IDEA

Innovations Deserving
Exploratory Analysis Programs

*High-Speed Rail IDEA Program*

# Signal Transmissibility of Railcar Bearing Vibrations

Final Report for High-Speed Rail IDEA Project 56

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*February 2008*

TRANSPORTATION RESEARCH BOARD
*OF THE NATIONAL ACADEMIES*

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***Signal Transmissibility of Railcar Bearing Vibrations***

IDEA Program Final Report

For the Period April 2007 through February 2008

High-Speed Rail-IDEA Project HSR-56

Prepared for

The IDEA Program

Transportation Research Board

National Research Council

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**February 2008**

## IDEA PROGRAM

Funding and technical support for this project was provided by the High-Speed Rail IDEA Program. The mission of the High-Speed Rail-IDEA Program is to foster innovation in rail transportation by providing start-up R&D funding and support for promising but unproven concepts.

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- NCHRP Highway IDEA, which focuses on advances in the design, construction, safety, and maintenance of highway systems, is part of the National Cooperative Highway Research Program.
- Transit IDEA, which seeks advances in efficiency, safety, and maintenance of transit systems, is part of the Transit Cooperative Research Program and funded by the Federal Transit Administration.
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# ABSTRACT

This report summarizes research into the transmissibility of signals from a defective rail car wheel bearing from the source of the defect to rail-mounted accelerometers. The project evolved from an initial proposal to develop a wayside defective bearing detection system using rail-mounted accelerometers. It was not clear if the defective bearing signals can be transmitted to the rail through the rolling wheel-rail contact patch. The rolling contact patch could, especially, pose a challenge for the technology. Possible contamination at the wheel/rail contact may further complicate the situation. The objective of the project was to investigate the transmissibility of the wheel bearing vibration signals through the complicated path from the defective bearing to the rail-mounted accelerometers via the rolling contact patch.

Following successful lab tests, field tests were conducted to collect sufficient data to enable detailed analyses to determine how well the bearing vibration signals could be transmitted from the bearings to the rail. The tests involved the use of a known defective bearing fitted on a test car hauled over a rail section equipped with accelerometers. The data collected from the field tests were analyzed using a high-frequency vibration envelope detection technique. Data analysis results for the onboard data indicated a bearing cup defect. The results of the wayside data analysis indicated the bearing defect signature was evident even under worst-case test conditions.

Further development of this concept will require additional tests at higher speeds with better track conditions, using a full array of track sensors to fully determine its feasibility.

**Keywords:** railroad wheel bearings, bearing defects, defect detection, growlers, wayside defect detection, health monitoring.

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# EXECUTIVE SUMMARY

For decades, the railroad industry has continuously invested in technology for monitoring and diagnosing rail bearing conditions and defects. The harsh railroad operating conditions have made in-situ testing of rail bearings more challenging than testing of other industrial bearings. Existing technologies include onboard condition monitors, workshop diagnosis systems and trackside detecting systems. The main challenges these systems face are the capability of early detection, reliability and cost of the systems.

Among widely used products are wayside hot box detectors, which use infrared technology to detect heat emitted from defective bearings. These detectors cannot catch the bearing defects until they have already developed to unacceptable levels. Furthermore, these sensors can detect bearings only in the direct line of sight. Therefore, they often miss inboard bearings due to obstruction of the heat transmission path.

In 1980s, the Federal Railroad Administration (FRA) and the Association of American Railroads (AAR) joined forces to develop alternative wayside detection systems. A representative system is the Trackside Acoustic Detection System (TADS) developed by the Transportation Technology Center, Inc. (TTCI). This system uses microphones to detect interfering airborne acoustic signals from the surrounding train noise and all other wheels. The TADS system has been successful in detecting a majority of defects at different stages. However, the system can miss certain types of defects and falsely condemn bearings with minor defects that do not warrant removal from service. In addition, this system has difficulty in detecting inboard bearings.

It is desirable to have a technology that reliably detects bearing defects early on in their development. This would allow the developing defect to be repaired at the earliest opportunity when the car is available for maintenance and result in fewer operation interruptions.

The promising technology for the desired systems appears to be direct detection of bearing vibration signals. Spectral analysis of vibration signals from defective bearings in rotating machinery is a well-developed technology and widely used in many industries. In this methodology a vibration sensor is mounted near an operating bearing. A solid mechanical vibration path from the bearing to the sensor can generate a strong and isolatable bearing vibration signal for spectral analysis. Common examples of this application are electric motors and pumps in industry. In theory, detecting bearing defects using vibration signals from a direct mechanical path can yield more accurate results because it will eliminate adverse effects of surrounding noises and other environmental parameters, such as wind noise.

A proposal for a project to develop a wayside defective bearing detection system using accelerometers **mounted on the rail** was submitted to the Transportation Research Board's High-Speed Rail IDEA committee. The committee suggested that some fundamental issues needed to be addressed before such a system could be developed. The main issue is the transmissibility of the vibration signals from the defective bearing to the rails. The rolling wheel-rail contact patch would, especially, pose a challenge for the technology. Possible contamination at the wheel/rail contact could further complicate the situation. A project of smaller scale was evolved to tackle these issues.

The objective of the project was to conduct laboratory and field tests to investigate the transmissibility of the bearing vibration signals through the complicated path from the defective bearing to the rail-mounted accelerometers via the rolling contact patch. The outcome from this project should shed some light on the feasibility of future development of a wayside bearing detection system based on rail-mounted accelerometers.

During Stage I of the project, a plan for the field tests was developed. The test plan incorporated suggestions from the first advisory panel meeting. Laboratory tests were conducted to evaluate the transmissibility of signals generated at the bearing in a controlled environment. The results showed that bearing signals could transmit from the wheel to the rail under the test conditions.

Field tests were then conducted in the second stage of the project. The goal was to collect sufficient data to enable detailed analyses to assess the transmissibility of the bearing vibrations from the bearings to the rail. The tests involved the use of a known defective bearing fitted on a test car hauled over the test site. One high-frequency accelerometer was installed on the adapter of the defective bearing. Another accelerometer was installed on the adapter of a good bearing for comparison. Three accelerometers were installed on one rail at the selected test site. Two mobile data collection units were used to collect bearing vibration data both onboard the hauling locomotive and at wayside. Due to the **necessity to change test sites,** the tests were not conducted according to the original plan. **The original plan was to use** a heavily-loaded test car on continuously welded rail (CWR) track with **test** speeds up to 35 mph. Instead, the tests were conducted on Class 1 jointed track with a speed limit of 10 mph. The test car was an empty box car with a wheel load of 8.8 kips, which is a fraction of that of a fully-loaded freight car. These changes **resulted in a worst-case test scenario, resulting from the combination of light axle loading, which reduced the transmissibility across the contact patch; slow speeds, which reduced bearing vibration energy; and rail joints, which introduced large noise spikes**. **[Yu-Jiang: Is this correct? If not, please revise.]** Nevertheless, preliminary examination of the sample test data seemed to indicate that the bearing signals were detected by the rail-mounted accelerometers.

During the third stage of the project, the data collected from the field tests were analyzed using a high frequency vibration envelope detection technique. **[Can you insert a brief explanation of this technique here? If not, it's not a problem as long as an explanation is included in the body of the report.]** The onboard data channels were filtered using a band-pass filter. The power spectra were computed. The envelope detection technique was applied to the filtered data. The results clearly indicated that the defective bearing signals were present in the onboard data. The dominant frequencies were distinguishable, which indicated a typical cup defect in the bearing. This finding was consistent with the analysis results of the acoustic data for the same bearing previously collected at an acoustic bearing (TADS) wayside detection site. The same analysis procedures were applied to the **data from the control bearing with no defects.** Only one test run seemed to indicate that the bearing defect was also detected by the control channel which, alone, may not give a definite indication of the bearing defects. This seems to indicate that the cross-transmission of the defective bearing signals to the adjacent axle was not significant, at least for the test format of this project.

Although the onboard data analysis results indicate that the defective bearing signals had the strongest power at the ranges of 8 – 9 kHz, they were present at all frequency ranges up to 20 kHz. This indicates that the defective bearing generated a broadband spectrum.

For wayside data analysis, the first step was to identify the time period when the defective bearing was above or in the vicinity of the three rail-mounted accelerometers. This was done by examining the strong spikes in the wayside time history generated when the wheels hit the rail joints. With known rail joint spacing and test car dimensions, the time when the defective wheel was above the accelerometer was easily identified. The segment of time history of interest was then cropped for analysis. The same band-pass filter used for onboard data analysis was applied to the wayside data**. The envelope detection technique** was then used to detect the defective bearing signals. The first round of analysis did not reveal the bearing signals. The background noise signals and the signals from the rail joints seemed too strong to allow the bearing signals to be detected. In the next round of analysis, the signals from the rail joints were removed. The defective bearing signals showed up in the power density spectra after **envelope detection**. However, the signal-to-noise ratio could have been improved if the desired test conditions were met. In addition, differential signal filtration using **the proposed 3-sensor noise cancellation configuration** [**needs an explanation]** along the rail should further improve signal-to-noise ratios **[how?]**.

**Do you want to include anything about the contaminated rail tests?**

In summary, although the field tests were limited to low speeds, which greatly reduced the bearing defect noise and therefore significantly reduced the signal-to-noise ratio, the bearing signatures were still evident. Since distressed bearing noise increases with the square of speed, a doubling of the speed would be expected to yield up to a four-fold increase in the bearing noise signature. Also due to last minute difficulties in obtaining access to the originally planned test site, the tests had to be conducted on a bolted, rather than a welded construction track, with less than ideal surface conditions. Each factor significantly raised the noise floor during the tests.

A second test, at higher speeds with better track conditions, is recommended, **along with application of the full array of track sensors necessary for evaluating the full noise cancellation concept. [Confusing: what's the full array of track sensors and how does it differ from the 3-sensor array used in the field tests? And, again, what's the full noise cancellation concept?]**

**The Executive Summary has to be a stand-alone document, so you can't introduce terminology without a brief explanation or, at least, a page number in the body of the report the reader can turn to for a full explanation.**

# 1. PROJECT OVERVIEW

## 1.1 INTRODUCTION

Wheel bearing failure is one of the major failure modes of railroad cars. Bearing failure is a serious safety hazard and costly to the railroad industry. There exist various methods for monitoring bearing conditions. These include onboard condition monitors, workshop diagnosis systems and trackside detecting systems. The main challenges these systems face are the capability of early detection, reliability and cost of the systems. Among the three categories of bearing monitoring and detecting systems, trackside detecting systems seem to offer the most promising solution.

Different technologies have been employed in trackside bearing monitoring and detecting. Examples include visual inspections, trackside heat sensors (hot box detectors), and trackside acoustic sensors. Visual inspections cannot detect a problem until the defect has already developed to unacceptable levels. Trackside heat sensors may only detect bearings near catastrophic failures when bearings heat up. Additionally, since most heat sensors use infrared technology, they often miss inboard bearings due to obstruction of the detection path.

Trackside acoustic bearing detection systems have been evolving since the 1980s. The available systems use microphones to detect interfering airborne acoustic signals from the surrounding train noise and all other wheels. They detect associated acoustic components instead of direct bearing vibrations. These systems also have difficulty in detecting inboard bearings. A representative system is the TTCI's Trackside Acoustic Detection System (TADS) [(*1*) and (*2*)]. This system has been successful in detecting a majority of defects at different stages. **However, due to the complexity of bearing acoustic signals, TADS may miss certain types of defects and falsely condemn bearings with minor defects that do not warrant removal from service. [Source?] Is this addressed in references 1 or 2? Would TTCI agree with this? If this is just an assertion, we can’t publish it.]**

It is therefore desirable to have a technology that **more** reliably detects bearing defects early on in their development. This would allow the developing defect to be repaired at the earliest opportunity when the car is available for maintenance and result in fewer operation interruptions.

