing equipment, but would interfere with normal track circuit operation by overloading the input stage. This would be a serious safety issue for grade crossing protection, etc. Forrest Ballinger (GETS Global Signaling) has suggested that a test could be performed to determine the interaction between the proposed system and existing track circuit controllers. This test could occur at a GETS workshop or at the TTCI facility. John Sharkey (Safetran Systems Corp.) is also interested in this research and has requested additional information on the proposed system. Details of possible cooperative arrangements with these companies would be included in any future proposals.

As the transmit power is reduced to avoid damage (or interference) to existing track circuit equipment, the range will also be reduced. Fortunately, the relationship between range and transmit power is logarithmic, i.e., the range decreases linearly with the log of the transmit power. As an example, for dry ballast conditions and wood ties with a 50 kHz pulse, the round-trip signal attenuation rate is 98 dB per mile, so for each 10 dB (10 fold) reduction in power, the range is reduced by 10/98, or approximately 0.102 miles. This relationship is further illustrated in the following table:

Track Conditions		Range (Miles) Verses Transmit Power					
Ballast	**Tie Type**	**100 mW**	**1 W**	**10 W**	**100 W**	**1,000 W**	**10,000 W**
Wet	Wood	0.74	0.79	0.84	0.90	0.95	1.00
Wet	Concrete	0.82	0.87	0.93	0.99	1.05	1.10
Dry	Wood	1.48	1.58	1.68	1.78	1.88	1.99
Dry	Concrete	2.98	3.19	3.40	3.60	3.80	4.00

TABLE 4 Maximum Range Verses Transmit Pulse Power.

5. PLANS FOR IMPLEMENTATION

With the completion of this Type 1 Concept Exploration study, the next step would be to submit an application for Type 2 Product Application funding to the Transportation Research Board. The Type 2 goals would include development of a prototype suitable for demonstrations at TTCI and to individual railroads; and extensive field testing to measure the actual electrical properties of U.S. railroad tracks at the anticipated test pulse frequencies. The general flow of work during Type 2 would be to perform very systematic equipment development in three stages. At the completion of each stage, a demonstration would be performed to establish that the goals of that stage had been met and that the theoretical expectations were validated. These tests would be performed at the most suitable location, with TTCI being the first choice.

The reason for a three-stage development process is that for each stage, critical questions would be answered and worthwhile tests and demonstrations would be performed to determine the merit of continuing to the next stage, rather than committing to the full complexity and expense of the final electronic and mechanical prototype system in one step. Each stage of equipment improvement would build upon the previous stage with the addition of more powerful transmit amplifiers and different methods of coupling to the rail, working towards the final prototype system with a minimum of wasted resources. Each stage would provide valuable information not previously available, such as measurements of the transmission line parameters of U.S. track for a wide range of frequencies in different regions and for different soil types and moisture conditions. This collection of data would progressively provide the required information for an accurate range prediction throughout the U.S. for any particular conditions and transmit power.

The first Type 2 stage would be the development of a portable system with a low-power transmitter that would demonstrate the basic concept of detecting broken rails and track occupation over a short distance, perhaps 1/4 mile. This first unit would be a static test unit that would attach directly to the rails using clamps, bolts or existing bond wires for the first set of tests, data collection and demonstrations. The preferable method of simulating a broken rail would be to use an insulated joint that could be temporarily bypassed with an electrical switch to demonstrate the difference in the signal between a broken and an intact rail. The next best option would be to unbolt a rail joint to perform a similar demonstration. If neither of these choices were available, the rail would need to be cut to allow the demonstration. To demonstrate the detection of track occupation, a shunting switch would be clipped or bolted across the rails to simulate a train axle. These demonstrations would hopefully confirm that the TDR method of detecting broken rails and track occupation is valid. The low-power unit would also allow direct measurements of the transmission line properties of the track, such as attenuation rate and propagation velocity, for a broad range of pulse frequencies to confirm or correct the predicted values.

