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Safety IDEA Program

Rail Vehicle Bearing Defects Detection

Final Report for
Safety IDEA Project 16

Prepared by:
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October 2011

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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

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EXECUTIVE SUMMARY

The purpose of this Safety IDEA project was to conduct field testing to investigate the feasibility of detecting defective rail vehicle bearings using rail-mounted accelerometers. For decades, the railroad industry has continuously invested in technologies for monitoring and diagnosing rail bearing conditions and defects. The harsh railroad operating environments have made in-situ testing of rail bearings more challenging than testing of other industrial bearings.

The challenges for existing technologies include early detection, reliability and the cost of detection systems. Wayside hot box detectors are among widely used detection technologies. They use infrared technology to detect heat emitted from defective bearings. These sensors can detect bearings only in the direct line of sight, which limits their used for detecting inward bearings. Also they cannot catch the bearing defects until they have already developed to unacceptable levels.

Another technology is the Trackside Acoustic Detection System (TADS) developed by the Transportation Technology Center, Inc. (TTCI). This system is a joint effort between the Federal Railroad Administration (FRA) and the Association of American Railroads (AAR) to develop alternative wayside detection systems. The 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 still faces challenges in detecting defects in inward rollers and cones.

In 2007, ENSCO, Inc. completed a preliminary research effort to investigate a technology designed to detect bearing defects early on in their development. That previous project was funded by TRB's former High Speed Rail IDEA program. If detected early, a bearing defect can be repaired at the earliest opportunity when the car is available for maintenance, which will result in fewer operation interruptions. In essence, the technology was to use accelerometers mounted on the rail to detect defective bearing signals. The scope of that previous project was to investigate the transmissibility of the vibration signals from the defective bearing to the rails, a transient mechanical path formed by the bearing, the axle, the wheel, the rail, and the accelerometers. The rolling wheel-rail contact patch was considered a challenge for the technology. The field test and data analysis appeared to indicate the defective bearing signal could transmit from the bearing down to the accelerometers on the rail. However, the field test was conducted under less than ideal conditions. A credible signal-to-noise ratio was not established to allow meaningful detection of bearing defects.

The objective of this Safety IDEA project was to test the technology under normal operating conditions to investigate if the bearing signal detected by the accelerometers on the rail had sufficient signal-to-noise ratio to allow for reliable detection of bearing defects. If successful, this project would build the foundation for potential future development of a prototype system for detecting defective bearings. To achieve the project goals, project investigators worked with Norfolk Southern Corporation (NS) to conduct the field test on a continuous welded rail (CWR) track.

The project tasks included test planning, test design, equipment preparation, field testing, data collection, data analysis and documentation. The project was conducted in three stages: Stage I test planning; Stage II field test; and Stage III data analysis. This report presents the research work conducted in all three stages of the project.

During Stage I of the project, a comprehensive plan for the field test was developed. Laboratory tests were conducted to evaluate the transmissibility of signals generated at the bearing in a controlled environment and to confirm the existence of the bearing defect. The laboratory tests also aimed to calibrate and validate the data collection units and accelerometers that were used for the field test. The results showed that bearing signals could transmit from the wheel to the rail under the test conditions. The bearing defective type and location were identified. The setup of the data collection units and accelerometers was found to be satisfactory for the intended field test.

A field test was conducted in Stage II of the project, which involved field testing and data collection according to the plan detailed in Stage I of the project. The field test took place on NS in Roanoke, VA in March 2010. A test axle with a known defective bearing was installed under a loaded gondola car. The test consist included a master (hauling) locomotive, a slave locomotive, the gondola car, and the research car, NS32. The slave locomotive was in the test consist for logistical reasons and the NS32 hosted the test equipment and supplied power for the onboard test equipment. 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 test consisted of a total of 24 test runs in both forward and backward directions, with speed range from 20 to 50 mph. One set of data collection unit, made by OROS, Inc., was installed onboard NS32. The other OROS unit was used to measure bearing signals at wayside. The OROS system recorded the bearing acceleration signals and output the data to the hard drive of the laptop computer. Both onboard and wayside data collection systems were activated several seconds before the test consist arrived at the test zone and kept recording the vibration signals until the test consist has cleared the test zone. Preliminary examination of test data indicated that the test was valid.

In the third stage of the project, the data collected from the field test was analyzed using a high frequency envelope detection method. The onboard data channels were filtered using a high band-pass filter. The envelope detection method was applied to the filtered data. The results clearly showed that the defective bearing signals were detected by the onboard accelerometers. The dominant frequencies confirmed a cup defect in the bearing, a finding consistent with the analysis results of the acoustic data for the same bearing previously collected by TADS.

The onboard data analysis results indicated that the defective bearing signals had the strongest power at ranges of 8 - 9 kHz. There was also some power concentration around 13 kHz. However, the defective bearing seemed to have generated a broadband spectrum because the defective bearing signals were present at all frequency ranges up to 20 kHz.

For wayside data analysis, the first step was to determine the time period when the defective bearing was in the vicinity of the three rail-mounted accelerometers. During the field test, a penny was placed at a fixed distance from the first and the third accelerometers. When the first wheel ran over the penny, a spike was generated in the time history. The pennies were pushed off the rail by the first wheel. With known test consist configuration, the penny signals were used to determine when the defective bearing would be above the accelerometers. The segment of time history of interest was then cropped for analysis. A band-pass filter similar to that used for onboard data analysis was applied to the wayside data**.** The same envelope detection technique was then used to detect the defective bearing signals.

Different band widths and ranges were attempted to derive the defective bearing signals. The defective bearing signals appeared to be present in the power density spectra after envelope detection. However, the signal-to-noise ratio would need to be significantly higher to allow meaningful defect detection. The reason that the signal-to-noise ratio did not reach the desired level is that the wheel-rail contact interface seemed to have generated noises which happened to coexist in the frequency range similar to that of the bearing defective signals. As test speed increased, the noises also increased proportionally. Although the power of the noises is not as strong as the bearing defect signals, their source is closer to the accelerometers than the defective bearing. Hence, the separation of these noises would be the key to meaningful bearing defect detection.