The promising technology for the desired systems appears to be direct detection of bearing vibration signals. Spectral analysis of vibration signals from defective bearings in rotating machinery is a well-developed technology and widely used in many industries. In this methodology a vibration sensor is mounted near an operating bearing. A solid mechanical vibration path from the bearing to the sensor can generate strong and isolatable bearing vibration signals for spectral analysis. Common examples of this application are electric motors and pumps in industry.

Detecting bearing defects using vibration signals from a direct mechanical path can yield more accurate results because it will eliminate adverse effects of surrounding noises and other environmental parameters, such as wind noise.

## 1.2 PROJECT BACKGROUND

A proposal to develop a trackside bearing detection system based on accelerometers was formulated and submitted to the TRB's High-Speed Rail-IDEA program. The system would employ rail-mounted accelerometers to detect defective bearings. When the wheel with the defective bearing rolls near the accelerometers on the rail, a short mechanical path is formed from the bearing to the rail. The vibrations signals generated by the defective bearing should be detectable by the accelerometers mounted on the rail.

The High-Speed Rail-IDEA Committee suggested that some fundamental issues be investigated before such a system could be developed. Specifically, there were concerns that the signals may not be strong enough to allow the defective bearing to be detected. It is suspected that the moving rolling wheel/rail contact patch may pose challenges to such a system, especially when the contact patch is contaminated.

Following the Committee's suggestion, a scaled-back project was formulated to conduct a proof-of-concept investigation into the transmissibility of bearing vibration signals from the source to rail-mounted accelerometers. An advisory panel was formed, comprising experts from the railroad industry and the Federal Railroad Administration (FRA).

## 1.3 PROJECT OBJECTIVES

The objective of the project was to conduct laboratory and field tests to study the transmissibility of bearing signals from the bearing through the mechanical path down to the rails. The study, if successful, would serve as a precursory investigation of an accelerometer-based, wayside bearing detection system. This project was divided into three stages. In

Stage I, a comprehensive plan was developed, incorporating suggestions and comments from an advisory panel. Details are given in chapter 2 of this report. Upon completion of Stage I, field tests were conducted based on the test plan developed in Stage I. Chapter 3 of this report describes the detailed test procedures. In Stage III, the data collected from the field tests was analyzed for objective evaluation of the proposed technology and recommendation for future research. Chapter 4 describes data analysis techniques and provides results of the analyses.

# 2. PROJECT PLANNING

## 2.1 SCOPE OF WORK

The scope of the Stage I of the project was to develop a plan for the field tests. Some logistics were also arranged and some data collection equipment was prepared. The first Advisory Panel meeting was also held following initiation of the project. Laboratory tests were conducted to evaluate the path of signals generated at the bearing.

## 2.2 PANEL MEETING

An Advisory Panel was formed to provide technical guidance and support to the project team. The panel consisted of experts representing the railroad industry and the Federal Railroad Administration. Table 1 lists the members of the Advisory Panel.

TABLE 1 Advisory Panel Members

| Name | Affiliation |
|---|---|
| Mr. Chuck Taylor<br>Program Manager | Rail IDEA Program<br>National Academy of Sciences |
| Mr. Robert Blank<br>Director | Research & Tests<br>Norfolk Southern Railway |
| Mr. Paul Steets<br>Senior Director | Rolling Stock Engineering<br>National Railroad Passenger Corporation |
| Mr. Gary Garr<br>Division Chief | Office of Research and Development<br>Federal Railroad Administration |

The first panel meeting was held on May 10, 2007 through teleconference. A presentation was made to the panel, highlighting the objective and scope of the project, preliminary plan for the field test and data analysis. The following briefly summarizes the issues discussed at the panel meeting:

- Regarding the system's ability to isolate signals generated by wheel defects, and to detect journal bearings from locomotives, it was agreed that the scope of the current effort would not extend beyond proving the transmissibility of bearing vibration signal from the source to the rail mounted accelerometers.
- Similarly, the project scope also prevented it from identifying bearings of different types and sizes.
- The project team informed the panel that the current project was a scaled-back effort from an early proposal in which a signal detection and isolation algorithm would be fully developed and tested.
- It was reiterated that the purpose of the project was to address the concern that bearing defect signals might not easily travel down to rail-mounted sensors due to the impedance of a noisy rail/wheel contact patch.
- One of the attendees stated that if the accelerometers were proven to be able to separate signals of wheel flats, they would have potential use for detecting wheel defects.
- Regarding the loading of the test car, it was understood that the load of the car Norfolk Southern Railway was to provide could not be altered.
- The IDEA program manager informed the project team that TTCI management was willing to provide the raw TADS data from the defective bearing of the selected wheel set.
- It was decided that a control sensor on a "good" bearing would be installed during field tests to ensure the tests capture some comparison signals.
- The second and final panel teleconference would be held towards the end of the project to review findings and recommendations.

## 2.3 LAB TESTING

### 2.3.1 Test Objectives

The objectives for the laboratory tests were identified as follows:

- To develop a better understanding of vibration signals transmitted through the wheel/rail contact;
- To provide inputs for planning field tests;
- To help determine test equipment requirements and mounting methods.

To meet the objectives associated with the laboratory vibration tests, lateral, vertical, and longitudinal accelerations were measured on the bearing adapter of a test wheelset and on a piece of rail over which the test wheel set was rested. All acceleration signals measured would be analyzed in the frequency domain.

### 2.3.2 Test Setup and Test Procedure

An indoor location relatively flat and away from any extraneous vibration sources was selected for the lab test. A freight wheel set (two wheels mounted on an axle) with outboard bearings was used for the tests. The test wheel of interest was placed on a 3-foot long piece of rail. The other wheel was supported by a wooden chock to ensure that the wheel/rail contact was tangent and to prevent the wheel set from rolling, turning, or sliding during the tests.

Three (3) PCB single-axis variable capacitive accelerometers were connected to a portable computer-based data acquisition system that utilizes its driver specific software for data processing. Each accelerometer was stud mounted on an aluminum square block. The aluminum block was adhesively mounted onto the measurement locations. Three (3) particular locations of interests were selected along the vibration signal path as shown in Figure 1.

- A bearing adapter was placed over the bearing. A measuring fixture (accelerometer and the mounting block) was then installed at the center of the bearing adapter. This accelerometer measured input vibration signals generated directly on the bearing adapter.
- The second measuring location was on the web of the rail directly underneath the wheel/rail contact patch. The accelerometer mounted at this location measured vibration signals transmitted from the bearing adapter to the rail through the bearing, axle, wheel, and the wheel/rail contact patch.
- The third measuring location was on the web of the rail 18" away from the second accelerometer. This third accelerometer measured the output vibration signals that had traveled over a certain distance in the rail.

All sensors were properly aligned relative to the Earth's gravity and routed to a three (3) channel signal conditioner/power supply unit, which was connected to an OROS$^{tm}$ portable computer-based data acquisition system. Vibration signals from the three accelerometers were simultaneously passed through the signal conditioner and OROS analyzer into a computer utilizing OROS proprietary software for recording and processing. Data passed to the computer were displayed as an acceleration time history for examination. Signals were zeroed out using the potentiometers on the signal conditioner, and proper frequency bandwidths were chosen for data collection.

A hammer drill was used as an input vibration device. The hammer drill was held vertically in line with the vertical center plane of the wheel set to produce downward strokes onto the bearing adapter. While steady and consistent hammering signals were being applied to the bearing adapter, the acceleration signals from all three (3) measuring locations in the frequency range of 0 to 500 Hz were recorded simultaneously for 30 seconds at 1280 samples/sec. Sensor orientations on the aluminum mounting blocks were changed, and the measurements were made in a similar fashion until acceleration signals in vertical, lateral, and longitudinal direction were captured.

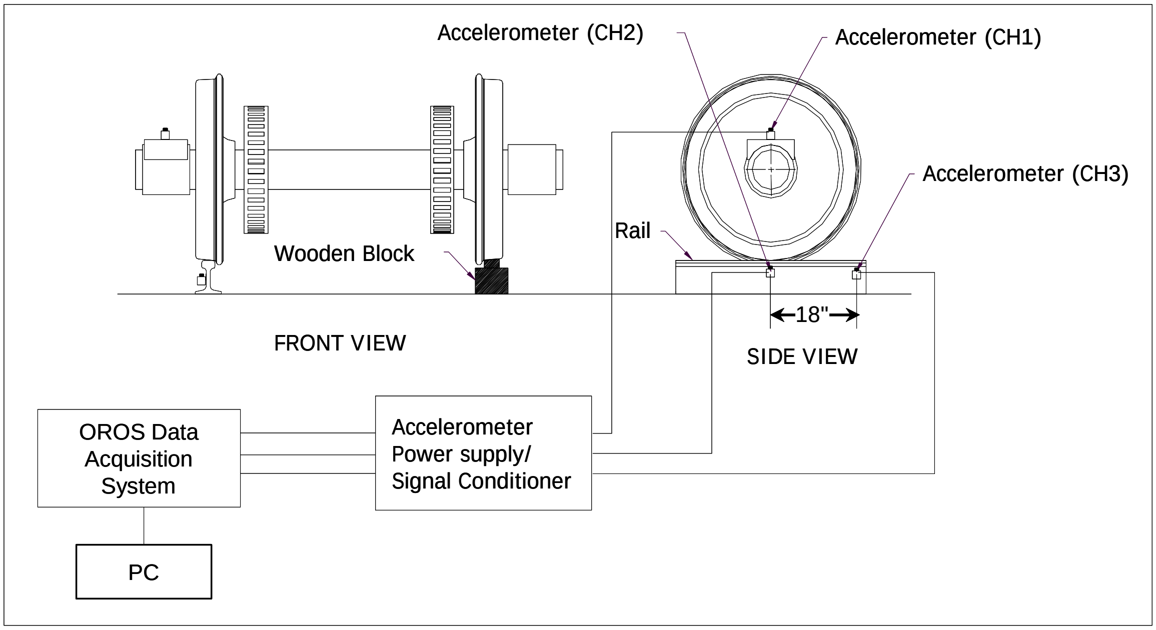



**FIGURE 1 Diagram of lab test instrumentation.**

### 2.3.3 Laboratory Test Results

To characterize the vibration signals measured in the test wheel set, the acceleration data collected in each test run was processed using a Fast Fourier Transform (FFT) to determine the frequency content of each signal. However, prior to performing FFT analysis, each signal was filtered and reduced to only look at the time window with acceptable consistency in the data. A 4$^{th}$ order high-pass Butterworth filter was applied to the raw signal to remove an offset resulting from DC components in the acceleration measurements. A sample of the filtered acceleration time history is shown in Figure 2. The specific impulses for each hammer strike were very clear and separated in time by about 0.03 seconds. The frequency content of the time signatures ranging from 0 to 500 Hz was examined solely due to the sensor's performance specification.