The second Type 2 stage would be the development of a static demonstration of the inductive loop coupling method. Initial static testing would use a cable to represent the train axle. With the successful completion of these two stages, the test method would be validated and an actual detection range would be established for various pulse frequencies using the low-power transmit pulse. The transmission line characteristics of the track, the reflection coefficients of broken rails and track occupation, and the efficiency of the coupling coil would be measured. With this information the range that could be achieved using high-powered pulses could be accurately predicted. If the resulting range was close to or better than the estimated range from this Type 1 study, development could continue into the third stage.

The third Type 2 stage would be the development of a high-power version and a demonstration test carriage that could be pushed or towed by a hirail vehicle for dynamic testing. Since most hirails are insulated from the rail, a brush or conductive wheel shunt would be provided. This system would allow testing and demonstrations of the system performing at various speeds to confirm reliable detection of broken rails and track occupation up to a specific range ahead of the vehicle.

U.S. Patent Application titled "Method and Apparatus for Detecting Rail Breaks and Occupation" was filed on September 5, 2003. With intellectual property protection in place, partnering with railroad signaling companies or other technology-based railroad equipment developers and manufacturers could be investigated. Partnering with a suitable company throughout the various stages of equipment development and testing would be preferable with the final aim of licensing the manufacture, sales and support to this partner. The role of Analogic Engineering, Inc. (AEI) would be to develop a prototype system for testing and demonstrations, a production version for field trials, and then continue concept development for this and other applications.

6. CONCLUSIONS

The purpose of this IDEA Type 1 Concept Exploration research project, HSR-38, was to determine the feasibility of treating railroad track as a two-wire transmission line and adapting Time Domain Reflectometry to the task of detecting broken rails. This research was in response to the TRB Committee Research Problem Statements seeking an alternative broken rail detection method to work in conjunction with CBTC. The aim is to cover all the functions of the present signaling systems so that track circuits, signaling infrastructure, and the associated maintenance problems and costs can be eliminated. Track circuits successfully detect most broken rails by determining a loss of electrical conductivity at the break. Other detection technologies are known that are more sensitive to some types of break where electrical continuity is maintained, but these technologies have other disadvantages such as producing too many false-positive indications or requiring specialized wayside infrastructure. Therefore, a novel method was devised that would detect broken rails based on changes in electrical conductivity like track circuits, but in a format that could be mounted on the lead locomotive of each train. As a replacement for the signaling system function of detecting broken rails, the proposed system would probably be no better or worse at detecting problematic broken rails such as partial breaks, breaks on tie plates or breaks under compression, but may offer significant cost savings by replacing a system having "per-mile" capital and maintenance costs with a system mostly based on "per-train" capital and maintenance costs.

A locomotive-based approach could also offer other advantages over fixed wayside infrastructure. The main safety advantage would be that the warning information would be generated directly in the lead locomotive so the crew could respond immediately. This could be especially useful when closely following another train since broken rails sometimes occur under the preceding train. Since there would be no dependence on external equipment, radio communications, cab signaling, or wayside signals, there should be no opportunity for warnings to be delayed or lost due to radio network failure, wayside power failure, loss of visibility, or other possible external conditions. Removing the dependence on external wayside infrastructure would eliminate problems caused by equipment exposure to environmental extremes, loss of power in remote locations, accidental wayside equipment damage, vandalism or sabotage. The general economic advantage would be that there are generally far fewer trains than track circuits, so fewer systems would be required. Initial installation and ongoing maintenance could be centralized, utilizing the same locomotive maintenance workshops and personal that would install and service the Communication-Based Train Control system, rather than requiring a distribution of specialist technicians throughout the rail network.

The results of the research are encouraging, indicating that the principle of operation is theoretically plausible, and that a practical system could possibly be implemented. The major difficulties to overcome would be the mechanical support system required to align the coupling coil close to the track; the effect of electrical anomalies and track shunting structures such as turnouts; and electrical compatibility with existing track circuit controllers. An analysis of the requirements for a locomotive-mounted system based on Time Domain Reflectometry indicated that detection range would be mostly limited by the high signal attenuation rate along the track. This in turn is mostly determined by the value of shunt conductance through the ballast and ties. To predict range, the track attenuation rate was estimated based on calculated transmission line parameters and values extrapolated from previous field measurements. Based on the available data, a detection range of 1 to 2 miles was indicated depending on track conditions such as the tie type (wood or concrete) and the ballast moisture content.