The project investigators suggest that any future follow on efforts be focused on characterizing the wheel-rail contact patch signals so that the background noises can be isolated from the bearing signals.

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 that is costly to the railroad industry. There exist various technologies for monitoring bearing conditions. They include onboard condition monitors, workshop diagnosis systems and trackside detecting systems, such as hot-box detectors, and acoustic sensors. The main challenges in monitoring or detecting rail vehicle bearings include early detection, detection reliability and system cost. Since early detection is only practical while rail vehicle are still in operation, a trackside detection system seems to offer the best opportunity to overcome the challenges.

In the 1980s, the FRA initiated an effort to develop trackside acoustic bearing detection systems. A large amount of data was collected on various defective bearings. TTCI pioneered the technology, using microphones to detect interfering airborne acoustic signals from the surrounding train noise and all other wheels [1, & 2]. The resulting system is the Trackside Acoustic Detection System (TADS). Due of the nature of the technology, inward bearings can be difficult to detect. Also the system can miss certain types of defects and falsely condemns bearings that do not warrant removal from service.

It is therefore desirable to have a technology that can reliably detect bearing defects in the early stage of their development. This would allow the developing defect to be repaired at the earliest opportunity when the rail vehicle is available for maintenance, resulting in fewer operation interruptions. In addition, the environmental noise and location of the bearings will have minimal effect on the probability of defect detection.

Direct detection of bearing vibration signals and 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. Examples of this application include electric motors and industrial pumps. When the rail vehicles pass through the detection zone, the bearing, wheel, and rail form a direct mechanical path for the bearing vibration signals to be transmitted to the accelerometers on the rails. Detecting bearing defect signals from this direct mechanical path will yield more accurate results, because it eliminates adverse effects of surrounding noises and other environmental parameters, such as wind noise. However, there were concerns about the transmissibility of the signals though the small, moving and sometimes contaminated wheel-rail contact patch, which is about the size of a penny.

In the previous research effort, ENSCO investigated the transmissibility of bearing signals through the moving wheel-rail contact patch. The field tests were conducted in an environment that significantly exaggerated the external adverse effects. The study concluded that even under the worst case scenario, defective bearing signals could be transmitted to the accelerometers on the rail.

This Safety IDEA project further investigated the transmissibility of bearing signals through the moving wheel-rail contact patch through field tests under more normal operating conditions that are comparable to those of the TADS installations. Specifically, the tests were conducted on a tangent CWR track which allows vehicle speeds up to 50 mph. Rail top contamination should not be of concern since such trackside detection systems are normally installed at strategic locations where most rail vehicle traverse and that are not subject to constant or frequent contamination. Anyhow, in the previous research effort rail top contamination by fine sand which simulated airborne dust did not show noticeable effects on the bearing signals detected on the rail.

The project consisted of three stages. Stage I includes laboratory tests and field test plan development. Stage II will mainly be field tests and data collection. Stage III involves data analysis and reporting. In the remainder of this report, the progress made during the first stage of the project is summarized. It mainly includes the laboratory test results and a plan for the field tests to be conducted in the second stage of the project.

1.2 Project Objective

This report describes the investigation of signal transmissibility of defective bearings from a moving rail car to the rail.

The purpose of this project was to conduct field testing to investigate the feasibility of detecting defective rail vehicle bearings using rail-mounted accelerometers. The objective of this project was to test the technology under normal operating conditions to investigate if the bearing signals detected by the accelerometers on the rail have sufficient signal-to-noise ratio to allow for reliable detection of bearing defects. This project will build the foundation for future development of a prototype system for detecting defective bearings on railroad vehicles.

During Stage I of this project, 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 condition and in absence of any background noises. The laboratory tests also further confirmed the existence of the bearing defect on the outer race of the bearing.

The objective of Stage II of the project was to collect bearing vibration signals from a known defective bearing using accelerometers both on the car and on the rail in an operational environment.

This report details the field test and data collection in Stage II according to the test plan developed in Stage I of the project. The field test took place on NS in Roanoke, VA in March 2010. The test axle with a known defective bearing was installed under a loaded gondola car. The test consist included a master (hauling) locomotive, a slave locomotive, the test car, and NS's research car – NS32. The slave locomotive was in the test consist for logistic reasons and the NS32 hosted the test equipment and supplied power for the onboard test equipment.

The test was conducted on March 19, 2010. A total of 24 test runs were completed in both forward and backward directions, with speed range from 20 to 50 mph. The collected data will be analyzed in detail in Stage III of the project to determine the feasibility of detecting defective bearings using accelerometers mounted on rails.

2 LABORATORY TEST

2.1 Laboratory Testing

2.1.1 Test Objectives

During Stage I of the project, preliminary laboratory tests and evaluation of the rail vehicle axle to be used in the field tests were conducted at ENSCO's lab facility in Springfield, VA. The objectives for the laboratory tests included:

- Calibrate accelerometers and data collection equipment;
- Collect sample data in laboratory environment;
- Evaluate the test axle; and
- Provide inputs for planning the field test in the next phase of the project.

2.1.2 Test Setup and Test Procedure

The first set of the laboratory tests was conducted on a short segment of test track. Three (3) single-axis PCB ICP accelerometers were adhesively mounted on top of one rail, spaced 30" apart (FIGURE 1). The accelerometers, designated as channels 1, 2 and 3 from right to left in FIGURE 1, were connected to an OROS[tm] portable computer-based data acquisition system via BNC-terminated cables (FIGURE 2). Signals detected by the three accelerometers passed through the OROS analyzer into a computer utilizing OROS proprietary software for recording and processing.

For this test, a fire bell was used as an input vibration source. The bell plunger vibrated the rail vertically at different locations in the following sequence: outside accelerometer 1, at the middle point between accelerometers 1 and 2, at the middle point between accelerometers 2 and 3, and outside accelerometers 3. Each test run lasted approximately 60 seconds. Two repeating runs were taken for each location.