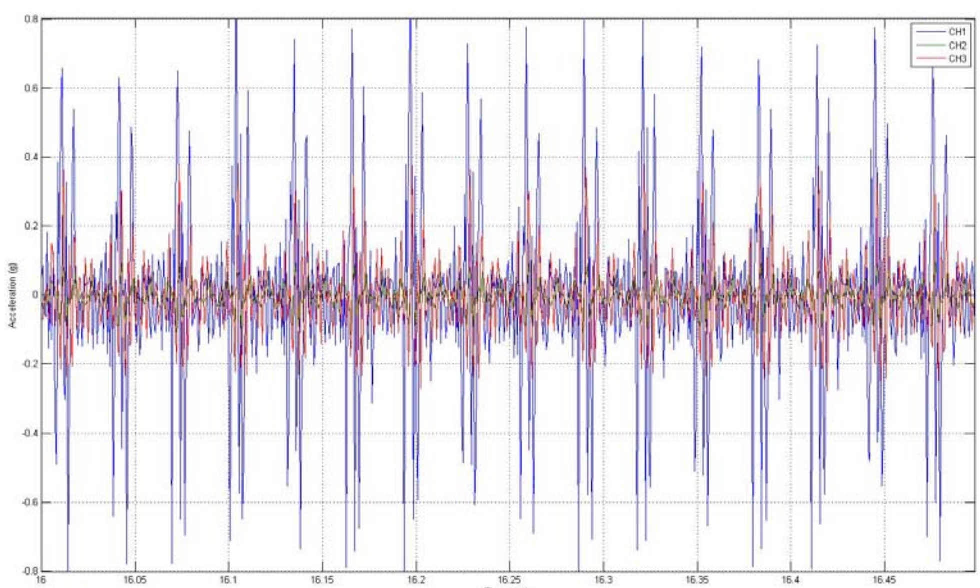



**FIGURE 2 Sample acceleration time history with DC offset removed.**

The procedure was applied to data collected from all three channels. The channel designation was as follows:

- Channel 1 - vibration acceleration measured on the bearing adapter;
- Channel 2 - vibration acceleration measured on the rail directly underneath the wheel/rail contact point; and
- Channel 3 - vibration acceleration measured on the rail 18" away from the contact patch.

Vibration acceleration data were collected for three sensor orientations: vertical, lateral and longitudinal. The lateral and longitudinal signals showed the same frequency patterns but were of lower amplitudes, as expected. The following summarizes the data results for the vertical direction only.

The time histories of the acceleration signals in the vertical direction from channel 1 are given in Figure 3. The time histories of channels 2 and 3 showed a similar pattern as that for channel 1 but with smaller amplitudes. The corresponding frequency spectra for all three channels are given in Figure 4. Based on the spectra, dominant peaks were detected at 34 Hz and its harmonics in all three channels. This was consistent with the hammer impulse time separation of 0.03 seconds. Amplitudes of the peaks were greatest on the bearing adapter (channel 1). The values from channels 2 and 3 indicated that acceleration was relatively lower but similar to each other.

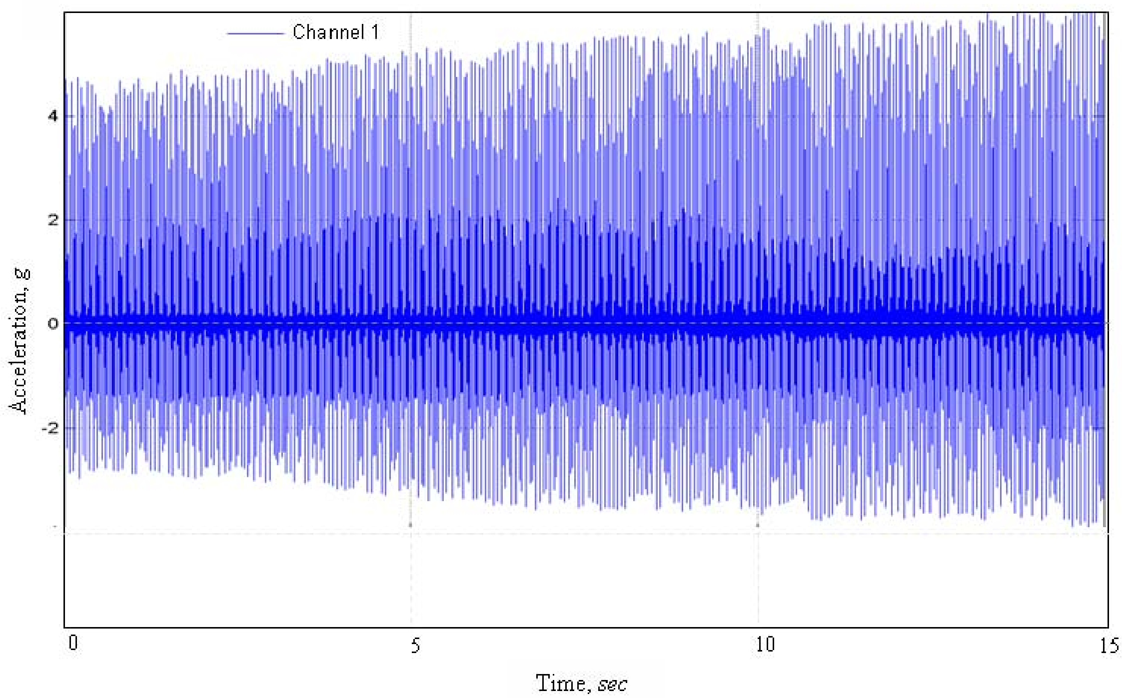



**FIGURE 3 Vertical acceleration time history.**

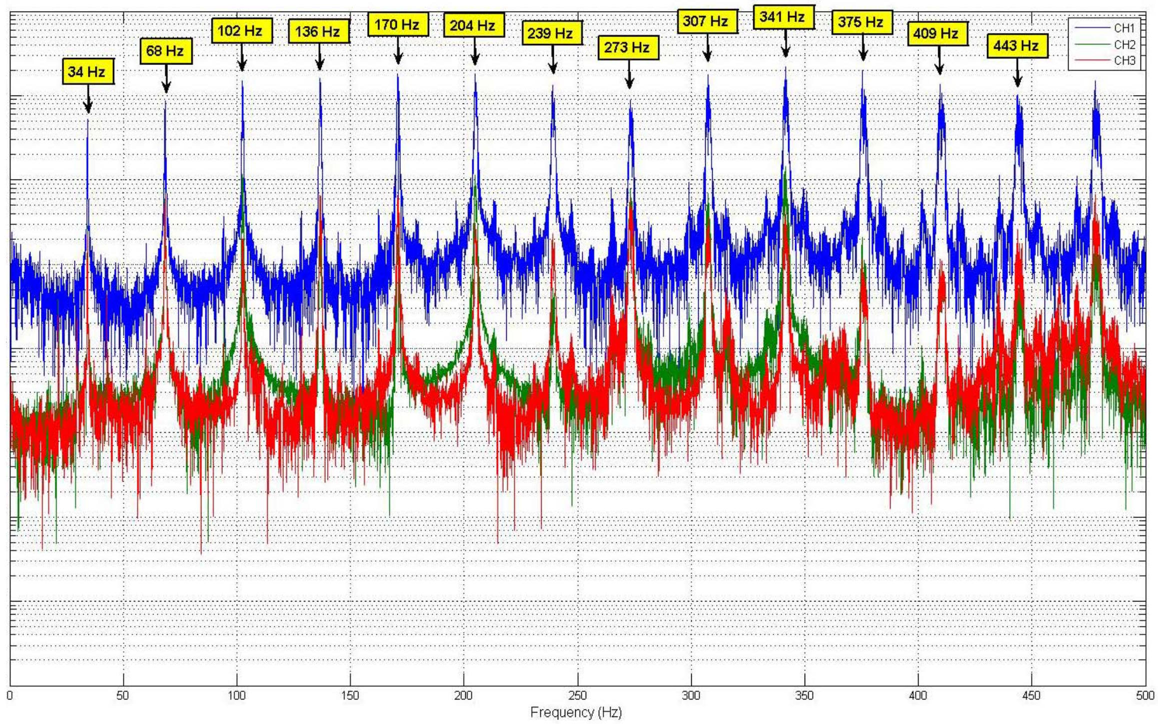



**FIGURE 4 Vertical acceleration frequency spectrum.**

**Need brief paragraph on whether and how lab test results met 3 test objectives.**

# 3 FIELD TESTS

## 3.1 SETUP OF TEST SYSTEM

### 3.1.1 Overall System Design

A test plan was developed in the first stage of the project. According to that plan, a freight car with a pre-identified defective bearing would be used. The bearing would preferably be a "growler" which is defined as a bearing with multiple large spalls on the outrace, or the cup of the bearing. The car would be heavily loaded if not loaded to its full capacity. A locomotive would haul the test car over a section of CWR track at speeds ranging from 10 to 35 mph.

Due to unforeseeable circumstances, the plan had to be changed significantly. A new test site was secured. However, the available test track was a Class 1 jointed-rail track with a speed limit of 10 mph. This was a significant decrease from the originally planned test speeds. In addition, the rental test car was an empty box car that could not be loaded due the logistical limitations. These changes posed additional challenges to the technology. Because signal strength is proportional to the car weight and to the square of the car speed, these changes would result in much weaker bearing signals than signals produced under a higher speed and heavier load.

The overall test set up was finalized as shown in Figure 5. The test system included the following components:

- The box car fitted with a known defective bearing on the axle at "A" end
- The locomotive with its short-hood coupled to the "A" end of the box car
- Three high frequency accelerometers on the rail that the defective bearing traverses
- Two high frequency accelerometers installed on the test car's "A" end truck at the bearing adapters, one for the defective bearing and the other for the control bearing
- Two data acquisition units, one onboard the hauling locomotive and the other at trackside

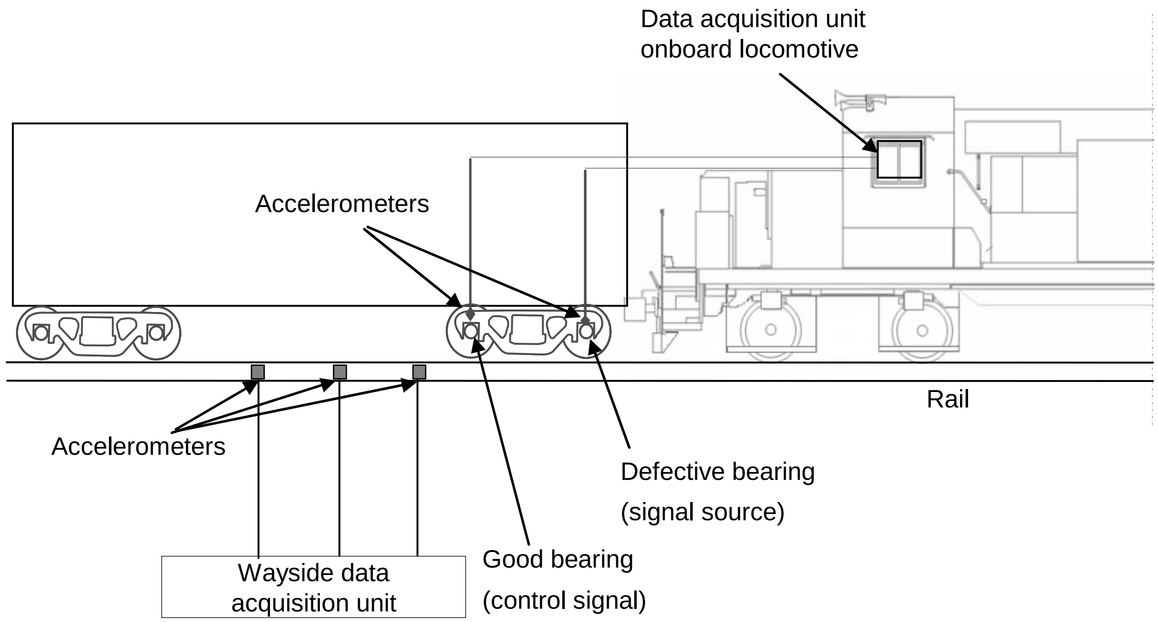



**FIGURE 5 Overall test setup.**

Three accelerometers would be mounted on one of the rails at the selected test site. A test car with a "growler" bearing would be instrumented with two accelerometers. One accelerometer would be installed at the closest point possible to the "growler" bearing housing. Another accelerometer would be installed at a good bearing as a control signal source. A locomotive would haul the test car at different speeds passing the test site. Two data collection units would be used, one onboard the locomotive and the other at trackside to collect bearing vibration signals at both the source and on the rail. The data would then be analyzed to establish the transmissibility of the signals.

