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High-Speed Rail IDEA Program

Application of Lahut Technology for Wayside Cracked Wheel Detection

Final Report for High-Speed Rail IDEA Project 47

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a Subsidiary of the Association of American Railroads

June 2005

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APPLICATION OF
LAHUT TECHNOLOGY FOR
WAYSIDE CRACKED WHEEL DETECTION

IDEA Program Final Report
For the Period March 2004 through May 2005
HSR - 47

Prepared for
The IDEA Program
Transportation Research Board
National Research Council

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ABSTRACT

Current nondestructive inspection techniques available to the railroad industry today require the removal and testing of wheel sets in maintenance shops to accurately detect wheel defects. These techniques also require contact or near contact conditions between the tested wheel and inspection probe.

The development and testing of a prototype system to inspect wheels under a moving train began with defining a set of requirements and specifications needed to meet the overall objective for this project. This objective was to develop a wayside detection system capable of remotely inspecting railcar wheels for shattered rim cracks. Other tasks performed included laboratory experimental work to find optimal positions for laser generation and detector transducers; system design; prototype development and assembly; and field testing and evaluation of the prototype. The initial results indicated that this application of laser-based ultrasound has the potential to perform wayside inspections of moving wheels. However, the field testing revealed several problems that would have to be solved if the system is to be successfully implemented. The field test prototype was unable to reliably identify wheels with known defects due to such factors as a lack of stability and durability of the wheel tracking and laser beam delivery system. Other improvements that will be either necessary or desirable include determination of flaw size rather that merely whether flaws exceed a threshold limit, increasing the maximum inspection speed, ensuring an acceptable false alarm rate, increasing the types of flaws that can be detected beyond shattered rim cracks, developing a wheel tracking and identification system, and identifying a method of remote data transmission from trackside to a receiving station.

Keywords: Railroad Wheels, Laser Ultrasound, Air-Coupled Transducer, Shattered Rim Cracks, Fatigue Cracks, Non-Contact Ultrasound, Nondestructive Testing, Wayside Detection, Wheel Defect Detection.

EXECUTIVE SUMMARY

This project examined the feasibility of a laser-based ultrasound system for automatically detecting shattered rim cracks in railcar wheels as trains roll by wayside inspection stations. It also identified the need for further improvements to the system that will be required or desirable before it can be fully implemented in the field.

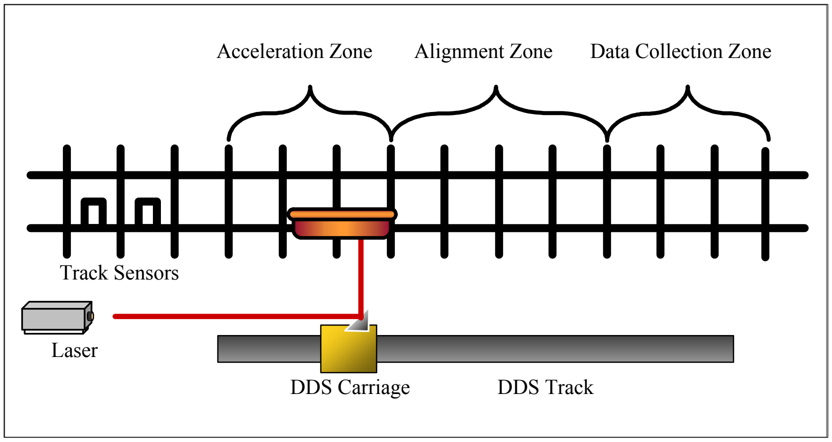
Between January 1998 and January 2003, there were about 340 wheel-related accidents according to the Federal Railroad Administration's statistics. Over 300 of these resulted in derailments, with a cost of over $68.4 million. These statistics emphasize the importance of improving wheel safety and decreasing the costs incurred by defective wheels in revenue service. In addition, automated wayside wheel defect detection could dramatically reduce wheel inspection and maintenance costs.

The automated cracked wheel detection prototype system developed by the Transportation Technology Center, Inc. (TTCI) under contract with the Transportation Research Board's (TRB) High-Speed Rail IDEA Program utilizes a high-energy laser and an air-coupled ultrasonic transducer to ultrasonically inspect wheels as trains roll by an automated wayside inspection station. As a wheel passes the inspection station, the laser impacts the plate of the wheel, exciting ultrasonic signals within the wheel. The ultrasonic transducer is placed below the tread of the wheel and monitors the ultrasonic signals produced by the laser excitation. When a defect is present, it causes attenuation, reflection, and diffraction of the ultrasonic signals, which can be identified using digital signal processing techniques.

In order to inspect an entire wheel, this inspection process must be repeated around the circumference of the wheel as it rolls through the detection system. This is done using a Dynamic Detection Station (DDS), as shown below. The DDS includes a carriage that is capable of tracking a wheel passing through the inspection station. The carriage contains a mirror/lens assembly that steers and focuses the laser beam on the wheel, and an ultrasonic transducer that receives the ultrasonic signals.

The development of the automated cracked wheel detection system was accomplished in two stages. Stage 1 included lab work, system design, prototype development, and construction. Stage 2 focused on installation and testing of the prototype system. This prototype was designed to detect shattered rim cracks, which is a major cause of wheel defects.

Stage 1 activities included determining the optimal placement of the laser beam and ultrasonic transducer, the development of the system requirements and design, and the production of the prototype version of the DDS. Subsystems developed during this stage include a section of special track work designed to allow access to the tread of the wheel for inspection, the DDS track and carriage system, control system hardware and software used to accurately track passing wheels, a data acquisition and processing module, and an environmental enclosure to house the entire DDS.



Dynamic Detection Station Conceptual Overview

Prototype testing occurred in Stage 2 of the project. First, wheel sets with no defects and with known defects were rolled by an inspection station in a laboratory environment to test the DDS tracking mechanism and to determine how accurately the system detected the known defects. The system was then tested in a field installation at TTCI using a test train with five cars containing wheels with no defects and wheels with known defects. The results from the laboratory wheel set testing indicated that the system was capable of tracking a wheel through the entire inspection station, directing the laser beam to the rim of the wheel, and that the system was capable of distinguishing between non-defective and defective wheels. Data from the consist testing in the field were not sufficiently accurate to reliably identify wheel cracks. This was due to such factors as instability of the prototype carriage resulting in unreliable tracking and laser beam placement.

Development of a final product will require modifications to better stabilize the DDS carriage to improve wheel tracking and laser beam delivery. Other modifications required include better alignment of the DDS track and changing the data transfer methodology. This further development should also address issues raised by the expert review panel for this project. These include the capability to detect actual flaw size rather than just whether a flaw exceeds a threshold limit, achieving sufficient reliability and accuracy to provide an acceptably low false alarm rate, increasing the maximum inspection speed above the current 5 MPH, procedures to ensure employee safety in a laser environment, and detection of flaws other than shattered rim cracks, e.g., vertical split rim defects and surface cracks on the tread and flange.

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BACKGROUND AND OBJECTIVES

This project focused on the design, development, and testing of a prototype laser-based ultrasonic inspection system that can be applied to wayside detection of shattered rim cracks (SRCs) in railcar wheels. This report describes work completed for the IDEA Program as part of the overall research, laboratory work, design, and implementation of a wayside system being directed and largely funded by the AAR's Strategic Research Initiative Program. Both AAR and IDEA funding were used for the development of a limited alpha prototype system capable of inspecting a single wheel per car, on one-side of the track, for shattered rim cracks.

Safety statistics published by the Federal Railroad Administration reveal some of the challenges the railroad industry faces to increase safety and decrease costs associated with defective wheels. Another challenge is timely wheel maintenance. Most wheels removed from service today contain multiple defects or have a defective mate wheel and are taken to a maintenance shop for manual inspection. The ability to inspect for wheel flaws without removing cars from service and remove damaged wheels prior to failure is of great importance to the railroad industry.

Each year, thermal cracks result in about 8,000 to 10,000 defective wheel replacements and a number of derailments while shattered rims account for an additional 300 to 500 wheel replacements and about 15 derailments a year. These numbers are increasing as axle loads increase. Figure 1 displays the breakdown of wheel related derailments by defect type, according to AAR car repair billing data, and shows that shattered rim defects have resulted in over 1,100 failures between 2001 and 2003.