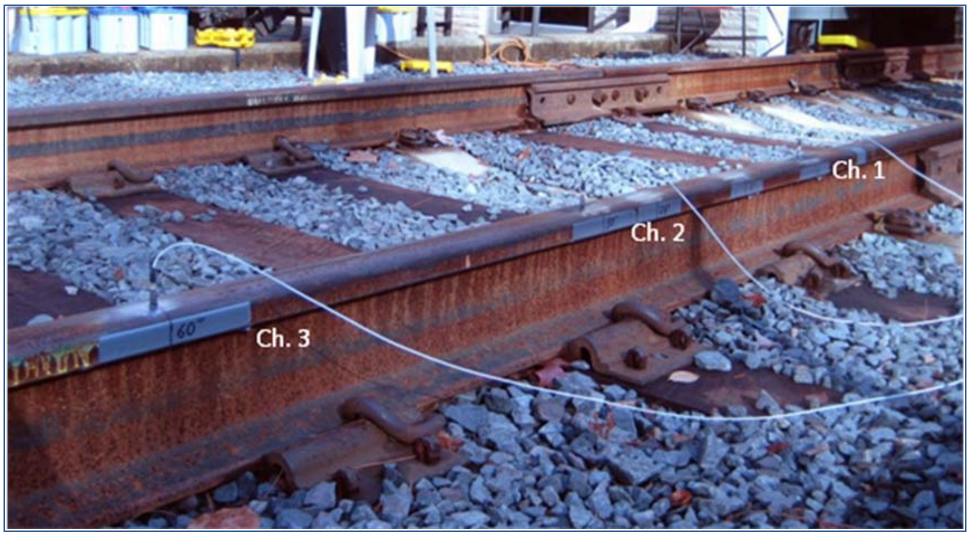


FIGURE 1 Sensor installation on the test rail.

FIGURE 2 Data acquisition equipment.

The second set of tests was conducted on the testing axle to confirm the defect detected by TADS. The axle was off a revenue hopper car. One of the bearings had been tagged by the TADS system as defective. The defective axle passed through the TADS site several times between 2006 and 2007 at operating speeds between 36.6 to 43.2 mph, and the hopper car was loaded. The TADS detected the defect for each train pass except once when the train passed the test zone at 36.6 mph. The defect was categorized as a single outer race (or cup) defect three times and a "growler" (multiple outer race defects) once. Many factors could have contributed to the inconsistency. The way the rail car axle was assembled in the truck under the car body did not prevent the bearing outer race from creeping against the bearing adaptor. This was evident from the bearing adaptor mark all around the outer race surface.

The axle testing in the laboratory aimed to indentify if the bearing contained a single defect or multiple defects. When the axle was rested on the laboratory floor, the bearing outrace was manually turned and wiggled while applying a vertical pressure. A knocking could be felt or heard at only one location. This may indicate that the bearing contained only one outer race defect, or it may have contained multiple defects but the one found was the severest.

The axle was then placed on jack stands, supported by two bearings (FIGURE 3). An accelerometer was installed on the bearing adaptor over the defective bearing as shown in the insert at the bottom right corner of FIGURE 3. A ring mark was painted at the outmost of the bearing cup and marked at 30 degree intervals. At each marked position, the bearing signals were recorded for 30 seconds while the axle was turned. After each run, the axle was jacked up and the bearing was rotated 30 degrees so that the vertical load from the axle weight was applied at each marked position.

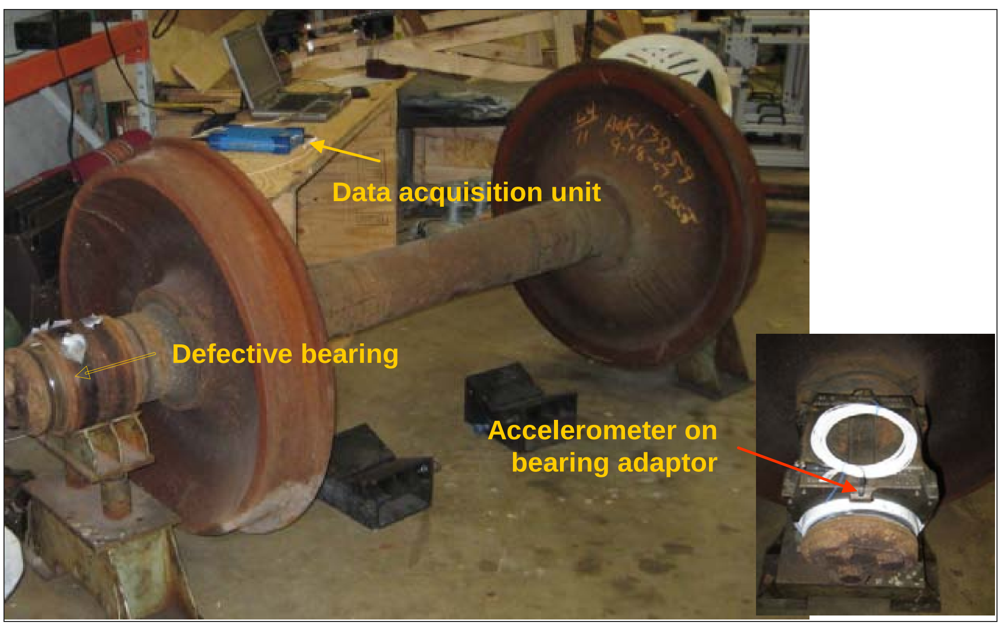


FIGURE 3 Axle testing setup.

2.1.3 Laboratory Test Results

Sample Data and Analysis Results from the Track Test

A sample of time histories of the acceleration signals is given in FIGURE 4. The plot shows 0.1 seconds of data. For this particular test run the input signal source was outside accelerometer 3. The 0.1 seconds time history clearly shows the excitation frequency of 60 Hz which is the specified frequency of the fire bell. The time delay between the three accelerometers is distinguishable, as expected. It can be clearly seen that at the location highlighted by the red arrows in FIGURE 4, the vibration signals reached accelerometer 3 first, and then accelerometers 2 and 1. This delay is the essential factor for signal isolation for the future development of a prototype bearing detection system.

Cross examination of the data using the MATLAB program revealed that the data from the 3 accelerometers correlated very well in the frequency range where the signal powers are high. This provides further confidence that the vibration signals could be isolatable using 3-accelerometer arrays.