### 3.1.2 Accelerometers

Five broadband accelerometers (1-20 kHz) with adjustable preamps were used for the test. Three accelerometers were installed at predetermined spacing on one of the rails of sufficient length allowing continuous transmission of vibration signals.

### 3.1.3 Multi-channel Data Collection Unit

Two multiple digital data collection units were rented. One unit had 8 channels and the other had 32. Both units could accommodate a sampling rate up to 50 kHz. The data storage limits were more than sufficient for the tests because the data were logged directly to the hard disk of the computers connected to the units.

### 3.1.4 Test Equipment Set Up

Arrangements were made with Gettysburg & Northern Railroad to provide the test track and a box car for the field tests. Gettysburg & Northern Railroad also provided a locomotive and crew to haul the test car. The steps for equipment setup were as follows:

- Have a moveable test car and test track available for up to one week for the tests
- Gather the defective bearing data from TADS for comparison analysis
- Install three (3) accelerometers at the selected track site
- Install the fourth accelerometer near the defective bearing
- Install the fifth accelerometer at a good bearing
- Have a locomotive available to haul the test car over the test site at specified speeds

### 3.1.5 Power Supply

A portable car inverter was used for the wayside data collection unit system. Two UPS packages were used to power the onboard data collection system.

## 3.2 TEST MATRIX

To test different scenarios for a thorough evaluation of bearing signals, a test matrix was designed. The wheel/rail contact band would be modified by fine sands, to simulate scenarios of contaminations. The tests were designed for different speeds based on the consideration that the defective bearing signal strength, contact patch conditions, and background noise would vary with speed. The maximum test speed in this matrix was 15 mph. Because the Gettysburg & Northern Railroad offered exclusive use of the test track for the entire test period, multiple test runs could be conducted within a limited track window. A total of 20 test runs were designed as shown in Table 2.

TABLE 2 Test Matrix

| Run Number | Vehicle Speed, mph | Rail Condition | Direction |
|---|---|---|---|
| 1a | 7 | Dry, Clean | North |
| 1b | 7 | Dry, Clean | South |
| 2a | 10 | Dry, Clean | North |
| 2b | 10 | Dry, Clean | South |
| 3a | 12.5 | Dry, Clean | North |
| 3b | 12.5 | Dry, Clean | South |
| 4a | 15 | Dry, Clean | North |
| 4b | 15 | Dry, Clean | South |
| 5a | 12.5 | Dry, Sand | North |
| 5b | 12.5 | Dry, Sand | South |
| 6a | 15 | Dry, Sand | North |
| 6b | 15 | Dry, Sand | South |
| 7a | 10 | Dry, Clean | North |
| 7b | 10 | Dry, Clean | South |
| 8a | 12.5 | Dry, Clean | North |
| 8b | 12.5 | Dry, Clean | South |
| 9a | 15 | Dry, Clean | North |
| 9b | 15 | Dry, Clean | South |
| 10a | 12.5 | Dry, Sand | North |
| 10b | 12.5 | Dry, Sand | South |

## 3.3 TEST SITE

The test site was on Gettysburg & Northern Railroad, in Aspers, Pennsylvania. The test track was north-south oriented, class 1 jointed track with a speed limit of 10 mph. The detailed test site layout is shown in Figure 6. The instrumented rail was close to a crossing for easy access to set up wayside equipment and a mobile power supply. For the first few test runs, the road crossing was used as the northern end start/stop point. The start/stop point was changed by one rail length to the north for the later runs. The two start/stop points were 85.5 feet apart, giving sufficient time for the data collection equipment to be initialized to capture the defective bearing signals while the wheel traverses the rail instrumented with accelerometers.

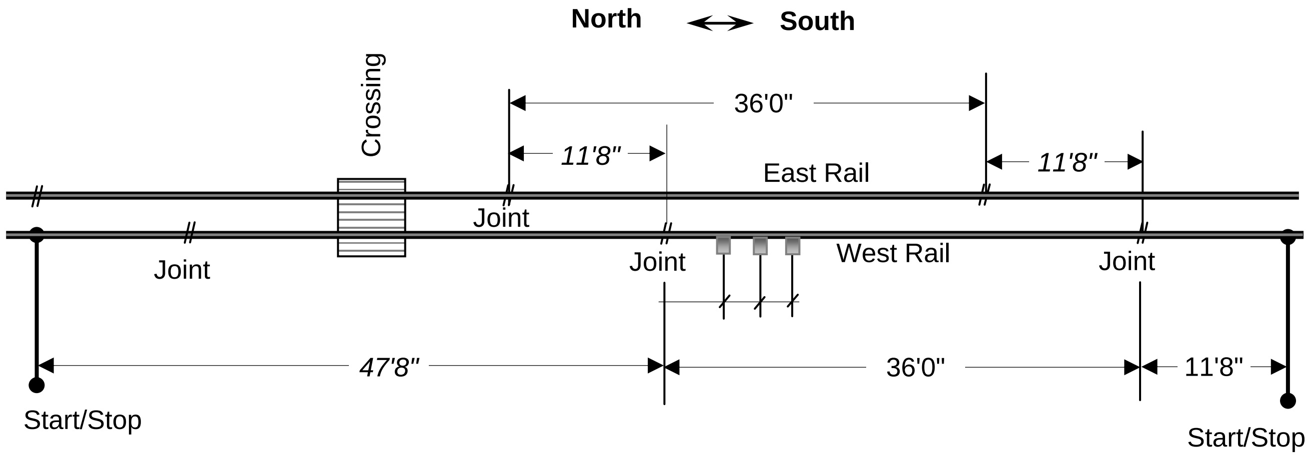



**FIGURE 6  Test site layout.**

Three high-frequency accelerometers were affixed to the west rail, designated as channels 1, 2 and 3 from north to south (Figure 7). The first accelerometer was approximately 70" from the closest joint to the north, and the three accelerometers were 32" apart.

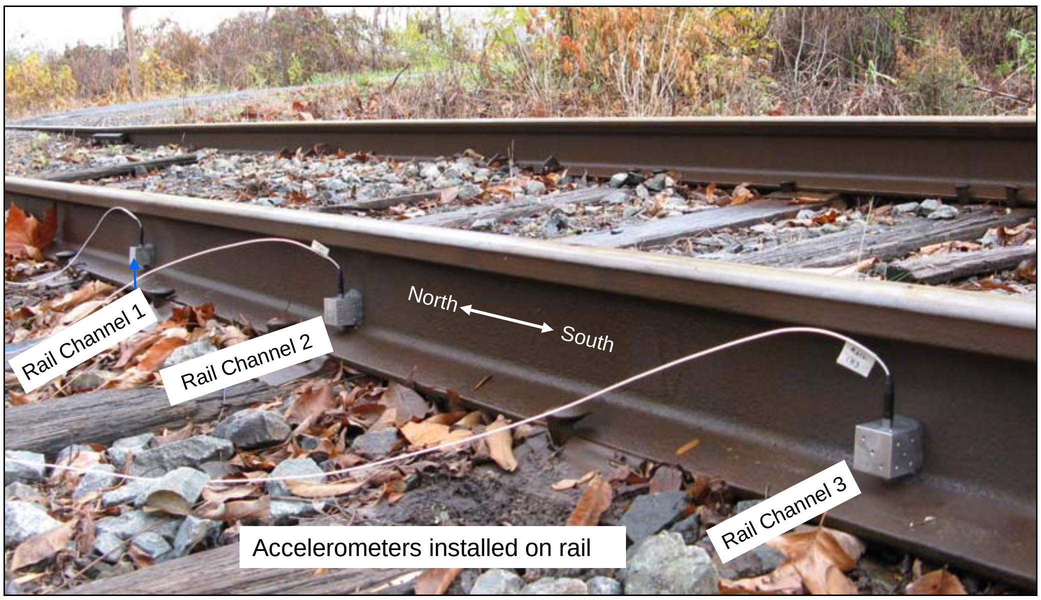



**FIGURE 7  Sensor locations.**

## 3.4 TEST EQUIPMENT

### 3.4.1 Test Car

A rental box car from Pioneer Railroad was used for the tests. The car had the following specifications:

| | |
|---|---|
| Empty weight | 70,500 lb **(actual weight)** |
| Length | 50'7" |
| Truck wheelbase | 5'9" |
| Wheel Diameter | 32" |
| Bearing class | E6 x 11 |

A wheel set with a known defective bearing was provided by the Norfolk Southern Railway (NS). It was from an in-service, 70-ton hopper car. The wheel set was mounted on the truck at the "A" end of the box car. Two accelerometers were installed on the truck, one for the defective bearing and the other for the control bearing. In order to collect good quality data, the accelerometers were installed on the bearing adapters which were the nearest locations possible to the bearings. The installation is shown in Figure 8. Channel 1 was on the defective bearing at the "A" end or southern end of the car during the tests. Channel 2 was on the control bearing.

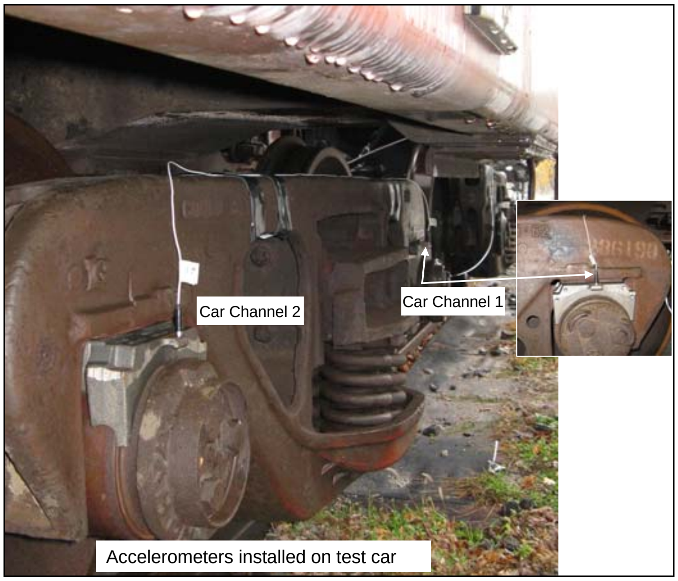



**FIGURE 8 Two accelerometers installed on bearing adapters.**

### 3.4.2 The Defective Bearing

The defective bearing contained in the wheel set provided by NS was a class E roller bearing. Its specifications are given in Table 3.

TABLE 3 Bearing Specifications

| | |
|---|---|
| Size, inches | E 6 x 11 |
| Roller Diameter, $B_d$, inches | 0.7047 |
| Pitch Diameter, $P_d$, inches | 7.031 |
| Contact Angle, $\alpha$, degrees | 10 |
| Number of rollers, N | 24 |
| Standard wheel diameter, inches | 32" |

Before the wheel set was removed, the loaded hopper car passed the TADS site five times from 10/27/2006 to 09/16/2007. NS and TTCI provided the time history on the bearing when it passed the TADS site. Of the 5 passes, the bearing was identified to have a cup defect three times. It was identified as a growler on 09/02/2007. On 8/21/2007 no defect was detected. It should be noted that TADS was not designed to catch every defect each time the bearing passes the TADS site, because the defect may not be in the loading zone when it passes the TADS detection window. The average speed of the car passing the TADS site was approximately 40 mph. The five passes are summarized in Table 4.