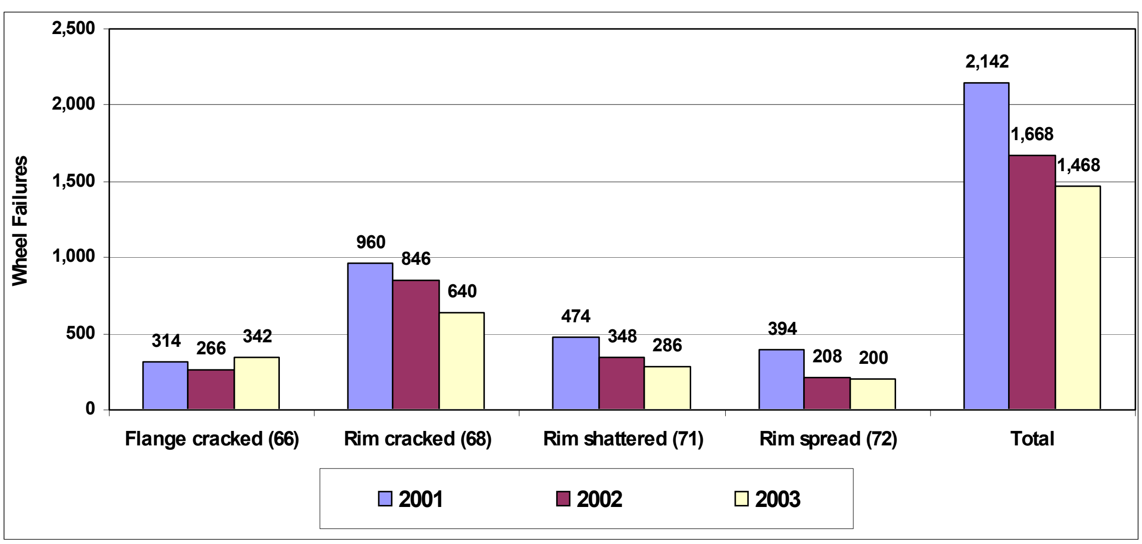

Figure 1 - Graph of Wheel Failures between 2001 and 2003

In 1999, the AAR initiated a research program to detect cracks in railroad freight wheels using ultrasonic testing methods. Johns Hopkins University (JHU) completed preliminary AAR-funded research on the reliability and practicality of several ultrasonic testing techniques in 2002. JHU used the results of these studies to determine that a laser based ultrasonic system using air-coupled detection was the most promising candidate for a field-worthy wayside cracked wheel detection system. TTCI, in a joint effort with the JHU, began development efforts of a wayside detection system using laser-based ultrasound in 2002. The results from both the feasibility experiments at the JHU and the Proof of Concept (POC) demonstrations at the Transportation Technology Center, (TTC), Pueblo, Colorado, suggested that laser-based ultrasonic inspection of railroad wheels could be engineered into a high-performance wayside inspection system for identifying cracked wheels in passing trains. This project focuses on using the laser-based ultrasonic technology to design a system with the ability to inspect railroad wheels in a wayside environment in order to increase the number of wheels inspected each year and reduce the total number of wheel failures experienced by the railroad industry.

IDEA PRODUCT

Implementation of a wayside inspection system that is designed to detect cracks in wheels is expected to improve the safety of railroad operations by removing cracked railcar wheels from service prior to failure. The reduction in service failures attributed to cracked wheels could potentially decrease associated derailment-related costs as well as safety hazards associated with broken wheels.

The work completed in this project focused on using a dynamic laser-based ultrasonic system to identify SRCs in one wheel per car on one side of the track. The SRC, in comparison to surface breaking thermal cracks, is the most challenging defect to identify because it requires a segmented inspection of the entire circumference of the wheel. The SRC is a horizontal crack that runs circumferentially around the wheel. SRCs initiate and grow below the tread of the wheel and are oriented parallel to the tread running surface. Initiation and growth usually occurs internally and below the work hardened region of the wheel tread. The SRC becomes a safety concern when it turns up toward the tread, turns down toward the rim, or both – thus allowing the crack to propagate to either the tread or plate surfaces of the wheel. Once the SRC breaks out to the wheel surface, the propensity for wheel failure is increased, thereby increasing the potential for derailment.

Economic analyses performed by TTCI have estimated that less than ten percent of the wheels in service are sent through a maintenance shop each year. Currently, wheels are inspected at a maintenance shop where removal of the wheel sets from the railcar is required. Wayside inspection of wheels could reduce maintenance costs and significantly increase the number of wheels inspected per year. The laser-based inspection system can be adapted to perform ultrasonic inspection of wheels without direct contact with the wheel. This technique enables dynamic, non-contact, ultrasonic inspection of railroad wheels with the potential for use in wayside applications.

CONCEPT AND INNOVATION

The cracked wheel detection prototype is being developed as a wayside system that uses a Class IV laser to generate ultrasonic signals through a wheel and an air-coupled transducer to monitor those signals. The ultrasonic signal is influenced by the geometry of both the material being inspected and by any flaw the signal encounters. SRCs are comprised of air gaps oriented parallel to the tread of the wheel. The air gap is an internal interface between the steel of the wheel and the air that produces an impedance mismatch at that interface. The impedance mismatch will act to reflect (redirect), dampen, or eliminate the ultrasonic signal. Inspection of small segments of the wheel rim using laser-based inspection allows for the detection of SRCs. By repeating this inspection over the entire circumference of the wheel, it is possible to determine if the wheel contains SRCs.

A 5 mile-per-hour speed restriction is imposed on the system due to the current capability of the laser-based system. The laser pulse rate determines the maximum test speed attainable for inspecting a wheel for shattered rim cracks. The maximum speed, 5.1 miles per hour, is determined by dividing the desired inspection unit (in this case 3 inches) by the laser pulse rate (30 Hz) and converting the units to miles per hour. In the future, this speed limitation may be increased by either increasing the length of the inspection zone, using beam splitting or other optical techniques to enhance a single lasers capability, or finding a higher pulse rate laser with the required energy output at a reasonable cost.

In order to apply laser-based ultrasonic inspection to a wayside system capable of inspecting wheels on a moving train, the inspection process must be performed on the wheel a number of times as it rolls through a detection station. This is accomplished through the use of a Dynamic Detection Station (DDS), which follows the wheel and performs the necessary inspections. The DDS includes a DDS track that runs parallel to the railroad track and a DDS carriage that travels on the DDS track as shown in Figure 2.

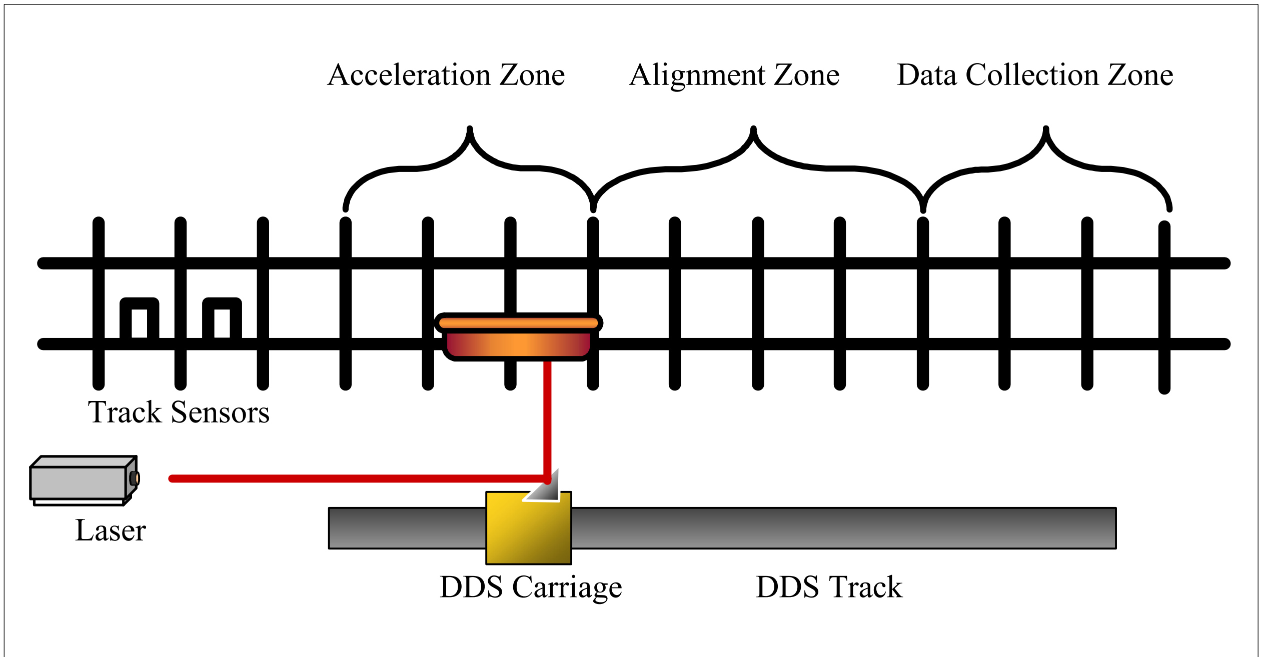

Figure 2. Prototype Concept Overview

The cracked wheel detection prototype design integrates the laser air-hybrid ultrasonic technique developed by JHU with a Dynamic Detection Station. The inspection facility for cracked wheel detection is installed at a wayside site and is capable of detecting SRCs as a train passes the facility.