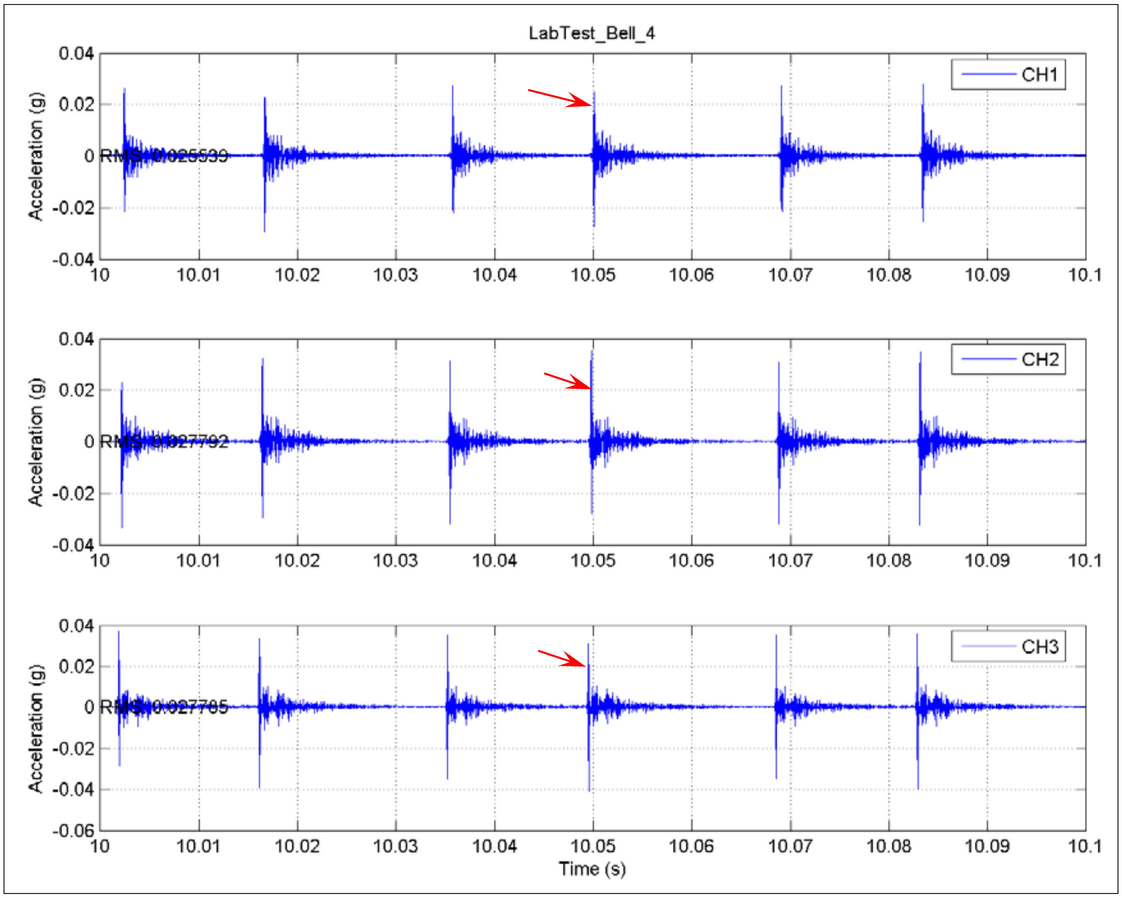


FIGURE 4 Acceleration time history.

Sample Data and Analysis Results from the Wheel Test

Starting from the 90^o position (at top) and the loading point at the bottom of the bearing, the wheel was turned at about 0.5 Hz. The acceleration signals were recorded for 30 seconds for each run. The bearing was then rotated 30 degrees and the test repeated until a complete rotation of the bearing outer race was recorded.

The 30 degree rotation increment will put the outer race defect at or near the loading position. The signal should be detected if the signal power is strong enough. The first position (90^o on top) was pre-identified as the worst spot from manual twisting.

With a known wheel rotation frequency and bearing specifications as shown in TABLE 1, the defect signal repeating frequency can be determined using the following equation:

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

Using the above equation, the defective signal repeating frequency is calculated to be approximately 5.41 Hz for the wheel rotating at 0.5 Hz.

A two-second time history of the recorded acceleration signals from the suspected defective bearing is shown in FIGURE 5. This plot corresponds to the worst location where the defect on the outer race is under loading. The two-second history of the recorded acceleration signals from the good bearing is given in FIGURE 6. It is obvious that the defect signals are visible in FIGURE 5 but not in FIGURE 6, as expected.

TABLE 1 Bearing Specifications

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

As can be seen from FIGURE 5, the defect signals repeat at about 6 Hz, which agrees well with the above calculation. The small difference is because the wheel was turned manually and the wheel rotation frequency might not be exactly 0.5 Hz. The 6 Hz signal repeating frequency shown corresponds to a 0.55 Hz wheel rotation frequency.