TABLE 4 Five Passes of Defective Bearing Through TADS Site

| Date/Time | Axle ID | Car Speed | Defective Type | $F_{cup\_t}$ | $F_{cup\_c}$ |
|---|---|---|---|---|---|
| 9/16/2007 7:40 | 077 | 38.9 | Cup defect | 73.66 | 72.6 |
| 9/2/2007 16:45 | 400 | 38.4 | Growler | 72.71 | 71.68 |
| 8/21/2007 12:22 | 056 | 36.6 | no defect shown | 69.30 | none |
| 11/5/2006 22:36 | 216 | 43.2 | Cup defect | 81.80 | 80.68 |
| 10/27/2006 1:38 | 423 | 40.1 | Cup defect | 75.93 | 74.28 |

Using the bearing parameters in Table 3 and the car speed data in Table 4, the theoretical cup defect frequency can be calculated using the following equation:

$$F_{cup} = \frac{F_w N}{2}\left(1 - \frac{B_d}{P_d}\cos\alpha\right)$$

Where

$F_w$ = wheel rotational speed, which can be determined with known train speed and wheel size
N = number of rolling elements
$P_d$ = pitch diameter, inches,
$B_d$ = rolling element diameter, inches
N = number of rollers in bearing
$\alpha$ = Angle between the roller's spin axis and the rotation axis of the bearing

The calculated results for the five passes are given in the fifth column in Table 4. A Fast Fourier Transfer and envelope detection were applied to the time history data to confirm the bearing defects. The detection frequencies from the analysis are shown in the far right column of Table 4. These results confirmed that the bearing defect was present as identified by the TADS system. Figure 9 shows the power spectral density (PSD) for the pass on 10/27/2006 when it was identified to have a cup defect. **[Explain significance of circles.]** The detecting frequency is 74.28 Hz. It should be noted that the car speed was 40.1 mph when the defective bearing passed the TADS site. That speed is 3 times higher than the test speed in this project. The speed factor alone can result in approximately a 9-times difference in the bearing signal power, as the power is proportional to the square of the speed.

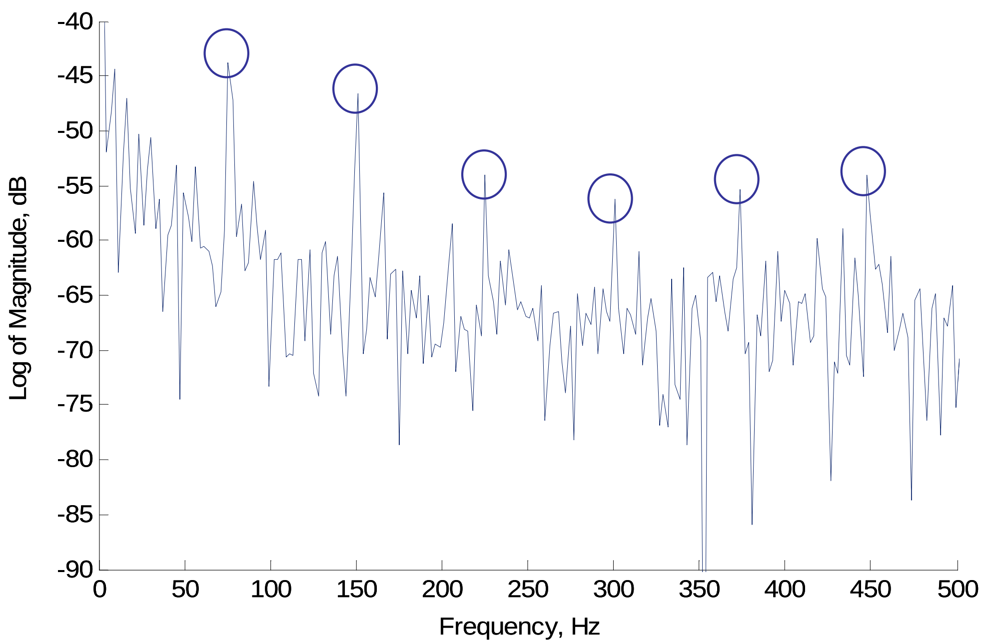



**FIGURE 9 Enveloped PSD plot for TADS data for the pass of 10/27/2006.**

#### 3.4.3 Wayside Data Collection System

The wayside data collection unit was an OROS 16-channel data collection unit with specialized software for real time and post data analysis. Only three channels were utilized for this project. The data collection unit was connected to a laptop computer which was loaded with specialized OROS software for data collection and analysis. Figure 10 shows the wayside data collection system set up.

**FIGURE 10 Wayside data collection system.**

### 3.4.4 Test Consist and Onboard Data Collection System

The test car was hauled by a GP10 diesel locomotive. The onboard test equipment, which was similar to the wayside system, was located in the locomotive cab. The onboard data collection system had the same configuration as the wayside system. The unit, as well as the laptop computer, was powered by a UPS unit for the entire test duration. The locomotive's short-hood end was attached to the "A" end (southern end) of the test car to minimize the cable length. Figure 11 shows a diagram of the test consist.

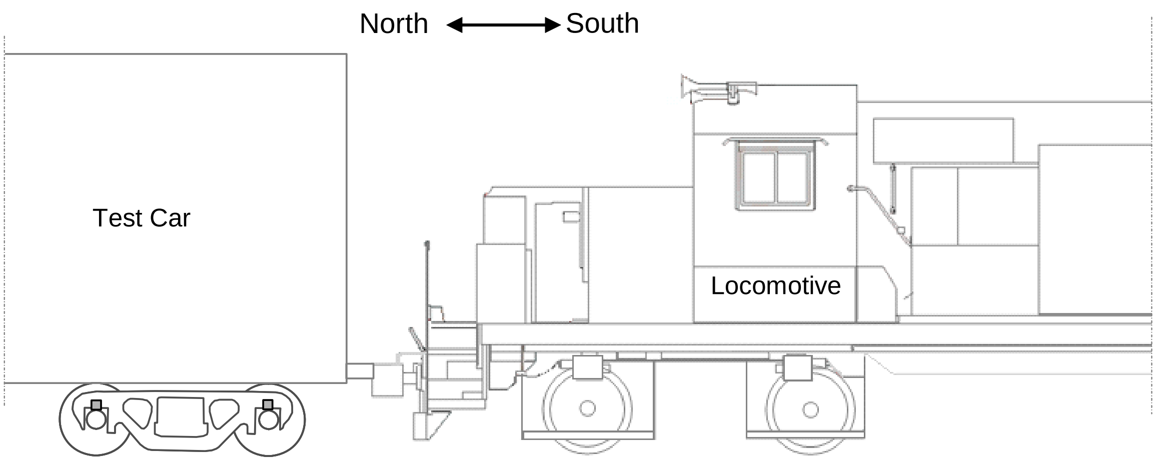



**FIGURE 11 Test consist.**

## 3.5 TEST RUNS

All data collection equipment was tested in the laboratory prior to the field tests. The field tests were conducted on 11/20/2007. Each test run started northbound. The onboard and wayside data collection units were started and stopped at the same time when the defective bearing reached the start/stop points (as depicted in Figure 6).

It was raining early on the test day but stopped after the first two test runs. This provided a wet condition for the first two runs. However, wet rail may not be a factor that affects the transmission of bearing signals. The first wheel passing the sensor location will propel rain water out of the rail/wheel contact band.

For test run numbers 9 and 12, the rail with accelerometers was spread with fine sand to modify the contact condition. Due to logistical limitations and the scope of the project, other contamination scenarios were not attempted.

Although the test matrix was designed for speeds up to 15 mph, only for a short segment of test run number 6 did the speed actually reach 15 mph. First, the legal speed limit on the test track is 10 mph. Second, the speedometer on the locomotive was broken. The engineer had to estimate the speeds. This should not pose a problem for data analysis since the car speed can be determined using the rail joints. When the wheels hit the joints, the accelerometers received very strong and distinguishable signals. The length of the rails over the test section was measured as part of the test procedure. The car speed can be **(was)** determined based on these measurements.

During the allocated 6-hour track window, 22 test runs were conducted. The completed test runs are shown in Table 5. These runs vary slightly from those listed in Table 3 (**Table 3 is bearing specs)**. Because at low speed the signals are weak, the tests started with a high test speed **(Which runs were these and what were the speeds?)**. The speeds listed in Table 4 **(Table 4 is for TADS site?)** are indicative of the designed testing speeds that the driver **(**should ?**) (Was asked to approximate?)** follow. The actual speeds **differed** and **were** determined in the data analysis process. **This paragraph needs to be rewritten. Table 5 should include a column for actual (calculated) speed**

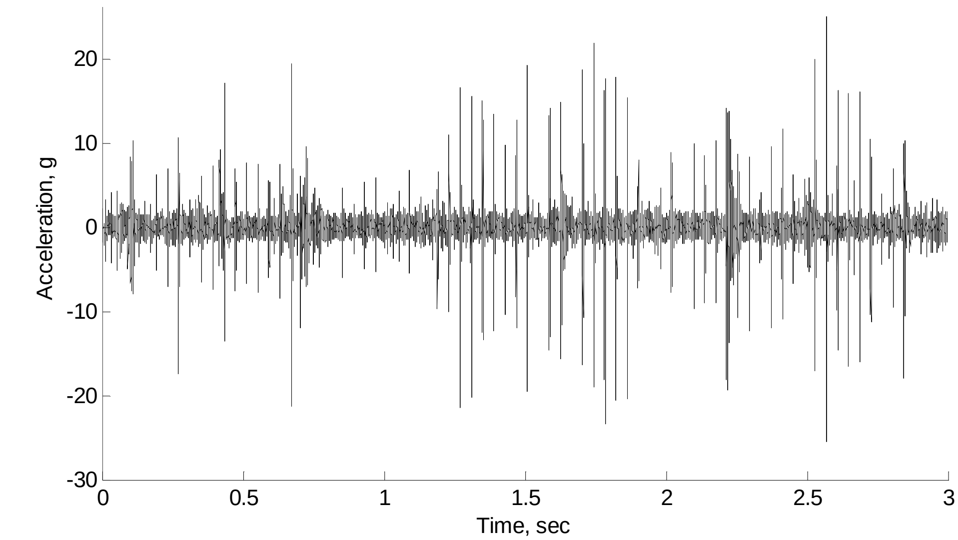
TABLE 5 Completed Test Runs

| Run Number | Run ID | Indicative Speed, mph | Direction | Rail Condition |
|---|---|---|---|---|
| 1 | 2a | 10 | North | Wet, Clean |
| 2 | 2b | 10 | South | Wet, Clean |
| 3 | 3a | 12.5 | North | Dry, Clean |
| 4 | 3b | 12.5 | South | Dry, Clean |
| 5 | 4a | 15 | North | Dry, Clean |
| 6 | 4b | 15 | South | Dry, Clean |
| 7 | 4a2 | 15 | North | Dry, Sand |
| 8 | 4b2 | 15 | South | Dry, Sand |
| 9 | 5a | 12.5 | North | Dry, Sand |
| 10 | 5b | 12.5 | South | Dry, Sand |
| 11 | 5a2 | 12.5 | North | Dry, Clean |
| 12 | 5b2 | 12.5 | South | Dry, Clean |
| 13 | 2a | 10 | North | Dry, Clean |
| 14 | 2b | 10 | South | Dry, Clean |
| 15 | 3a | 12.5 | North | Dry, Clean |
| 16 | 3b | 12.5 | South | Dry, Clean |
| 17 | 10a | 12.5 | North | Dry, Sand |
| 18 | 10b | 12.5 | South | Dry, Sand |
| 19 | 13a* | 12.5 | North | Dry, Clean |
| 20 | 13b* | 12.5 | South | Dry, Clean |
| 21 | 14a* | 15 | North | Dry, Clean |
| 22 | 14b* | 15 | South | Dry, Clean |