The general principle of applying TDR to railroad track also has great potential for fixed site applications where measuring the exact speed and distance to an approaching train would allow accurate prediction of arrival time. One example could be an advanced train arrival "predictor" for grade crossings to operate warning signals and gates so that road drivers have adequate warning to stop even for the fastest trains, but do not become impatient (and perhaps attempt to circumvent the barrier) waiting for the slowest trains. Another possible application is to provide data for a low-power radio warning system to broadcast voice messages and digitally encoded train ETA for school buses, emergency vehicles, HazMat transportation, motor homes, etc. There is also interest in long-range train arrival prediction to allow more effective traffic preemption at controlled road intersections adjacent to rail crossings. A reliable and cost-effective sensor might also encourage the installation of active warning systems at unprotected public and private rail crossings. Other examples could include rail worker warning devices and train arrival warning indicators for passenger platforms and pedestrian crossings.

7. INVESTIGATOR AND CONSULTANT PROFILES

7.1 PRINCIPLE INVESTIGATOR - STEVEN TURNER

Mr. Turner, the Principle Investigator and President of Analogic Engineering, Inc., has successfully researched, designed and manufactured various ultrasonic test equipment for rail defect detection during the past sixteen years. Mr. Turner has performed or directed all aspects of instrumentation design, creation and development including circuit design and prototyping, PCB layout, surface mount prototype assembly, low-level micro-controller and programmable device coding, and C++ programming for overall system control and real time display functions. He was solely responsible for the design and implementation of the ultrasonic instrumentation and the radio data transfer system for the first high-speed, non-stop chase car verified testing systems in the U.S. in 1989. The most recently commercialized design was a high-speed twenty-four channel ultrasonic system with real time defect recognition and real time colorized B-scan display. Four systems were produced by Analogic Engineering, Inc. and delivered to the client, Herzog Services, Inc. A vehicle incorporating one of the systems was tested on the Rail Defect Test Facility at TTCI in Pueblo CO in August 2000. Tests were very successful, locating more of the deliberately incorporated defects than any previous system tested. In particular, all defects that could be located and verified on the day by manual ultrasonic testing from the top surface of the rail were clearly displayed and identified, and two previously unknown defects were found in adjoining welds. It is estimated that at least twenty five percent of rail defect detection vehicles operated by U.S. rail test contractors use equipment based on Mr. Turner's designs.

7.2 CONSULTANT - DR. JOHN HILL

Dr. Hill, an independent consultant based in Bath, England, has researched and published extensively on the subject of analyzing railroad electrical behavior in terms of transmission line modeling. This research was mostly targeted at determining the behavior of power feed and return currents for electric locomotives, and the range and sensitivity of conventional fixed block signaling systems. Dr. Hill has provided a summary of previous work on transmission line modeling in terms of the present application, and an estimate for behavior at higher frequencies, including estimated attenuation rates for concrete and wooden ties, for both wet and dry conditions. This analysis was based on Dr. Hill's extensive experience and knowledge of research in this field, including all relevant published material in which he has been directly involved, other work of his fellow researchers, and other sources of related research. This report is available upon request.

7.3 CONSULTANT - DR. ROBERT KUBICHEK

Dr. Kubichek, Associate Professor, Department of Electrical Engineering, University of Wyoming, Laramie, has research and/or teaching experience in many fields that are relevant to this research, including signal processing, radio frequency radiation characteristics, and transmission line theory; and has numerous related publications to his credit. In addition, he has extensive experience using mathematical modeling software for electrical circuit modeling and signal analysis. For this project, Dr. Kubichek provided advice on MATHCAD modeling and some aspects of signal processing, reviewed the mathematical models for validity and accuracy and was a participant on the Advisory Panel.