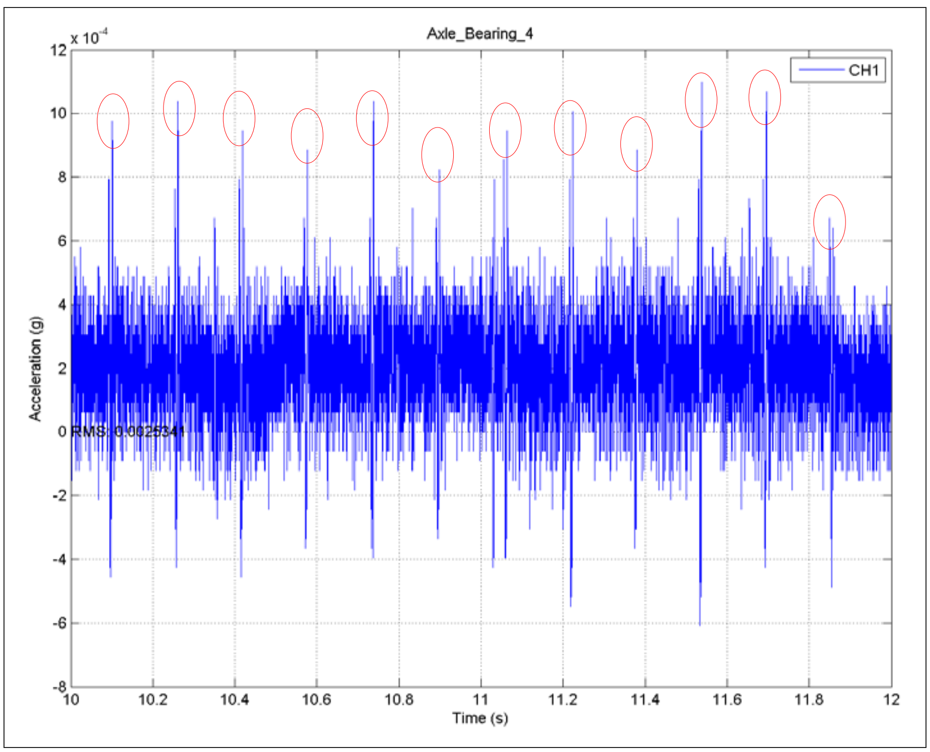


FIGURE 5 Sample of acceleration time history from the defective bearing.

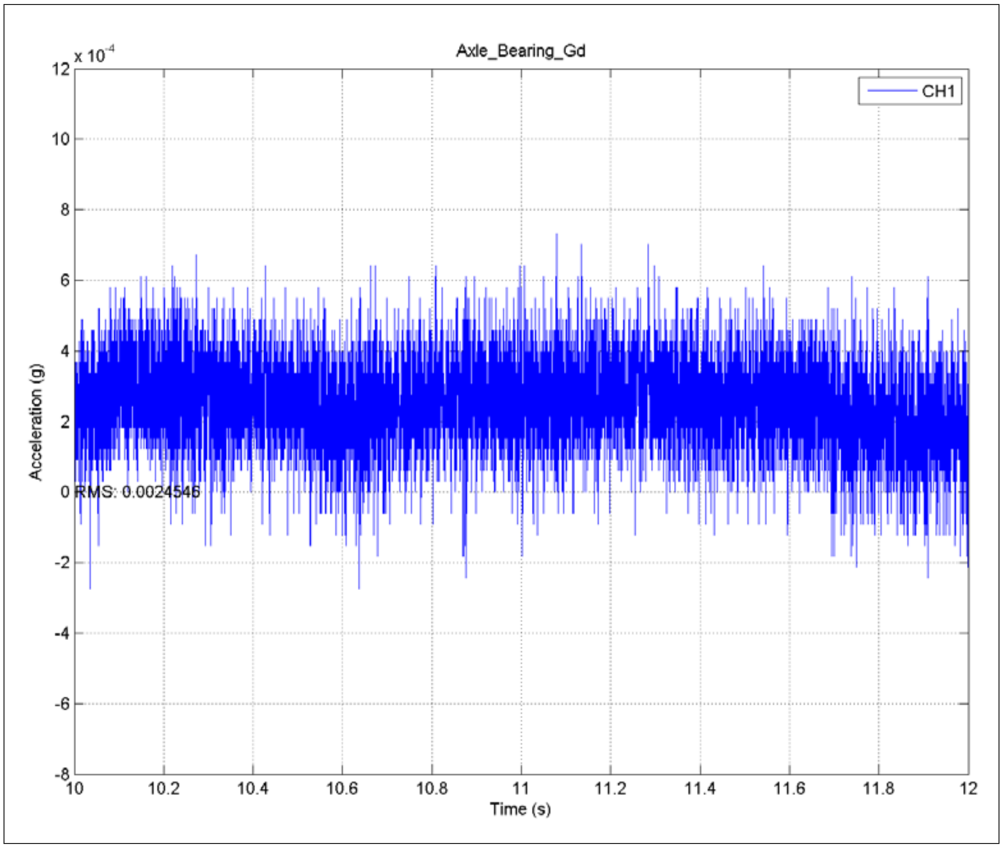


FIGURE 6 Sample of acceleration time history from the good bearing.

The results of the laboratory test are significant in two aspects. First, the test confirmed the bearing defect on the bearing cup. And second, the clear bearing signals at very low wheel turning speed seemed encouraging.

2.2 Field Test Plan

2.2.1 Task Scope

One of the objectives of Stage I of the project was to develop a field test plan. The comprehensive test plan would ensure the field test in Stage II could be conducted efficiently to avoid potential repeating tests. This is particularly important since the field test was to be conducted on an NS revenue track and required tremendous effort by NS in coordinating the track window, test vehicles and hauling locomotives.

The test plan was executed in Stage II of this project. The following sections briefly summarize the components of the test plan.

2.2.2 Setup of Test System

Overall System Design

The overall system design is illustrated in FIGURE 7. The test system is to include the following components:

- A loaded freight car with the test axle
- A locomotive to haul the test car
- A CWR track allowing the test car to travel at the designed test speeds

- Five high frequency accelerometers
- Two data acquisition units to collect data both from the test car and at trackside

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

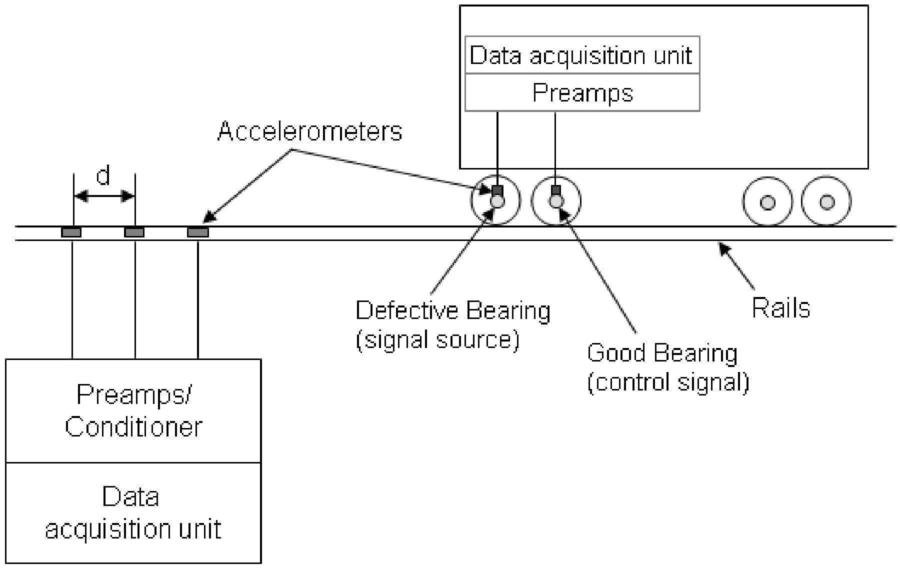


FIGURE 7 Diagram of the test system setup.