The station contains a fixed laser, a 40-foot (12.2-meter) length of flange-bearing track section, a mobile carriage, and a data acquisition unit. The mobile carriage is equipped with a retractable detector mechanism that can be extended to position the air-coupled transducer and wheel tracking sensors beneath the tread of the wheel. The wheel tracking sensors monitor the position of the wheel and send a feedback signal to drive the carriage along a rack and pinion track. When the carriage is centered on the wheel, the control system triggers the laser and initiates the inspection sequence. A mirror and lens assembly mounted on the carriage directs the laser beam toward a specific position on the wheel. The DDS carriage is also equipped with digital signal processing capabilities that determine the presence of SRCs based on signal characteristics of the collected data.

The test cycle of the mobile carriage consists of three general zones: The acceleration zone, the alignment zone, and the data collection zone. The acceleration zone is used to determine the approximate velocity of the wheel using two wheel sensors embedded in the track a known distance apart. The carriage is driven to match the approximate position and velocity of the wheel.

The alignment zone uses feedback from the wheel tracking sensors to precisely align the position of the carriage to the center of the wheel. Once the position of the carriage is synchronized with the moving wheel, the laser is triggered and the carriage enters the third zone, the data collection zone. Throughout the data collection zone, the laser is triggered at 30 Hz for one revolution of the wheel. At the conclusion of the inspection, the carriage returns to its initial position to repeat the process for the next wheel.

The laser is located in a bungalow near the inspection station, with the beam directed towards the mirror/lens assembly through an enclosed beam path using turning mirrors. The DDS system is enclosed entirely within an environmentally controlled enclosure. The enclosure design includes a shutter system that opens when it receives a train presence signal and activates extension of the retractable detector mechanism and laser beam placement.

Other items discussed in the requirement specifications document include a more detailed description of the components utilized to achieve a working prototype, safety and environmental concerns, site specifications, and the approach used for integrating and installing the prototype system.

INVESTIGATION

The development approach and testing of the Cracked Wheel Detection prototype included two stages; Stage 1 involved developing the system specifications and requirements, designing the system, and assembling the prototype, and Stage 2 involved installation, calibration, testing the system at TTC, and analyzing the results to determine system performance based on system requirements and specifications.

Stage 1: Prototype Development

Stage 1 tasks included the development of the system requirements and specifications, laboratory investigations to determine the optimum configuration of the laser beam, completion of the system design, construction of the system prototype, and the development of a test plan. A panel of experts was convened to provide guidance and support for the development of the prototype. This panel included experts from the railroad industry in wheel flaws and wayside detection systems, as well as experts in non-destructive testing. . The panel reviewed the program objectives, approach, and design of the prototype system and offered suggestions to the design team.

System Requirements and Specifications

Product Requirements Document

The purpose of the Product Requirements Document is to collect, analyze, and define high-level user needs and features of the prototype system. The document focuses on capabilities needed by the target users and why these needs exist. Details of how the application fulfills these needs can be found in the System Requirements Specification, available from TTCI.

System Requirements Specification

The requirements specification provides detailed information on the hardware and software components of the system, as well as details on system integration. The purpose of the document is to define all of the requirements the system must meet in order to fulfill the needs outlined in the product requirements document. These requirements were used as a guideline for the design team to develop the system. The following paragraph includes a general description of the system design as described in the System Requirements Specification.

The DDS carriage contains a wheel tracking control system that accelerates and aligns the carriage with the passing wheel and triggers the data collection process. The stationary laser produces a beam that is steered and focused to the rim of the wheel using a mirror/lens assembly located on the DDS carriage. A Retractable Detector Mechanism, also located on the DDS carriage, extends from the DDS carriage to position the ultrasonic transducer below the tread of the wheel where it can monitor the ultrasonic signals. The signals from the transducer are sent to a Digital Signal Processing unit, which collects and processes the data before sending the results and raw data to a host computer.

Laboratory Work

Objective

The purpose of the laboratory experiments was to determine the feasibility of detecting a SRC by generating ultrasonic waves perpendicular to the rim face, Figure 3(a), rather than near the rim-plate radius, Figure 3(b).

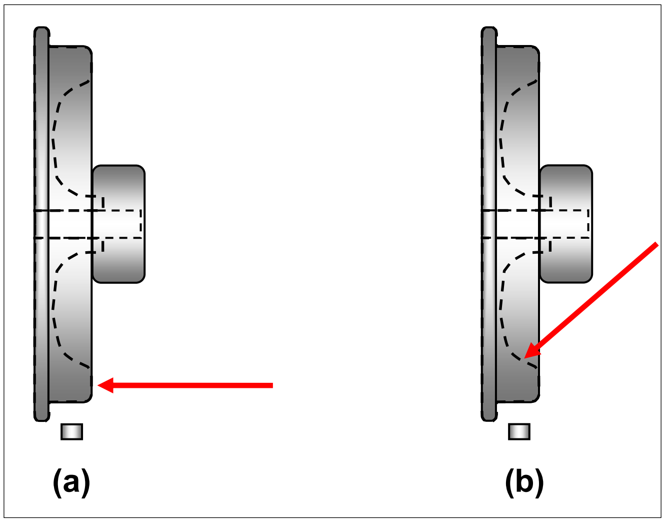

Figure 3. Laboratory Configurations for MLA Positioning

Background

The lab experiments discussed in this section are based on laser generation and air-coupled detection of ultrasonic waves. Ultrasonic testing introduces high frequency sound waves into the wheel and determines information about the wheel by the characteristics of the received signal. Three main wave types are observed using this technique: longitudinal, shear, and surface. Longitudinal waves, also known as compression waves, travel at the highest velocity of the three. The particle motion in a longitudinal wave is parallel to wave travel. The next fastest wave is the shear wave, also known as a transverse wave, where particle motion is perpendicular to wave travel. Finally, the Rayleigh wave, also referred to as a surface wave, travels at about 90 percent of the shear wave velocity and propagates along the surface of the specimen being inspected.

The lab experiments used an alternate configuration with the potential to simplify the DDS carriage design and also reduce the overall height of the system. In this configuration, the laser illuminates the side of the wheel rim Figure 3(a) instead of the plate-rim radius Figure 3(b).

The laboratory work was divided into two areas: 1) acquisition of detailed data on the geometric variables, such as rim and flange thickness and wheel diameter, that can influence the test configuration, and 2) developing a thorough understanding of the resultant laser-illuminated field and how the acoustic waves interact with the SRC.

Initial configuration: Laser illuminating plate under rim

In this configuration, Figure 3(b), the distance propagated by the surface wave is nearly twice that of the longitudinal and shear waves. In addition, the velocity of the shear wave is slightly higher than the surface wave, while that of the longitudinal wave is almost twice as fast. As a result, the signal obtained with this configuration is comprised of the longitudinal wave arriving first, followed by the shear wave, and then the surface wave. The Time of Flight (TOF) separation of the wave components is distinct and easy to identify. Furthermore, when a SRC is present, it falls directly in the path of the longitudinal and shear wave components causing substantial attenuation, diffraction, and reflection thereby making the detection of a SRC unambiguous.

Alternate configuration: Laser illuminating rim side

At the side of the wheel rim configuration, Figure 3(a), very little change has been introduced with regards to the length of the propagation path of the longitudinal and shear waves. The surface wave, however, propagates a distance slightly longer than the longitudinal and shear waves but substantially shorter than the surface wave of the previous configuration shown in Figure 3(b). Accordingly, it is expected that the three wave components will arrive in the same sequence as mentioned; that is, the longitudinal wave arriving first followed by the shear and surface waves. However, the TOF separation between the shear and surface waves is shorter. Also, the interaction between the longitudinal and shear waves and the SRC is less direct.