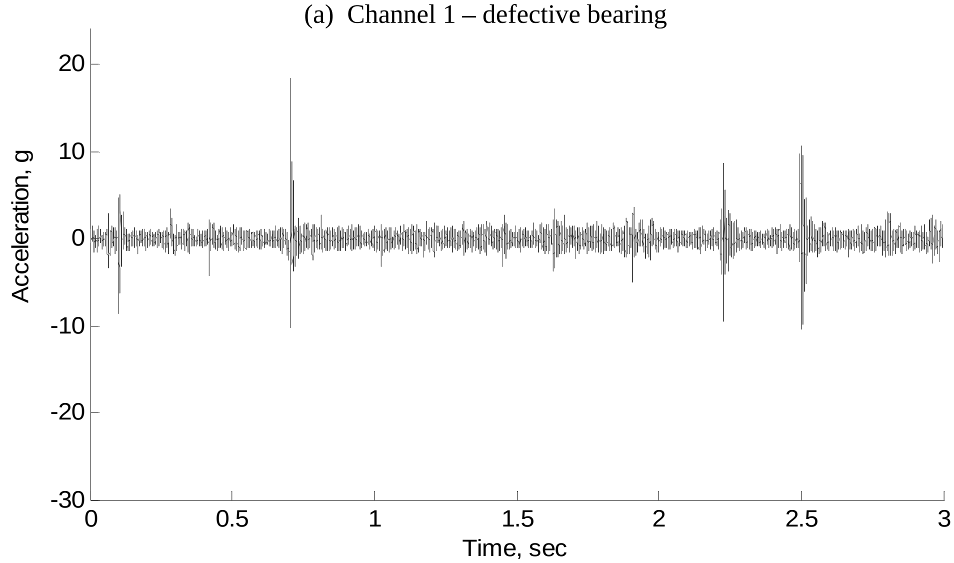
* Consolidation runs, during which wayside channel 2 was off the rail.

### 3.6 SAMPLE DATA AND PRELIMINARY EVALUATION

Preliminary examination of the test data indicated that all test runs were valid. However, due to a computer software glitch that was not discovered until test run number 18, the onboard data collection system might have missed some acceleration peaks. After the system was re-configured, four extra **consolidation runs (explain-are these runs for which wayside channel 2 was not used? I thought you only used 1 wayside channel anyway, once you determined that all 3 accelerometers were reading the same. The purpose/concept of the consolidation runs needs to be explained )**were conducted. The data from these consolidation runs would be sufficient for comparison analyses. Figure 12 shows a sample of data from the onboard system for test run number 20. The top figure represents the defective bearing signals and the bottom figure represents the control bearing signals. The two time-history traces differ significantly. It is clear that defective bearing signals were captured by the accelerometer on the defective bearing adapter. The periodic impulses caused by the bearing rollers contacting the defect on the cup are very strong.




(a) Channel 1 – defective bearing




(b) Channel 2 – control bearing

**FIGURE 12 Sample time history from onboard data collection system for test run #20.**

Figure 13 shows a sample of time history for channel 3 of the wayside data collection system for the same test run. The sample data represent 2 seconds of time history. Note that the scale is different from that of Figure 12 since the wayside signals are weak and would not display on the same scale. The defective bearing signals are not obvious in the time history, as expected. Several of the spikes are the lines created when the wheels of the locomotive or the test car hit one of the joints of the instrumented rail. The data are not aligned with the onboard data. The detailed analyses of both the onboard and wayside data later will reveal how the two sets of data are correlated.

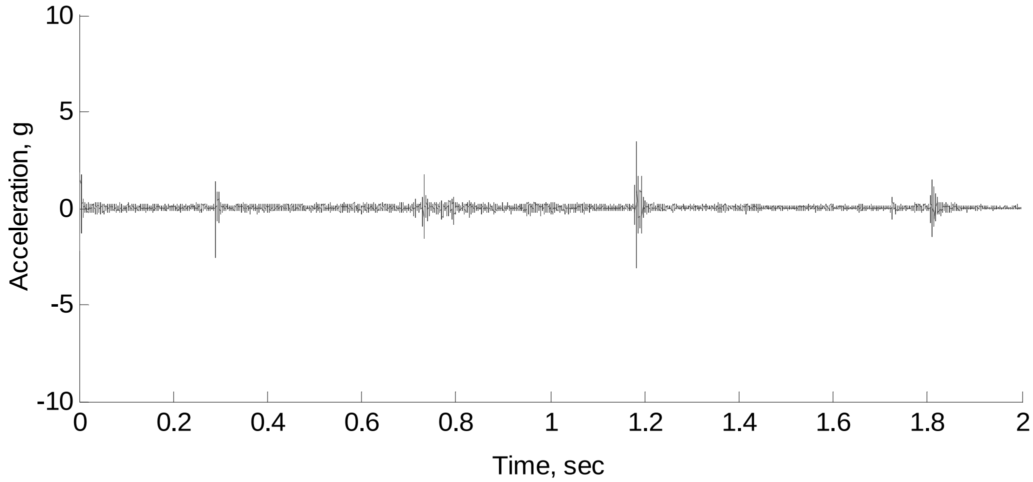



**FIGURE 13 Sample time history from wayside data collection system for test run #20.**

To verify that the data is valid, a quick Fast Fourier Transfer (FFT) analysis was done for both the onboard and wayside data. The PSD plot for the onboard data from the same test run is shown in Figure 14. **(Figure 14 not legible in black & white. Would different colors help?)** The lighter **(orange?)** trace is for the defective bearing and the darker **(green?)** trace is for the control bearing. It clearly indicates that the channel for the defective bearing has stronger power at frequency ranges between 8 – 10 kHz and between 12 – 14 kHz.

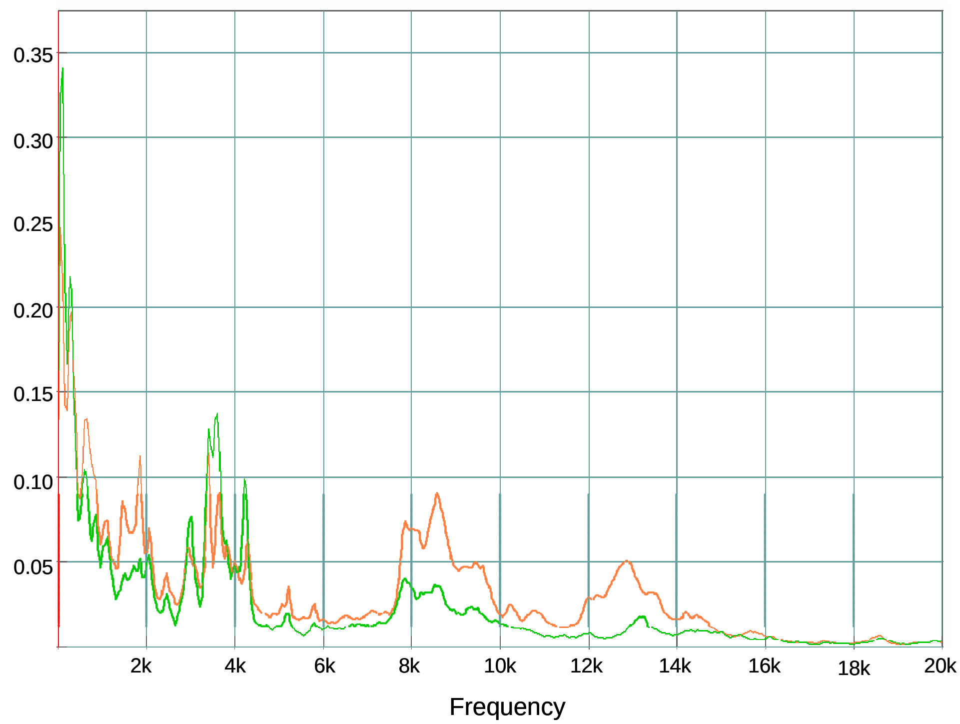



**FIGURE 14 PSD plot for onboard data.**

The PSD for the wayside data is given in Figure 15. **( Only one trace). Is this for the defective or control bearing? Can you show both? Use different colors?** It also shows high power concentration at 8 – 10 kHz and around 12 kHz. Without in depth investigation, this would appear to be an indication that the bearing behavior has been detected by the accelerometers on the rail. However, more thorough analyses, **to be described later,** will reveal that the defective bearing is not a sole contributing factor to the power concentration.

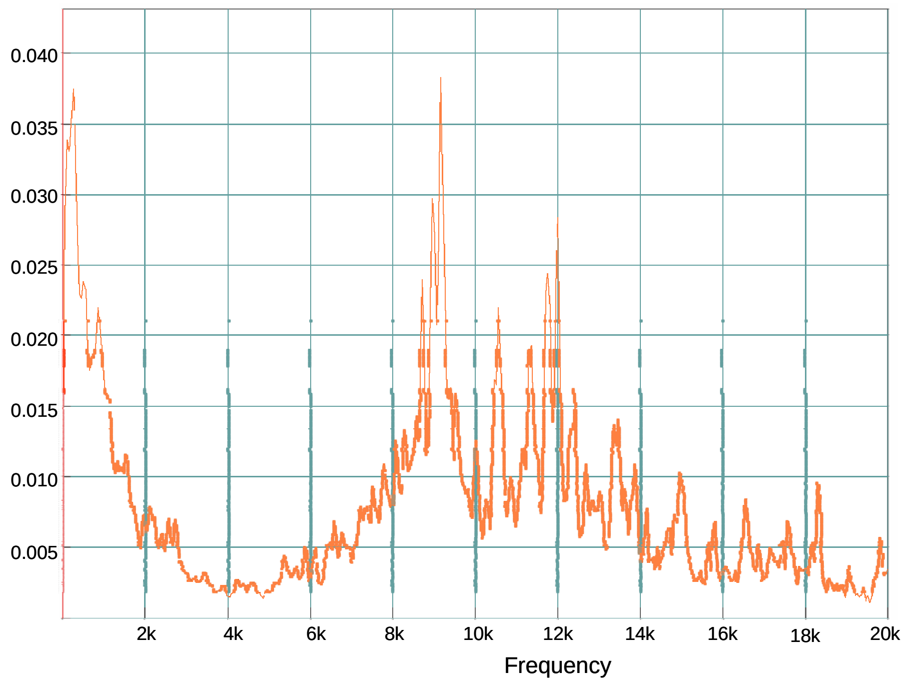



**FIGURE 15  PSD plot for wayside data.**

# 4. DATA ANALYSES

## 4.1 DATA ANALYSIS APPROACH

It is well known that for rolling element bearings, the most effective method for detecting bearing defects is high frequency (HF) vibration envelope detection. When a bearing defect is present, each of the rolling elements will sequentially impact the defect as the shaft and the bearing cage rotate. These sharp impacts result in a periodic excitement of the local bearing mechanical resonances. This includes the HF resonances of the bearing inner or outer races. The magnitude, and hence the detectability, of the HF vibration levels will depend on many factors including the force or weight on the bearing and the shaft rotation speed. The first step of envelope detection is high-passing the raw vibration data to retain only the HF components. The next step is to envelop the data by rectifying and low-passing the data. And finally, it involves estimation of the power spectrum by FFT spectral analysis. A defect will reveal its presence by a strong spectral component at the ball **( roller)** passing, or impact, frequency and its harmonics.

In order to prove that the bearing defect vibration is transmitted through the wheel to the tracks, the above analysis procedure was applied to the data collected during the field test. This consisted primarily of using this HF envelope detection method to detect a bearing defect in both the wayside data and the onboard data. It was expected that the onboard data would easily yield very strong detection results which would help identify the defect from the wayside data. In particular, the frequency of the bearing defect line from the wayside data will be identical to the defect frequency component from the onboard data.