Accelerometers

Five PCB 353B18 accelerometers were to be used in the test. Three accelerometers would be installed at predetermined spacing on one of the rails of sufficient length allowing continuous transmission of vibration signals. The spacing is not deemed critical since the bearing defective is known to be on the outer race and the defective signals should be detected both within and outside the three accelerometer array.

Multi-channel Data Collection Units

Two multiple digital data collection units were to be used for the field test. The units will meet the following requirements:

- Four or more channels
- Sample rate of 50 kHz
- Adequate data length and A/D convertor

Arrangement has been made to rent two OROS 35 integrated analyzers for the field test. The OROS 35 unit has 8 data input channels. It connects to a laptop computer and can be configured to store the raw data on the computer's hard disk drive. Data storage, therefore, is not a concern as long as the computer has sufficient hard disk space. It also has real time analysis functions, allowing quick diagnosis and data assurance during the test.

Test Equipment Set Up

The research team received agreement from NS to provide support. NS would supply the necessary track and a hopper car for the test free of charge. NS would also facilitate a locomotive to haul the test car. The steps for equipment setup are as follows:

- Have a moveable test car and test track available for the test duration
- Install the test axle with the defective bearing
- Install three (3) accelerometers at the selected test location
- Install the fourth accelerometer near the defective bearing
- Install the fifth accelerometer at the good bearing on the same side as the defective bearing
- Have a locomotive available to haul the test car over the test site at specified speeds (25 to 50 mph).

Power Supply

NS would facilitate power supply through its research car NS32 for the onboard data collection equipment. The project team would use either a generator or an AC converter connected to a trackside vehicle to power the trackside data collection system.

2.2.3 Data Collection and Assurance

It was anticipated that the test would start between late spring and early summer in 2010. NS would arrange the needed track window to conduct multi-run tests. This stage would start with the deployment of lab-calibrated test accelerometers. Field-calibration of accelerometers and test equipment would also be performed prior to the field test runs. The field test was to be conducted at the test site through multiple runs at speeds ranging from 25 to 50 mph.

The field test was expected to demonstrate that the signal transmitted to the accelerometers on the rail was similar to the signal recorded by the onboard accelerometer at the defective bearing after the passing through the wheel-rail contact patch and when contact impedances might vary. One round of tests would last approximately two days in order to test multiple scenarios. Preliminary data analyses and assurance would be conducted in parallel with the tests to ensure data quality. This would also help identify potential problems.

If all equipment performed as expected and data quality was satisfactory, there would be no need for further tests. Further tests would only be necessary if any issues with the equipment or the data were identified in the first round of tests.

During the tests, the wheel-rail contact band might be modified by fine sand if permissible, to simulate scenarios of contamination. This contamination would be optional since the previous research had proven that rail top contamination did not have significant effects on the signals measured by wayside accelerometers. The maximum test speed would be 50 mph. The test would be conducted at speeds of 25, 30, 35, 40, 45, and 50 mph. However, if the logistics could not accommodate the number of desired test runs, few runs would be conducted by skipping several speeds. Preliminary data analyses would determine the cut off speed for the test. The loading of the test car would remain constant due to logistic and operational limitations. Data would be recorded from all channels with the OROS multi-channel data acquisition units.

The exact location of the test track would be decided at the earliest opportunity in the Stage II of the project. Depending on the track type and location of the test track, the length of track windows may vary. The number of test runs within the available track windows would be dictated by signal control, dispatching and other operational rules. Details of the logistics would be worked out at the beginning of Stage II of the project. The test matrix for up to 20 test runs was designed as shown in TABLE 2.

The test would be conducted at different speeds based on the consideration that the defective bearing signal strength, contact patch conditions, and background noise would vary significantly with speed. For the contamination test runs, two runs were considered sufficient to confirm the possible effects of contaminations. The contamination conditions did not cover extreme situations where the contact bands of the rails might be rusty due to lack of traffic. Also, the tests would not be able to simulate ice and snow conditions.

After the test system had been set up, sufficient data would be collected on the test track. The laptop computers had sufficient storage for large amounts of data to be collected. At the end of the test/data collection stage, the following would be achieved:

1) Data collected using multi-channel data collection unit for various test scenarios (different speeds, and other conditions where necessary)
2) Data quality assurance completed
3) Preliminary data analyses completed with potential issues identified
4) Sample data extracted for presentation

TABLE 2 Planned Field Test Matrix

Run Number	**Speed, mph**	**Rail Condition**	**Direction**
1	30	Clean*	F
2	30	Clean	R**
3	35	Clean	F
4	35	Clean	R
5	40	Clean	F
6	40	Clean	R
7	45	Clean	F
8	45	Clean	R
9	50	Clean	F
10	50	Clean	R
11	45	Clean	F
12	45	Clean	R
Optional (Time permits)			
13	45	Clean	F
14	45	Clean	R
15	40	Clean	F
16	40	Clean	R
17	40	*Sand*	F
18	40	*Sand*	R
19	25	Clean	F
20	25	Clean	R
21	20	Clean	F
22	20	Clean	R

* The rail is tested under "as-is" condition, dry or rainy

** Reverse runs will be tested for more efficient in test window utilization

3 FIELD TEST AND DATA COLLETION

3.1 Task Scope

The field test comprises the second stage of this project. In this stage the field would be competed. Sufficient data would be collected for the data analysis stage of this project. According to the test plan developed in Stage I of this project, the field test would be conducted on a continuous welded rail (CWR) track, allowing for a test speed up to 50 mph. The defective bearing would be installed on a loaded freight car, which was to be hauled by a locomotive.