Laboratory test results

The results from the laboratory work proved that generating ultrasonic waves at the rim face would not be feasible to reliably inspect wheels for shattered rim cracks. The varying rim thickness and the lack of interaction between the bulk waves and the SRC created a less desirable ultrasonic condition than that of generating the ultrasonic waves at the plate-rim radius. Therefore, the prototype was designed with laser generation introduced at the plate-rim radius. Figure 4 (a) and (b) are representative signals, displayed using wavelet analysis, for the selected beam delivery option. Figure 4 (a) is a 3-inch wheel segment containing no defects while Figure 4 (b) contains a SRC. After studying the wavelet plots a noticeable difference in signal TOF and frequency content can be distinguished between the two cases.

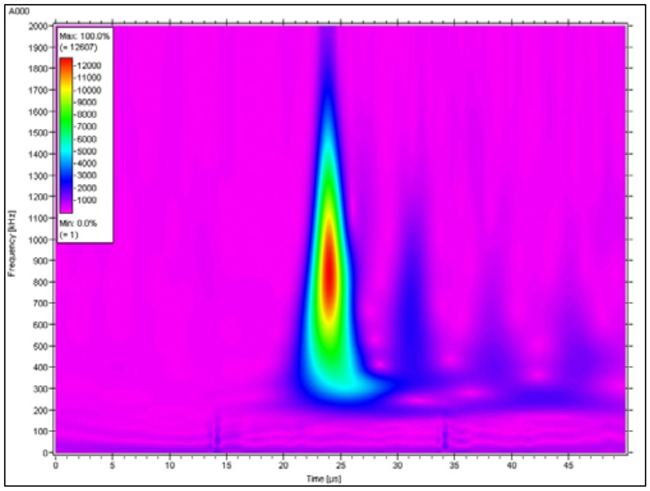

Figure 4(a). Wavelet Plot of Wheel Segment with No-Defects

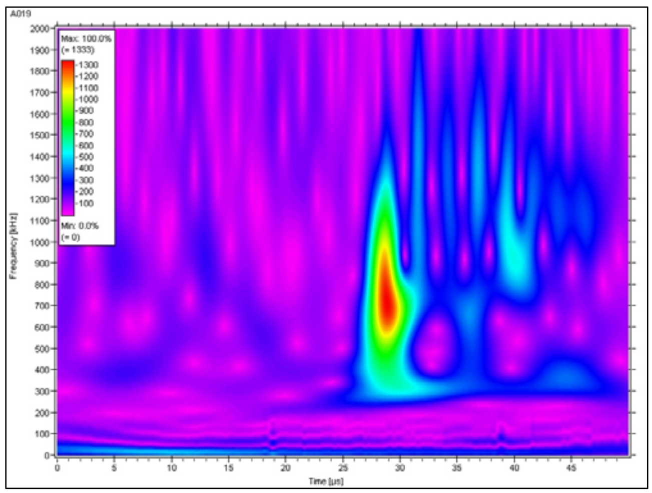

Figure 4(b). Wavelet Plot of Wheel Segment Containing Defects

System Design

This preliminary prototype design and development was limited to one-quarter of a complete wayside inspection station. The design is capable of inspecting one wheel per car per side of the track. This development approach was chosen because of the high equipment costs associated with building a full prototype system and because this approach was determined to permit an adequate assessment of whether or not this concept is feasible in a wayside environment. If the limited prototype proved successful, a complete inspection station capable of inspecting all wheels on both sides of the tracks can be constructed by adding either DDS carriages and lengthening the DDS track, or by adding additional stations.

The prototype system design and development process is outlined in this section. The design process included the initial research, design, and component selection for each subsystem. The original design has changed due to the expert review of the system design, and subsequent development efforts from the design team.

The prototype system design includes several components including special track work (a flange bearing track), DDS track and support structure, DDS carriage, control system hardware and software, data collection and processing hardware and software, laser and optics, enclosure and shutter system, and system integration.

Special track work

The purpose of the special track work is to expose the tread of the wheel by bearing the weight of the train on the flange. This is necessary to allow the ultrasonic transducer to be placed below the surface of the tread in order to monitor the ultrasonic signals. The design of the flange bearing track section was contracted out to a leading supplier of special track work.

Dynamic Detection System track and support structure

The DDS track was selected by the design team from a leading motion control manufacturer. The track has the ability to make controlled moves within a tolerance of 1 millimeter and has low maintenance requirements. The support structure consists of a series of adjustable stanchions designed to support the DDS track while providing height and position adjustability to fine-tune the location of the DDS track.

Dynamic Detection System carriage design

There are several components that make up the DDS carriage. These include the carriage frame, the retractable detector mechanism, the mirror/lens assembly, and the control and data collection components.

The carriage was designed to be structurally capable of supporting the necessary components, lightweight to reduce the resistance to motion, and rugged enough to withstand the railroad environment. The DDS carriage attaches to the DDS track through a small attachment plate and is driven by a servomotor that drives a rack and pinion on the DDS track.

The retractable detector mechanism positions the ultrasonic transducer below the tread of the wheel, and is retracted in order to bring the sensitive equipment within the environmental enclosure in the absence of a passing train.

The mirror/lens assembly is designed to steer and focus the laser beam from the laser head to a point on the wheel near the plate-rim radius. The design was taken directly from the results of the lab work discussed previously.

Control system

The control system is responsible for tracking the wheel as it passes so that the laser and transducer are centered on the wheel during data collection. The design includes a standalone motion control unit that contains the software necessary to track the wheel. In addition to the controller, a servo drive and servomotor are used to drive the carriage.

Data collection and processing

The Digital Signal Processing hardware includes a data collection module as well as a standalone signal processing module. The processing hardware is responsible for communicating with the motion controller, laser, and a host PC used to store raw and processed data from the signal processing hardware. The digital signal processing is also responsible for collecting the data and determining the existence of an SRC based on this data.

Environmental enclosure

The final piece of the design is the environmental enclosure, which protects the optics, sensors, electronics, and other sensitive equipment from the harsh railroad environment. The design of the enclosure includes a shutter system to allow for the extension of the retractable detector mechanism and laser beam steering, as well as an insulated heating and air-conditioning system to keep all the components at a reasonable temperature and dust-free.

Expert Review of System Design

The expert review panel was convened on June 10, 2004 to review the project's objectives, investigative approach, and deliverables as well as to provide technical guidance and discuss commercial application possibilities with the design team. The members of the expert review panel include Dr. Shant Kendarian (NASA Jet Propulsion), Dr. Dan Stone (railcar wheels and wheel flaws), Clay Norman (installation, operation, and maintenance of wayside systems, BNSF Railway), Chuck Taylor (IDEA Program Manager), Greg Garcia (TTCI Principal Investigator and Non-Destructive Technology (NDT) Level III). Mr. Taylor and Mr. Norman were unable to attend the meeting. Others present at the meeting included Dr. Duane Otter (TTCI CWD Design Review Team member) and the TTCI design team of Richard Morgan, Kari Gonzales, Joe Brosseau, Shad Pate, Jim Bilodeau, and Dan Carter.

The meeting agenda was as follows:

- Laser Technology review
- CWD Project background
- CWD design concept review
- Discussion of commercial application possibilities.

The review of the laser ultrasonic inspection method for use in wheel flaw detection was the first item on the agenda. There were several comments on the laboratory work performed during the research and development and the proof-of-concept demonstration conducted earlier. It was noted that no testing had been done on loaded wheel sets and that loading may or may not affect the integrity of the ultrasonic signals received. It was also suggested by the review panel that wheels with vertical split rims be tested, although these wheels may be difficult to locate. Spalling and other surface flaws that may be detected as wheel flaws were also discussed.

The project background and design concept discussion addressed several possible issues with the prototype. These included:

- Recognizing that defect sizes would not be measured accurately by the system as it is designed as a go/no-go detection process
- Suggesting that flaw sizing be added to future system development
- Questioning the impact of shallow surface cracks that appear along the entire tread surface of the wheel on the reliability of system defect detection
- Observing that wheels that have these shallow surface cracks have not been tested in the laboratory, and the shallow cracks may cause false positives in a wayside system
- Suggesting that wheels with shallow surface cracks be located and tested in the laboratory.