8. REFERENCES

(1) Transportation Research Board, Committee Research Problem Statements,
Group 2, Section M, A2M01 Committee On Railroad Track Structure, System Design,
Problem Number 3: Broken Rail Detection
http://www.nationalacademies.org/trb/publications/problems/a2m01ps.pdf, Posting 06/1999 to 05/2002

(2) Transportation Research Board, Committee Research Problem Statements,
Group 2, Section M, A2M04 Committee On Rail Transit System Design,
Problem Number 1: Broken Rail Detection For Communications-Based Control Systems,
http://www.nationalacademies.org/trb/publications/problems/a2m04ps.pdf, Posting 06/1999 to 05/2002

(3) R. J. Hill, *Identification of Railroad Track Parameters for Broken Rail Detection,*
Report prepared for Analogic Engineering, Inc., March 6, 2003

(*4*) R. P. Reiff, *Expanded Workshop on Rail Defect & Broken Rail Detection* Association of American Railroads, Transportation Technology Center, Inc., Pueblo Colorado, July 22 - 23, 1997

(*4a*) Prof. S. L. Chuang, G. Lin, *Broken Rail & Buckled Rail Using Fiber Optics,*
University of Illinois, pp. 421 - 437

(*4b*) H. Reis, *Broken Rail Detection Using Remote Sensing: Air Coupled Transducers and Laser Generation of Ultrasound,* University of Illinois, pp. 439 - 449

(*4c*) J. J. Coleman, *Broken Rail Detection Using Laser Scanning Devices*,
University of Illinois, pp. 451 - 464

(*4d*) S. Shooman, *Broken Rail Detection Without Track Circuits MTA - New York City Transit - A Proposal*, MTA - New York City Transit, pp. 465 - 473

(*5*) *An Investigation into the Use of Buried Fiber-Optic Filament to Detect Trains and Broken Rail*,
Texas Research Institute, HSR-IDEA Award #HSR-18, February, 1999

(*6*) *Guided Wave Ultrasonic Detection of Broken Rail*, Texas Research Institute Austin, Inc., SBIR DOT Topic: Broken Rail Detection, Award #37834, 1999

(*7*) S. Kalay, R. Morgan, R. Reiff, J. Peters, *Broken Rail Detection*, Transportation Technology Center, Inc., Pueblo Colorado, Manacle Point Engineering, Ltd., Malborough, Wiltshire, UK.

(*8*) L. Espenschied, *Railway Signal System*, U.S. Patent #1,517,549, December 2, 1924

(*9*) Code of Federal Regulations (CFR), Title 47 - Telecommunications, October 2002 edition

(*10*) Federal Communications Commission (FCC), Office of Engineering and Technology (OET)
Bulletin 65 - Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields, Edition 97-01

(*11*) Federal Communications Commission (FCC), Office of Engineering and Technology (OET)
Bulletin 65 Supplement A - Additional Information for Radio and Television Broadcast Stations,
Edition 97-01

(*12*) Federal Communications Commission (FCC), Office of Engineering and Technology (OET) *Bulletin 65 Supplement B - Additional Information for Amateur Radio Stations*, Edition 97-01

(*13*) Federal Communications Commission (FCC), Office of Engineering and Technology (OET) *Bulletin 65 Supplement C - Additional Information for Evaluating Compliance of Mobile and Portable Devices with FCC Limits for Human Exposure to Radiofrequency Emissions*, Edition 97-01

(*14*) Federal Communications Commission (FCC), Office of Engineering and Technology (OET) *ASD-9601, Measurements of Environmental Electromagnetic Fields at Amateur Radio Stations*

(*15*) US Navy, *Electromagnetic Radiation Hazards (RADHAZ), Hazard of Electromagnetic Radiation to Personnel, Ordnance and Fuels (HERP, HERO, HERF)*

(*16*) IEEE C95.1-1999, *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 Ghz* (adopted by ANSI as ANSI C95.1-1999, also basis for FCC regulations)

(*17*) IEEE C95.3-2002, *IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields - RF and Microwave*