3.2 Test Site

NS facilitated the test track near Roanoke, VA. The test site is on the double track section of NS main track at milepost N254.4, approximately 450 feet west of Berkley Road crossing, allowing easy access for wayside test equipment setup. FIGURE 8 shows the satellite image of the test zone. The test section is northeast-southwest oriented although the general direction of the track runs east to west. For ease of reference, the test zone is considered as east-west oriented. During the entire test, the hauling locomotive always faced east. The forward direction refers to the test train travelling eastbound and the backward direction is westbound.

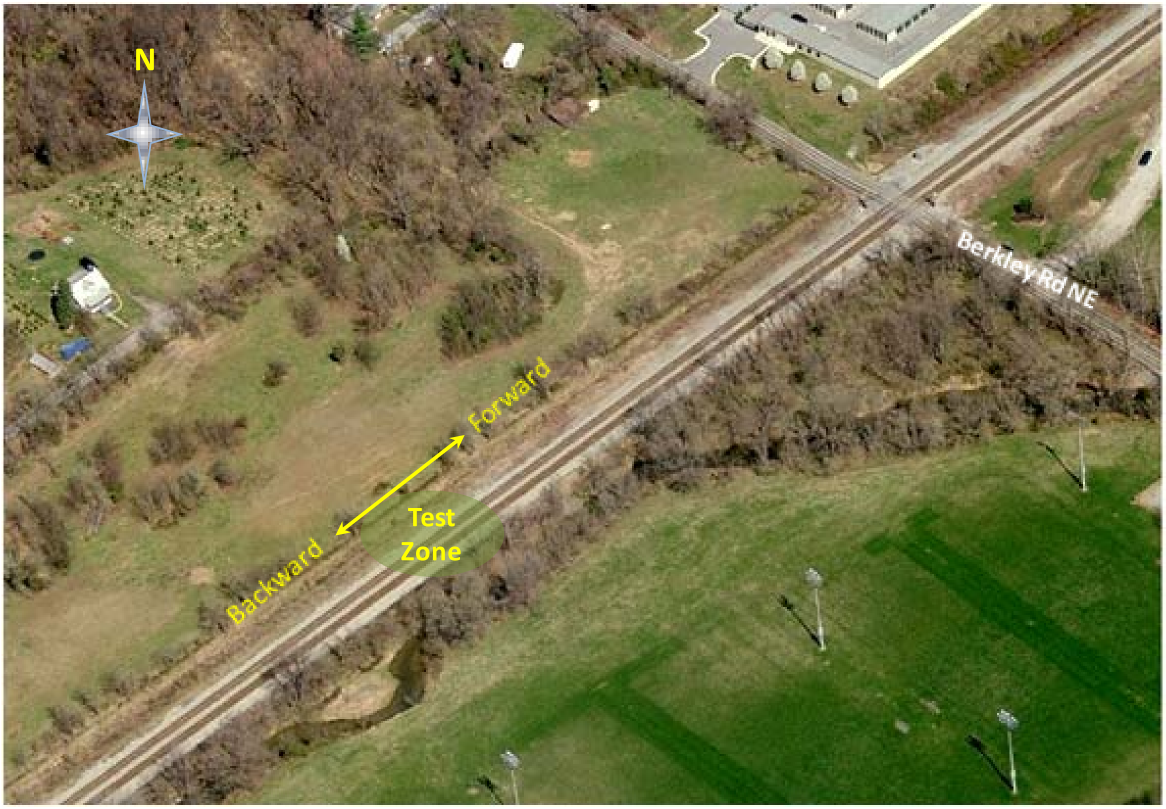


FIGURE 8 Test zone on NS track near of Berkley Road crossing.

Three high-frequency PCB 353B18 accelerometers were fixed on the north rail, designated as channels 1, 2 and 3, from west to east (FIGURE 9). Each accelerometer was stud-mounted on an aluminum block which was affixed to the rail web using a two-part epoxy glue. Uniaxial accelerometers were used since only vertical signals are of interest to this project.

FIGURE 9 Installation of accelerometers on rail.

The three accelerometers were 30 inches apart. The spacing of the accelerometers is not important for this particular test because the bearing defect is known to be on the outer race, or the cup, of the bearing. As long as the defect is placed at loading position during installation, the defect will be at a fixed location during the test. Vibration signals will be generated each time a roller hits the defect. The spacing would become important if the defect were on one of the moving components, such as the cone or rollers.

3.2 Test Equipment

3.2.1 Test Car and Test Wheel Set

The test vehicle was a gondola rail car (FIGURE 10), which has the following specifications:

Empty Weight	71,500 lbs.
Length	52'6"
Truck Wheelbase	5'6"
Nominal Wheel Diameter	32"
Bearing Class	E6 x 11

The gondola car was fully loaded with new wood ties, which helps generate stronger defective bearing acceleration signals. The test wheel set with the known defective bearing was off an in-service, 70-ton hopper car. Before the wheel set was removed, the loaded hopper car passed the TADS site several times. The latest pass was on September 16, 2007. The bearing was identified to have cup defects three times, non-defects once and growler (multiple, large cup defects) once. The average speed of the car passing the TADS site was approximately 40 mph.

FIGURE 10 Test car.

The wheel set and two modified bearing adaptors were installed at the NS Shop in Lynchburg, VA. The defect bearing and the location of the defect were clearly marked with white paint so that the defect would be at the loading position when installed on the test car. The wheel set was mounted to the rear truck at the west end of the gondola car which was coupled to the NS research car, NS32. The NS32 car was equipped with onboard data collection system. Two PCB 353B18 accelerometers were installed on the bearing adaptors, both on the north side of the test car. One accelerometer was above the defective bearing and the other was above the normal bearing to serve as a control channel. The installation of the accelerometers is shown in FIGURE 11. This configuration allowed the two accelerometers to be positioned at the closest locations possible to the bearing signals, ensuring that good quality signals would be collected by the accelerometers.