Discussion of commercial application possibilities concluded the meeting. Items brought up during this discussion included railroad opinions on thresholds for data processing (crack sizes) and speed control issues with the 5-mph restriction. The panel recommended these items be discussed further with representatives of the railroads. It was also noted that shattered rim cracks, vertical split rims, and flange cracks are more common on freight cars, and tread cracks are more common for passenger cars. The final consensus of the expert review was that the system had commercial application possibilities as both a wayside system and an in-shop wheel flaw detector.

Prototype Development and Assembly

The development of the prototype involved several stages, including control system development, laser ultrasound development, software development, and system integration. Many of these stages were run in parallel in order to optimize development time. Assembly of the system was partially completed during the development stage.

Laser ultrasound development included transducer optimization and optics configuration. These items relate directly to the laboratory work discussed in earlier sections. This work was completed in parallel to the control system and software development tasks.

The development of the control system was completed using the modified version of the DDS carriage and a calibration cart with a simulated wheel. The development was a multi-step process beginning with simple tasks such as driving the DDS carriage a known distance and resulted in a complete control system capable of tracking a wheel to within a 0.25-inch tolerance at speeds up to 8 mph.

Signal processing software integration was the final stage of the development. This task began with the analysis of laboratory data to define signal characteristics and continued through the system integration stage until the signal processing software was used to analyze data collected from the DDS.

Following the development of each subsystem, the prototype was assembled and system integration issues were addressed. These issues include communications between the components in the system, laser and optics alignment, and data collection and analysis.

Prototype Test Plan Development

The final Stage 1 task was the development of a field test plan to be used in Stage 2 for the system testing. Development of the test plan included determining the number and frequency of wheel inspections, arranging the test consist, and designing the test cycle.

Availability of defective wheels at TTC determined the number of wheels selected for prototype testing. Five wheels containing multiple shattered rim cracks were located and characterized using conventional NDT methods, along with 11 wheels containing no flaws.

The prototype system collected data from one wheel per car. The test consist was arranged to collect the most data with each pass of the five-car consist. The test cycle was designed as follows:

- The system will inspect the near side wheel of the lead axles of each car in one set of passes.
- The system will inspect the near side wheel of the trailing axle of each car in the next set of passes.
- The consist will be turned and the process will be repeated for the other side of the consist.

Stage 2: Prototype Testing

The tasks completed to fulfill the Stage 2 requirements included preparation and testing of the system developed in Stage 1. The preparation for testing followed the test plan prepared during Stage 1 and included site installation, wheel characterization, and consist assembly. Prototype testing included two types of testing. The first test of the system was accomplished by rolling characterized wheel sets by the system at walking speed. This allowed for initial data to be collected and analyzed while pieces of the prototype were still being assembled and developed. The system was then tested with a consist over the period of a week, during which final system development issues were resolved and initial consist test data was collected.

Installation and Test Preparation

The first Stage 2 task completed was the installation and preparation of the prototype. The test site was moved from the Precision Test Track (PTT), as originally planned, to the scale track near the Transit Maintenance Building (TMB). Stage 2 test preparation involved wheel selection and characterization and layout of the test consist.

Installation

The installation of the prototype system was completed in several steps. This supported initial data collection using characterized wheel sets while pieces of the system were still being installed and developed. Once the flange-bearing track section and enclosure were installed, the system was moved from its development site to the scale track test site. Following installation, all the components were checked out and trial runs with single wheel sets were performed to ensure proper operation of the system, prior to consist testing.

Wheel selection and characterization

The selection of test wheels included wheels with known shattered rim defects, as well as wheels with no defects. The wheels were sample sets removed from service and donated by AAR member railroads. A total of five wheels with known defects and 15 wheels with no defects were selected. The wheels were then characterized using conventional non-destructive testing methods (visual, liquid penetrant, magnetic particle, and ultrasonic testing) to confirm the presence, size, and location of the defects.

Test consist assembly

The layout of the test consist was designed to provide optimal test data with the fewest test runs. Five test cars were used in order to accommodate this design. It was determined that the leading and trailing axle of each car on the test consist would be replaced with a characterized wheel set. Each run would collect test data from either the leading or trailing axles on each car on one side of the consist.

Testing and Data Collection

Testing of the prototype system was accomplished in two steps: 1) Wheel set testing and 2) Consist testing. By testing the system in this manner, more data could be collected while parts of the system were still under development. This also provided the added advantage of being able to test the system using the consist wheel sets before running the consist test.

The wheel set testing took place in the Storage and Maintenance Building (SMB) at TTC. Due to unexpected delays in the delivery of the flange-bearing track section, a modified version of the DDS carriage was constructed to allow for testing the wheel sets without requiring the special track. As shown in Figure 5, the modified DDS carriage uses a retractable detector mechanism that positions the ultrasonic transducer and wheel tracking sensors above the wheel facing down towards the tread, rather than below the wheel facing up towards the tread. Also, the modified optics steers the laser beam toward the wheel rim at the top of the wheel, rather than toward the bottom. This modified carriage operates the same as the normal DDS carriage in all other aspects, meaning that the data collected in this test is representative of data that would be collected from a consist test.

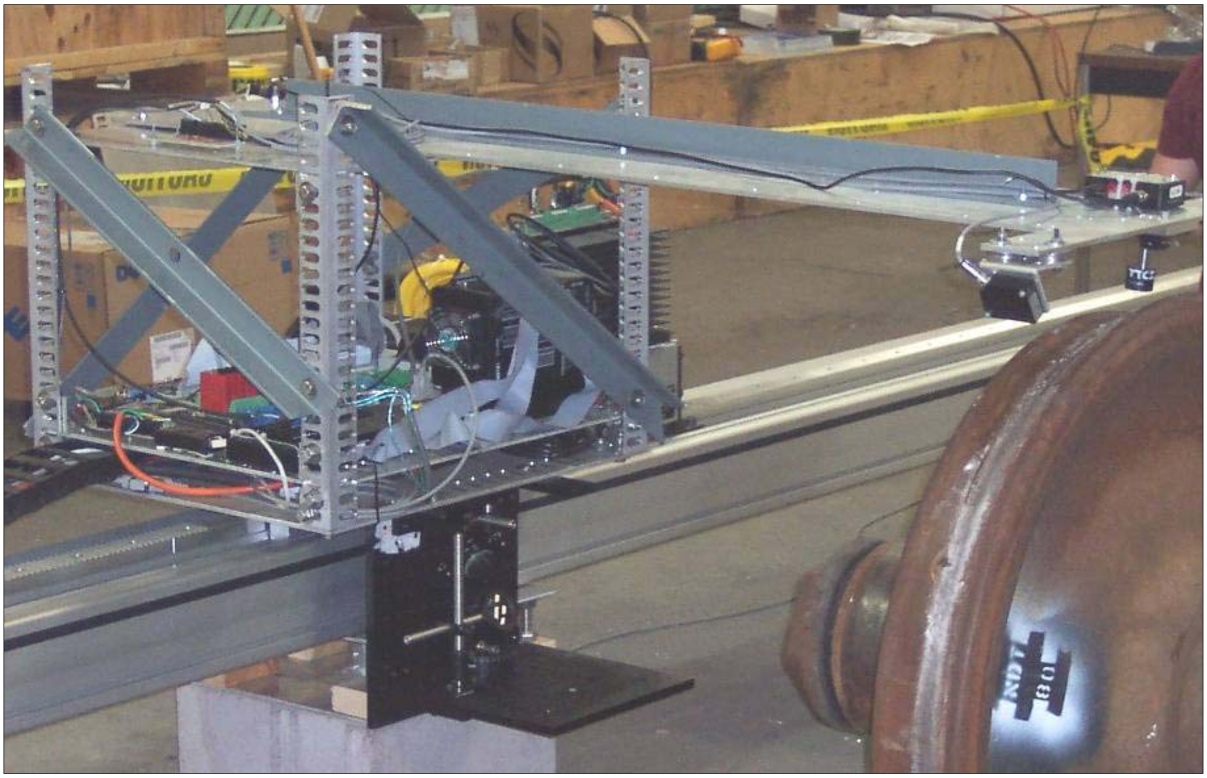

Figure 5. Modified DDS Carriage for Wheel set Testing

The data from the wheel set testing was collected with a digital oscilloscope as well as with the DDS data acquisition system, to ensure the integrity of the data collected. This also allowed for viewing the data in real-time, so that any necessary changes in the system could be made immediately. This was another advantage to performing wheel set testing, since use of the oscilloscope was not possible during consist testing.

Each of the 20 characterized wheel sets was rolled past the DDS at walking speed and the data was collected and stored for later processing. Each location on the wheel that was inspected was recorded so that every data point could be compared with the wheel characterization information. This information will be used to assist in developing automated signal processing algorithms in future developments of the system.