## 4.2 ONBOARD DATA ANALYSIS

A band-pass filter, with a pass frequency range of 8 -13 kHz was used to filter the onboard data. The PSDs for both the defective bearing and the control channels were computed. The envelope detection technique was then used to demodulate the defective bearing signals.

When analyzing the onboard data, it is not critical which segment of time history data is used since the accelerometer always follows the bearing signals. However, the dominant frequency will vary slightly depending on which segment of data is analyzed, since the test car may not have traveled at a constant speed for the entire data collection period. Therefore, the segment that contained the time when the defective bearing was on the instrumented rail was cropped for analysis. This provided a reference for wayside data analysis. For onboard channel 1 data from test run number 20, the bearing signals are visible in the time history (as shown previously in Figure 12 (a)).

The bearing signal line became even clearer after the band-pass filtering and envelope detection. Figure 16 shows the enveloped PSD for the same data segment. **(Replace all channel 1 with defective bearing, including in title for Fig. 16)** It clearly depicts a cup defect with a characteristic frequency of approximately 25.67 Hz. Note that the harmonics are not exact multiples of 25.67 but are within the resolution (about 1/3 Hz) for the data segment analyzed.

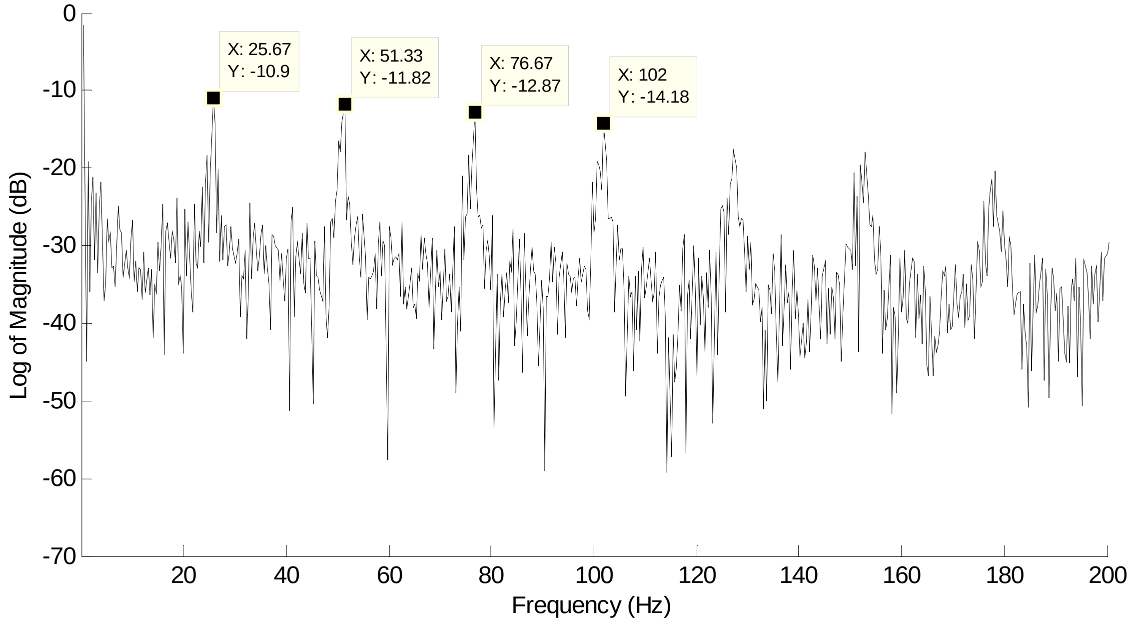
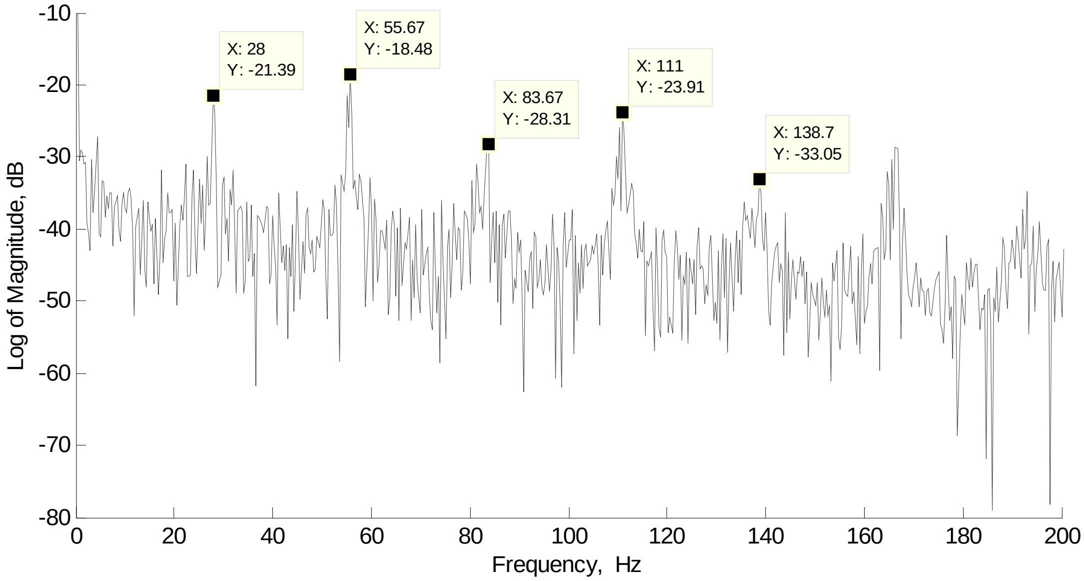
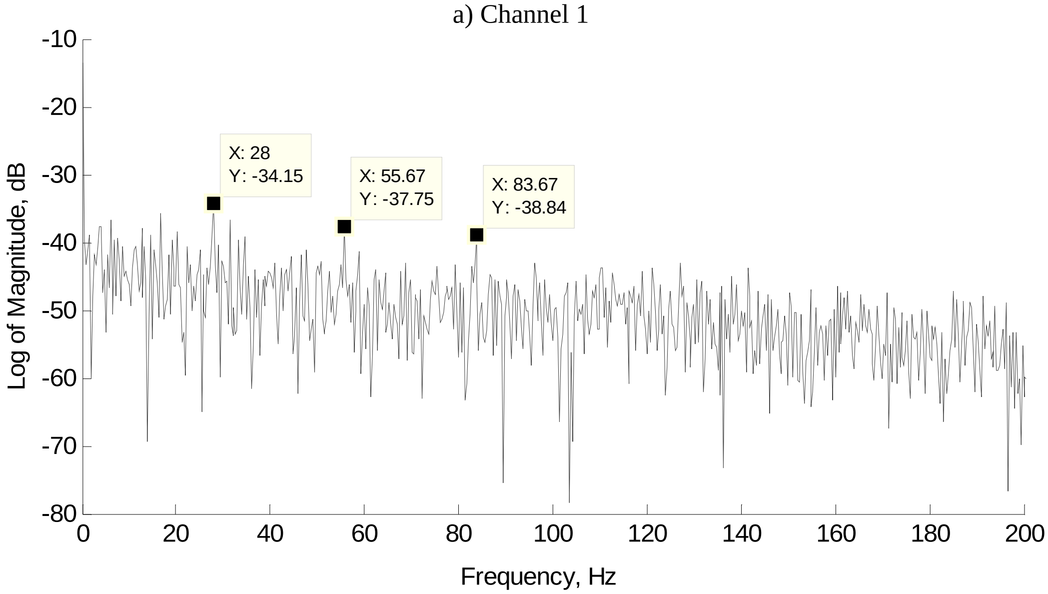



**FIGURE 16 PSD for channel 1 of onboard data for test run 20.**

Effort was also made to analyze if the bearing signals could be cross-transmitted to the adjacent axle. This was done by examining channel 2 of the onboard data which was measured from the control bearing on the adjacent axle. From analyses of channel 1 data, it was found that at 8 – 10 kHz the defective bearing signals have the highest power, although the signals show up in all frequencies up to 20 kHz. A narrower bandwidth with a pass band of 8 – 9.5 kHz was used to filter the control bearing (channel 2) data. Only in test run number 8 did the cross transmission seem visible. However, the power was significantly lower than that of channel 1. The PSD plots for both channels for this test run are shown in Figure 17. **(In titles for Figs 17 a and b, change channel 1 to defective bearing and channel 2 to control bearing.)**




a) Channel 1




b) Channel 2

**FIGURE 17 PSD for onboard data for test run number 8.**

## 4.3 WAYSIDE DATA ANALYSIS

The wayside data differed from the onboard data in several respects. The useful time history segment occurred when the wheel with the defective bearing traversed the rail with accelerometers. The rail joints generated huge spikes which fed directly into the data collection system. Defective bearing signals were**, as expected,** attenuated by the signal traveling path.

There were three wayside channels. Two of them were redundant for the purpose of this project. As expected, preliminary evaluation of the three channels revealed the same results. This also confirmed that the accelerometers performed consistently. Therefore, effort was concentrated on channel 3 in the subsequent analyses.

The first step was to identify the time segment when the defective bearing was above the accelerometers. In the test format, the joints were used to identify the wheel locations. When a wheel hit one of the two joints at either end of the instrumented rail, a sharp acceleration was recorded in the time history. With the known layout of the test site as shown in Figure 6 and the test consist as shown in Figure 11, the defective wheel location could be determined. Figure 18 shows the time history of test run number 8. The times of the defective bearing entering and leaving the instrumented rail were 2.8 and 4.57 seconds.

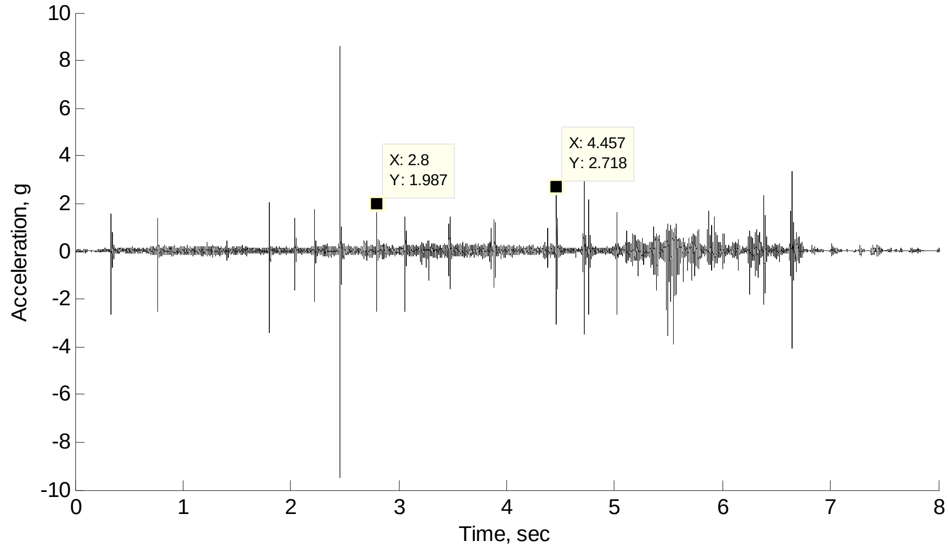



**FIGURE 18 Time history for channel 3 of wayside data from test run 8.**

For all test runs, the segment of time history when the defective bearing was on the instrumented rail was cropped for analysis. The same type of band-pass filter used for onboard analyses was applied to the cropped data, starting with a broadband width from 7.7 to 13 kHz. Envelope detection was then used to demodulate the bearing signals. The bandwidth was then gradually narrowed to 500 Hz and was used to slide through the frequencies from 7 kHz up to 20 kHz. This round of analyses did not produce very clear bearing signal lines in the PSD plots. There were some power concentrations in the vicinity of 8 kHz and 12 kHz. However, the powers seemed to be from many sources in addition to the defective bearing signals.