Consist testing took place on the scale track at TTC. The DDS carriage was re-assembled to its normal configuration as shown in Figure 6, and moved from the SMB to the track test site. The test plan developed in Stage 1 was used as a guide for the members of the test crew.

Figure 6. Final DDS Carriage Configuration

Consist testing was performed according to the test plan, with data being manually reviewed by the development team between test runs to ensure that the data acquisition system was working properly. Only one wheel per car on one side of the test consist was inspected.

Data Processing and Analysis

The data collected during the testing was analyzed using several different signal processing techniques, in order to determine the most consistent method for identifying the presence of a defect. The data collected from wheel set testing and the data collected from consist testing were analyzed and compared. The data collected from consist testing did not correlate with the data collected during wheel set testing. This was due to data quality problems from the consist testing. This was attributed to such factors as system carriage stability discussed in more detail in later sections. Due to the poor data collected during consist testing, the remainder of the discussion in this section will focus on the data collected during wheel set testing.

Each section of each wheel inspected produces a signal that can be processed to determine whether or not a defect is present. Figure 7(a) shows an example of a signal collected from wheel set testing where no defects were present, while Figure 7(b) displays a signal from the wheel set testing where a SRC is present. In Figure 7(a) the arrival of the direct longitudinal wave and shear wave components are apparent. Both signal amplitude and uniformity decrease in Figure 7(b). As the signal passes through the crack, energy is lost, which decreases the overall amplitude of the direct longitudinal wave. Also, as the wave passes through the defect, the signal waves are diffracted causing the signal to become more complex in the number of wave components present.

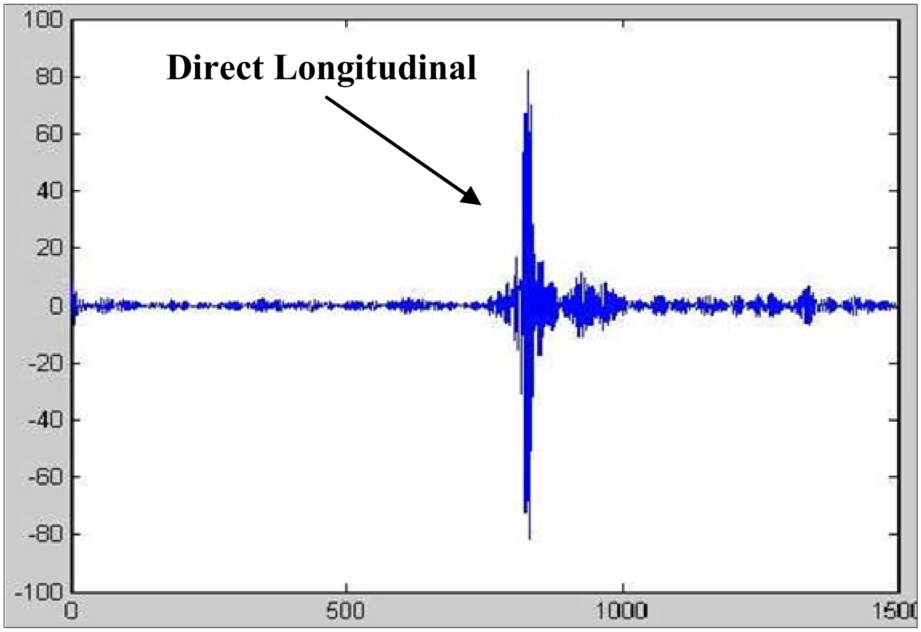

Figure 7(a). Typical Signal for No SRC Present

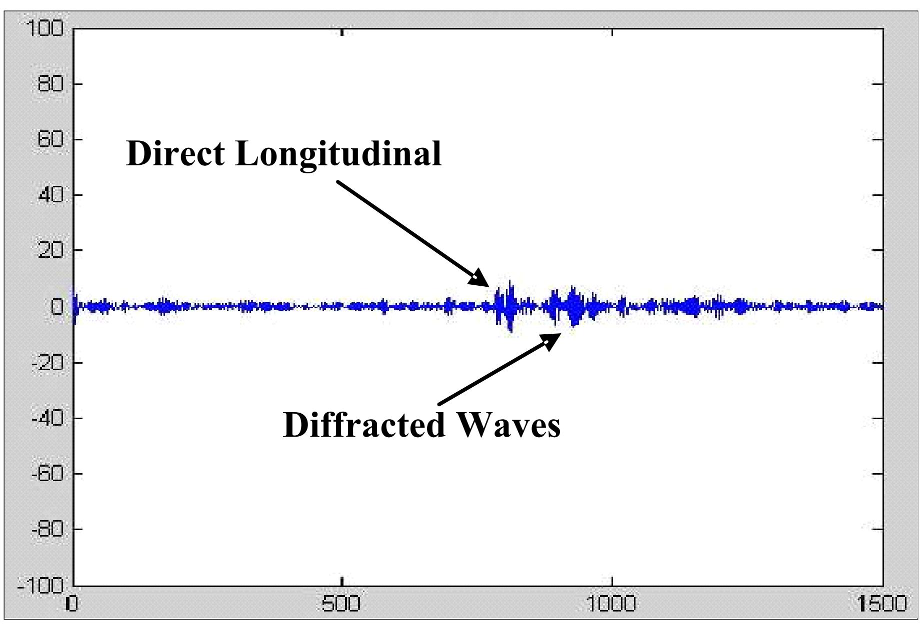

Figure 7(b). Typical Signal for SRC Present

Using data collected in the laboratory experiments and the wheel set testing with the modified prototype, preliminary algorithm development was completed. After studying several of the signal characteristics, it was determined that two signal features are affected by the presence of an SRC. Figure 8 shows these features plotted for two wheels, one containing SRCs and one without SRCs. The wheel with no SRCs is represented on the right side of Figure 8, while the wheel containing SRCs is represented on the left side of the figure. Comparing the output of Feature 1 and 2 shows the distinct separation between the no-defect and defect case for the majority of the wheel passes. Using these features, a threshold was set at approximately 0.058 (Reflect Ratio Amplitude), which would allow an automated decision process to distinguish if a wheel contains SRCs or not. Algorithm thresholds were set so that there were no false-positives found during this analysis, but some of the smaller SRC sections (i.e. less than 3 inches in circumferential length) were not identified. To verify repeatability 5 passes were completed with the two wheels represented in Figure 8. Post analysis showed that the results were repeatable, i.e., no passes of the non-defective wheel exceeded the threshold while all passes of the wheel containing SRCs exceeded the threshold.

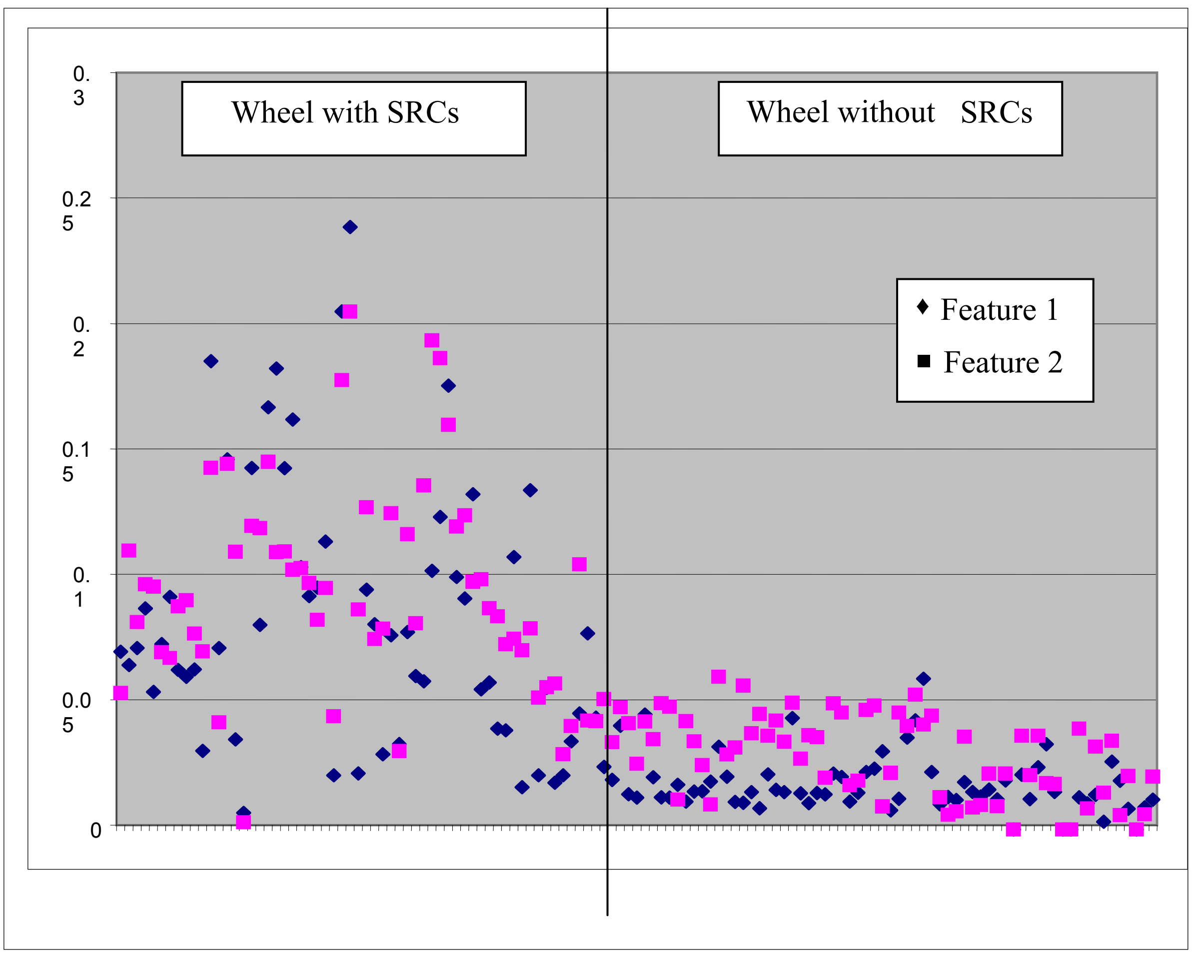

Figure 8. Automatic Algorithm Output Comparing Two Signal Features for Two Wheels

After consist data were collected, each file was manually scrutinized for quality. If the file was usable, automated signal processing was applied to determine if the algorithm produced during wheel set testing was applicable to consist data. The usable data from consist testing did not correlate to the wheel set results. This was due to an insufficient number of good data files collected, during consist testing, because of various design and implementation problems. Some of the problems identified during the testing include: carriage instability and high vibration, poor DDS and railroad track alignment, inadequate grounding and shielding, laser beam and optic alignment problems, and the lack of wheel tracking sensor calibration for various wheel positions. Although insufficient data were collected for a full analysis, several wheel passes were identified that contained usable data. This data was analyzed using only the raw data to determine if other signal features could be extracted to distinguish the difference between defective and non-defective wheels. The few usable signals showed similar results to Figure 7 (a) and (b). The false positive rate could not be determined from the consist data because of insufficient data.

Before a final decision on the capability of this system can be reached, system modifications must be completed and consist testing must be repeated. These modifications include stabilizing the DDS carriage to improve wheel tracking and laser beam delivery. Other modifications will include re-alignment of the DDS track and the flange bearing track, improved quality in the grounding and shielding of all power and signal cables, changing the data transfer methodology, and improved wheel tracking software. Funding limitations did not allow for additional system modifications to be made, but the development team is confident that with minor modifications to the prototype system, data from a modified DDS testing will permit accurate, reliable identification of SRCs.

EXPERT REVIEW OF TEST RESULTS AND FINDINGS

The expert review panel was convened in October 2004 following the AAR Railway Technical Research Committee meetings held at TTC. The panel reviewed the project objectives, investigative approach, and the prototype test results. The expert review panel included representatives of the BNSF Railway, Union Pacific Railroad, Norfolk Southern, and CN. Others present at the meeting included the design team from TTCI.

The meeting agenda included a review of the laser-based technology, the project background, an overview of the design, and a review of the data collected during the consist tests. There was a discussion of future implementation options and possible issues or concerns with the development process. Issues that concerned the review panel included the current speed of the system, detectable flaw size, false alarm rate, system robustness, types of flaws detected, and the safety of employees working on or around such laser systems.

Wheels being tested by this system can pass the detection site at a maximum of 6 mph, meaning that most trains will need to decrease their speed significantly to be tested. This caused some concern for representatives of the railroads because trains in revenue service are rarely moving at speeds that low. However, upon further discussion of this topic, it was determined that it is likely that the system will be used primarily in a yard or special inspection site. It was decided that this issue would probably not prevent the railroads from using this system, but a faster system would be preferred and can be made available at a later date by increasing the repetition rate of the laser or employing beam delivery techniques to reduce the total number of points collected along the circumference of the wheel.

Directly related to the speed issue is the detectable flaw size. The main concern with this issue is that the flaws need to be detected before they reach critical size. More investigation into the size of a critical SRC defect must be completed in order to determine the final design specifications for the cracked wheel inspection system.

The false alarm rate of the system was also a concern for the railroads, because pulling wheels out of service is a costly process, and if too many wheels are pulled out of service that do not have flaws, the system will not be economically viable for the railroads. A false alarm rate was not available due to the data quality problems. The acceptable false alarm rate for the final product must be determined by the end users, and system performance improved accordingly.

The final concerns of the expert review panel focused on the ability of the system to survive in the wayside environment and also the safety requirements for personnel working in or around the inspection system. The Class IV laser and number of moving parts raised some concerns for revenue service operations, and will need to be addressed in the final version of the detection system.

The panel requested updated information on system performance as work progresses.

ADDENDUM: ADDITIONAL DEVELOPMENT AND TESTING

At the conclusion of the 2004 testing, TTCI conducted additional research on the issues contributing to the poor data quality produced during the first set of consist tests. The following modifications were made to the system during this additional research to increase the overall reliability of the system:

- Reduced the weight of the DDS by relocating the control and data acquisition hardware to the bungalow
- Redesigned the RDM and MLA to be more rigid and contribute less vibration to the entire system
- Purchased more rigid optical mounts to decrease the effects of vibration on the turning mirror and focusing lens

- Replaced shielded power cables with double shielded cables to reduce the amount of noise produced on all channels
- Modified the wheel tracking sensor cable configuration to increase the coverage area on the tread of the wheel.

Once the modifications were complete, several days of on track testing was performed, beginning with wheel set testing. A total of 6 wheels, characterized in Stage 2, were rolled through the inspection station at walking speeds. Between 40-60 data points were collected for each pass of a wheel, and 3-7 passes were completed for each wheel. Of the 6 wheels tested, 3 wheels contained SRC's (Wheels 37, 79, and 80), and 3 wheels contained no defects (Wheels 25, 26, and 38). Data was collected and analyzed using the same process described for earlier wheel set testing. Figure 9 shows the results of the wheel set testing.