In the next round of analyses, the signals generated by the rail joint were clipped off from the cropped time history segments. The same analysis procedure was applied to the new data set. There were noticeable improvements in the results after envelope detection. More detailed analyses focused on test runs 6 and 20. The rail condition was dry and clean. Figure 19 shows the targeted time history for test run 20 before the joint spikes were clipped off.

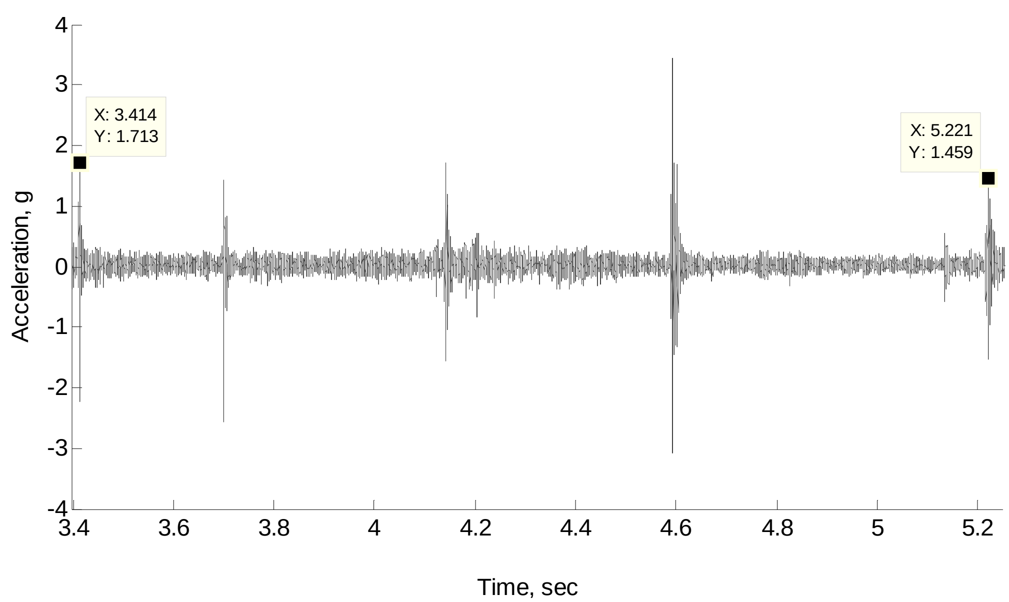



**FIGURE 19 Segment of time history for channel 3 of wayside data from test run 20.**

After the signals around the joints were clipped off, various bandwidths were tested. It was apparent that at frequency ranges of 11 and 11.5 kHz, the bearing signals were identifiable. The PSD after envelope detection is shown in Figure 20. The bearing signal lines detected by the onboard accelerometer (as seen in Figure 16) also appeared in the wayside channel. Although in this particular case the bearing signal is identifiable in the frequency range of 11 – 11.5 kHz, it may not necessarily mean that the bearing signals in this frequency range have the strongest power. It may indicate that the background noises in this frequency range are not sufficiently strong to completely mask the bearing signals.

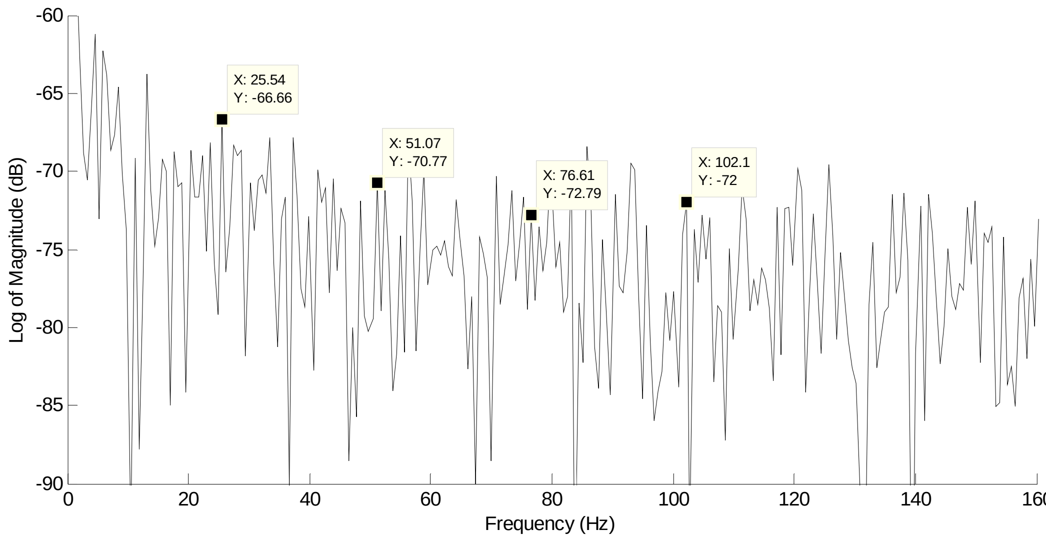
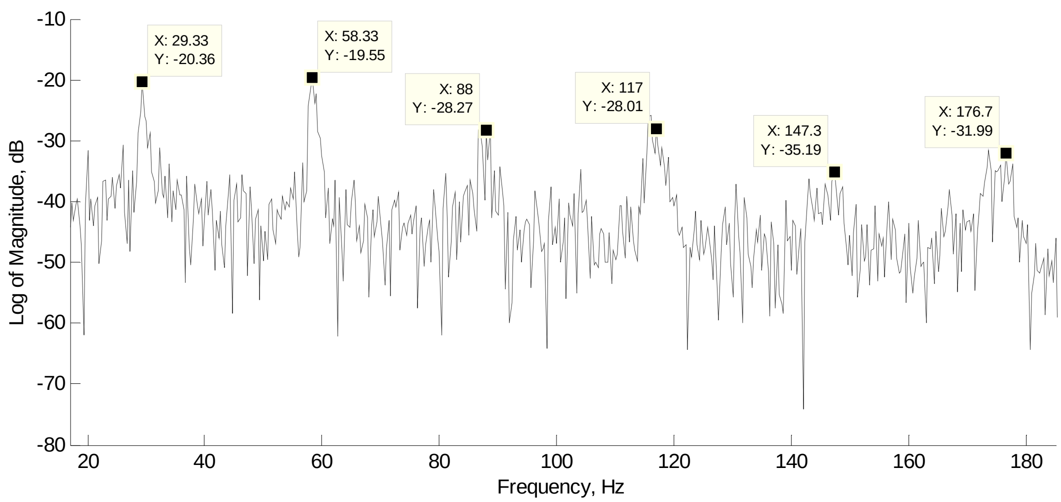
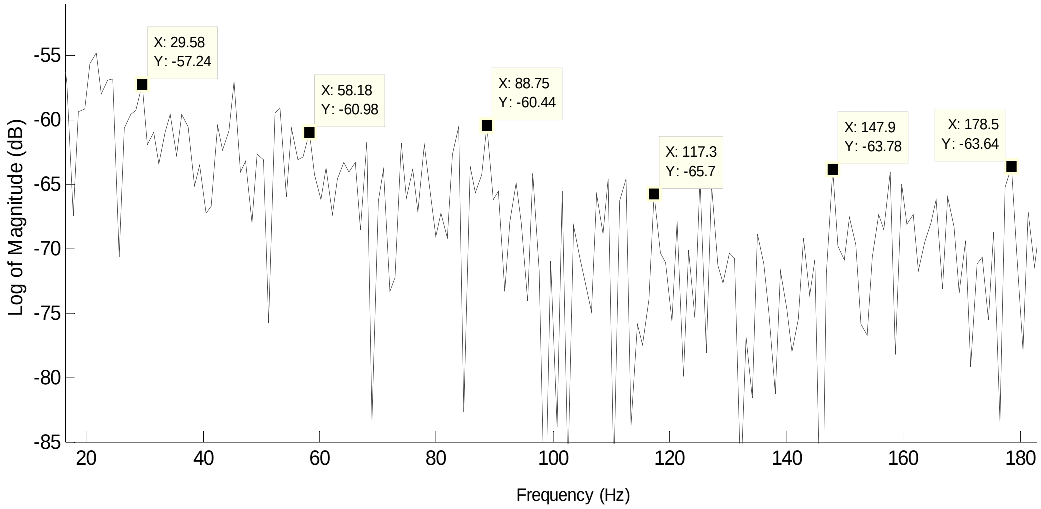



**FIGURE 20 Enveloped PSD for wayside data from test run 20.**

Similar analysis was performed for test run number 6. This test run happened to have the highest speed (15.2 mph) for the short moment when the defective wheel was on the instrumented rail. The PSD plots after envelope detection for both onboard data channel 1 and wayside data channel 3 are given in Figure 21 **(change channel 1 to defective bearing)**. In this test run the bearing signals are more distinguishable. This may indicate that the speed played a role in producing stronger bearing signals.




(a) Onboard channel 1




(b) Wayside channel 3

**FIGURE 21 Enveloped PSD for test run 6.**

The effect of **contaminated rail** conditions was not verifiable.**(?)** In four test runs, 9 through 12, the instrumented rail was spread with fine sands to modify contact conditions. The HF band-pass filtering and envelope detection for these runs <u>did not give clear bearing lines in the PSD plots</u>, <u>as with other test runs with clean rail conditions</u>. **(This suggests to me that the sand had an effect since, whenever it was used, no clear bearing lines were evident in the PSD plots.) It is not clear if sand contamination had additional adverse effects in masking bearing signals**. **(?) Are you concluding the sand had no effect?)**

Of course, there are many other factors which may affect the detectability of bearing signals. For example, wheel flats can generate sharp impacts in the detection zone. If it is a single flat in the wheel, the impact pulse rate will coincide with wheel rotation rate, which is much lower than a bearing defective frequency. Investigation of the effects of wheel flats and other factors is beyond the scope of this project.

## 5. CONCLUSIONS

This report described the effort to investigate the transmissibility of wheel bearing signals from the source to rail-mounted accelerometers. Laboratory tests successfully demonstrated that the signals were detectable by these accelerometers, barring background noises. Field tests and data analysis further proved that the bearing defect signals could be detected even in the worst-case scenario.

Although the field tests were limited to low speeds (below 15 mph), which greatly reduced the bearing defect noise and therefore significantly reduce the signal-to-noise ratio, the bearing defect signatures were still evident. Since distressed bearing noise increases with the square of speed, a doubling of the speed would be expected to yield up to a four-fold increase in the bearing defect noise signature. Also, due to last minute difficulties in obtaining access to the originally planned test site, this test had to be conducted on bolted rather than welded track with less than ideal surface conditions. On CWR track, the lower background noise is expected to improve the detectability of the defect signature.

**If further investigation of this concept is undertaken, additional tests** at higher speeds and heavier wheel loads with better track conditions, is recommended, **along with application of the full array of track sensors necessary for evaluating the full noise cancellation concept. (Again, what do you mean by a "full array of track sensors, and what is the full noise cancellation concept?** We would welcome any comments on the tests and the conclusions and any recommendations from the Advisory Panel.

## 6. REFERENCES

1. G. B. Anderson, J. E. Cline and R. L. Smith. Acoustic Detection of Roller Bering Defects: Phase II, Field Test. Report DOT/FRA/ORD-00/06.II.

2. G. B. Anderson, J. E. Cline and R. L. Smith. Acoustic Detection of Rail Car Roller Bering Defects: Phase III, System Evaluation Test. Report DOT/FRA/ORD-00/06.III.