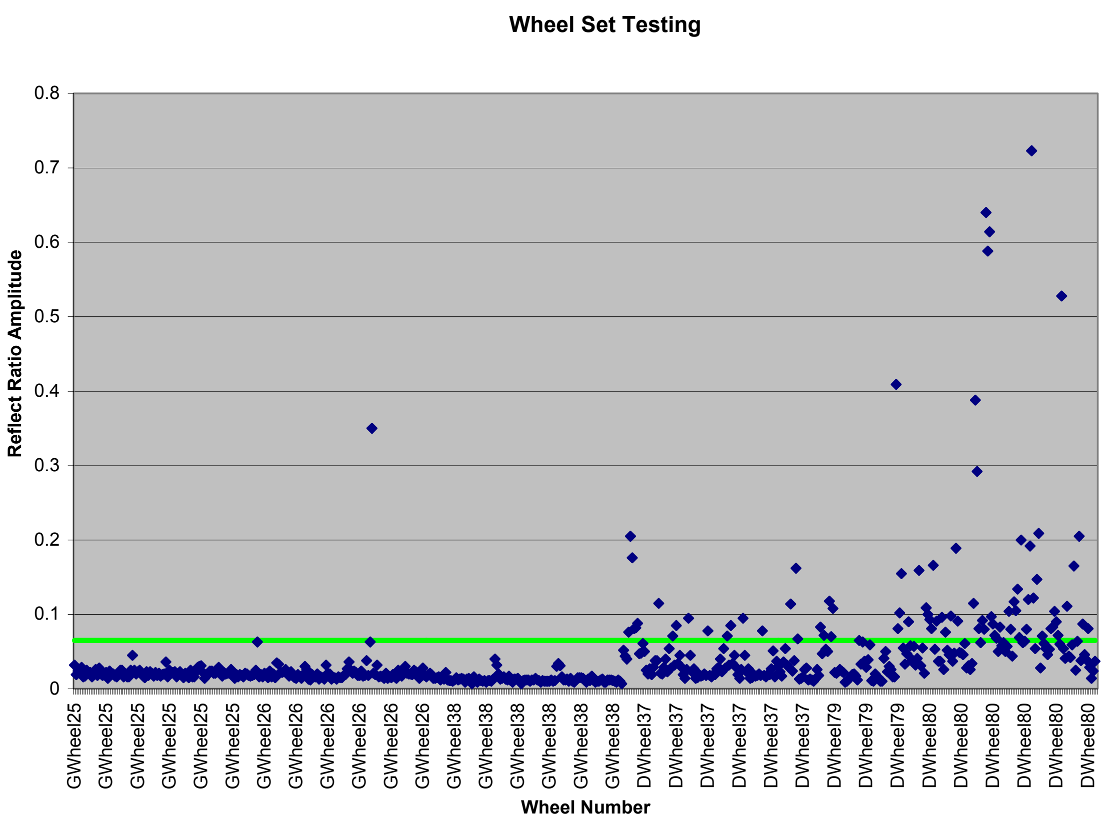

Figure 9 Wheel Set Testing

In Figure 9, the gray horizontal line is a threshold set at 0.065 (Reflect Ratio Amplitude) used to determine if a wheel has shattered rim cracks present. The left hand side of the graph represents data from good wheels, and the right hand side represents data from defective wheels. During analysis if a single wheel has more than some percentage of points over the threshold in a single pass, the wheel is considered to contain defects. Using this methodology, all three wheels containing defects were successfully identified for all passes.

After the wheel set testing was complete, the test train was re-assembled and data was collected. Eight test runs were completed on one side of the consist, so only 10 wheels were evaluated. Of these 10 wheels, only one contained SRC's. During this testing, several problems occurred during data acquisition, and a new noise source that had adverse effects on the signal quality was identified. Figure 10 shows the results from the second set of consist tests.

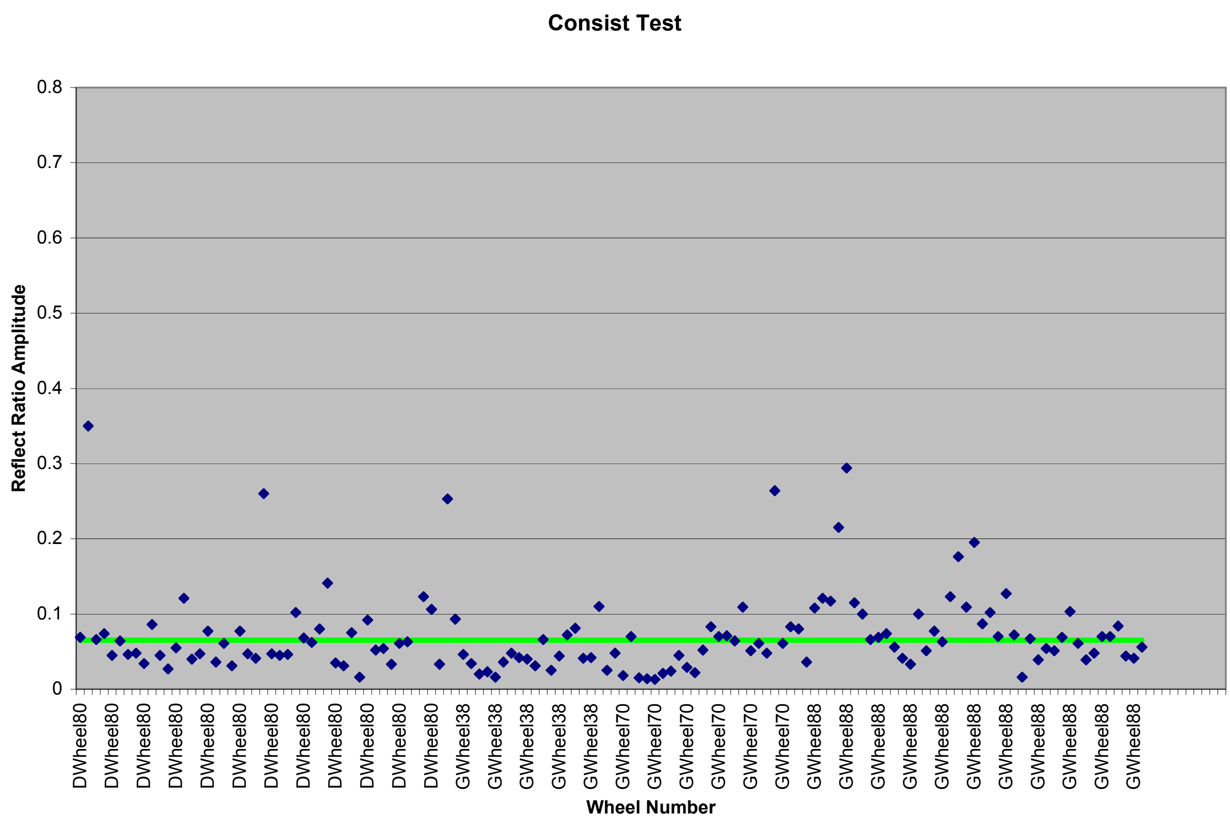

Figure 10 Consist Test

Using the same analysis technique as the wheel set testing, there is no clear separation between the defective and non-defective cases. Again, problems with data collection prohibited high quality data from being collected from the consist testing. The major problem identified in this set of consist testing is a noise source that has not been determined.

After reviewing this set of data it can be concluded that wheel set testing does suggest that the technique is feasible, but more development work is necessary before a decision can be made on the capability of the system to inspect entire trains for shattered rim cracks. All of the issues discussed after the first set of consist testing were addressed, but as development continued more problems arose. These issues must be addressed before any more testing is conducted.

It should be noted that after this phase of consist testing TTCI contracted with a third party to assist in further development of the prototype system. It was decided by the committee that provides oversight for the AAR's research program that further development of the laser-based system would be postponed and a conventional ultrasonic system would be developed in 2005. This decision was made after demonstration by the third party contractor of a conventional system that was closer to field implementation for detecting shattered rim and tread cracks. This system is scheduled for demonstration during fourth quarter 2005.

SUMMARY AND CONCLUSIONS

Tasks completed in Stage 1 of this research included the system design, review of that design by an expert panel, development of a prototype system and a system test plan. Stage 1 activities included lab work to determine the optimum location for laser generation and air-coupled detection of SRCs. This work determined that the laser impact point must occur at the plate-rim radius and the transducer must be placed directly beneath the surface of the wheel tread.

Stage 2 tasks included the installation and calibration of the prototype. A test train consisting of 5 test cars was used for the consist testing. Each car contained wheels that were previously characterized with respect to whether or not they contained SRCs. A total of 5 wheels in the consist contained SRCs and the remaining 15 contained no defects. Prior to consist testing, wheel set testing was conducted by rolling wheel sets past a modified DDS. Some of these wheels contained known SRCs and some did not.The wheel set testing results indicated that the laser-based prototype system was capable of satisfactorily detecting SRCs. Following the wheel set tests, the test train made several passes over the inspection station. The consist test data were analyzed to determine how the prototype system performed in comparison to the system specifications. Preliminary analysis showed that the data quality was poor. Further research was conducted to determine the causes of the poor data and also to determine why the consisting testing was unable to confirm the results of the wheel set tests. The findings were that stability, tracking, and alignment problems were major sources of the problem.

RECOMMENDATIONS AND PLANS FOR IMPLEMENTATION

As discussed in the previous section, the results from the initial limited prototype testing were inconclusive. It is the recommendation of the design and development team that the design be reviewed and modifications made to improve the performance and reliability of the system to acceptable levels. When these changes have been completed, it is recommended that further consist tests be conducted to evaluate the effect of the modifications and ensure that the system results can meet all performance specifications. This will be required to complete the initial step of the development process.

The prototype system developed in this project is an initial version of the system to assess the ability of laser-based ultrasonic inspection to perform in a wayside environment. There are several more steps in the overall development plan before arriving at a final product. Future development plans include adding hardware to detect SRCs on every wheel of the consist, adding the ability to detect surface cracks on the tread and flange of the wheels, adding the ability to detect vertical split rim defects, and ruggedizing the system for long-term survivability.

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