FIGURE 11 Two accelerometers on bearing adapters of the test car.

3.2.2 Data Collection Equipment

Two OROS portable data collection units were used for the test. The two units are of identical configurations except that one (OROS 35) has 8 input channels and the other (OROS 36) has 16. Both units exceed the requirements for the project. Each unit comes with the OROS NVGate® software for data collection and real time data view. They also have real time analysis functions, allowing quick diagnosis and data assurance during the test. The units have a maximum sampling rate of 102,400 samples per second although only a sampling rate of 51,200 was needed for this project. The OROS systems were connected to the accelerometers through BNC cable and to the laptop computer through RJ45 cables.

One OROS unit was installed onboard the NS32 research car (FIGURE 12), which has needed workspace and power supply. The OROS system and the laptop computer were located at the back (west) end of the car. The data will be saved on the computer's hard drive which has sufficient storage space.

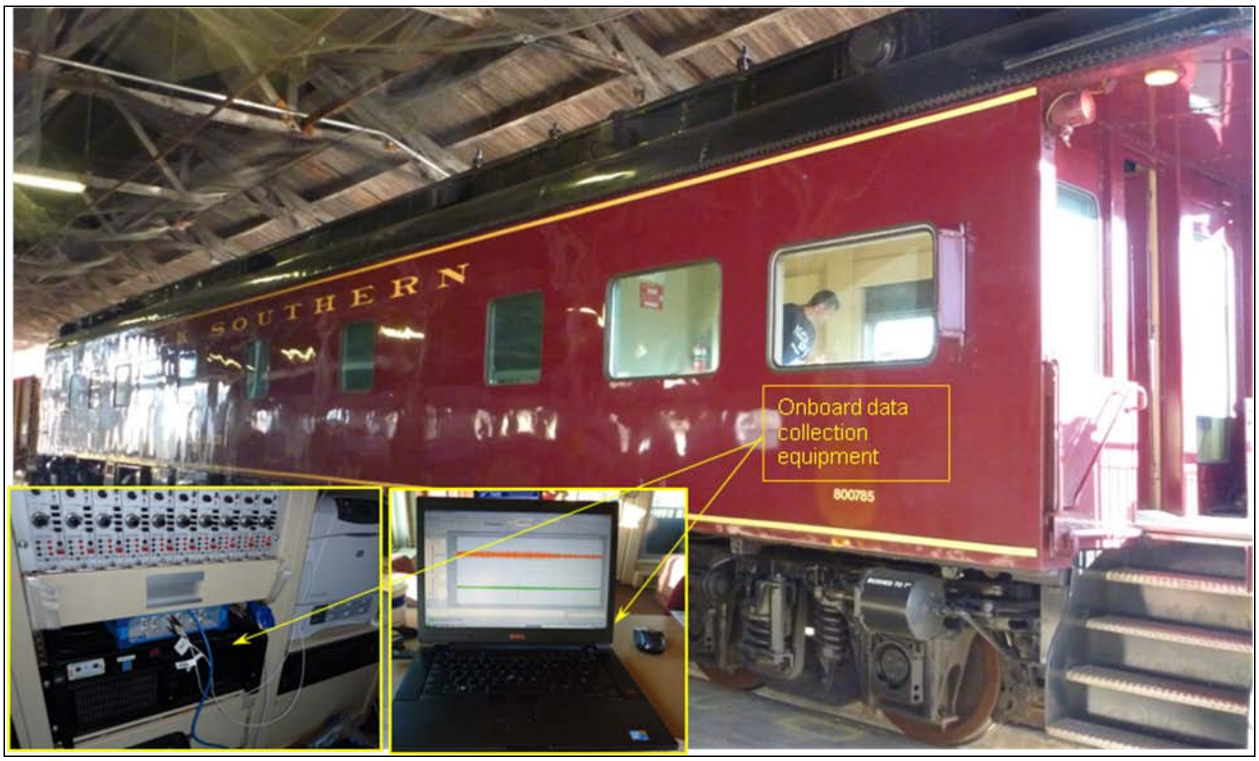


FIGURE 12 Data collection system onboard NS32.

The other OROS unit was set up on the wayside as shown in FIGURE 13. The data collection equipment was set up on the north side of test rack. The position provided sufficient sight distance in both east and west directions. A portable generator was used to supply power to the wayside data collection system. An engineer from NS served as the watch person during the accelerometer installation and field test. Another NS engineer riding the test train coordinated the test preparation and field test.

FIGURE 13 Wayside data collection system.

3.2.3 Test Consist

The schematic diagram of the test consist is shown in FIGURE 14. The test consist was hauled by a GP22ECO-M locomotive. The locomotive was paired with a slave locomotive which, when engaged, can provide additional traction power at low operating speeds. For this test, the slave locomotive was disengaged so that the master locomotive could run at speeds up to 50 mph. The test car was coupled to the back of the slave locomotive. The NS research car NS32 was placed at the back of the test consist, hosting onboard data collection equipment and providing a work space and power supply.

During the test, the orientation of the test consist remained east to west so that the defective bearing always traversed on the north rail installed with the accelerometers in both forward (eastern) and backward (western) directions. FIGURE 15 shows a photo of the test consist at the test zone, facing east.

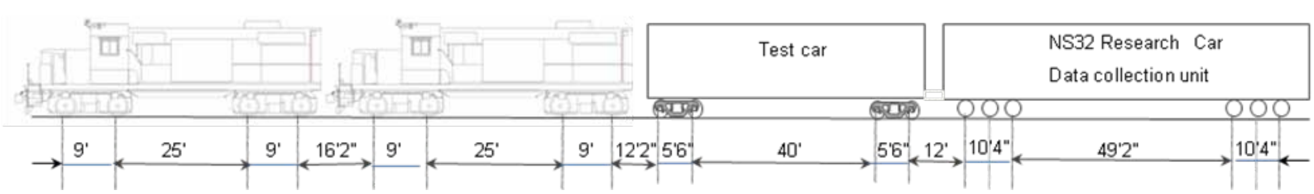


FIGURE 14 Sketch of test consist.

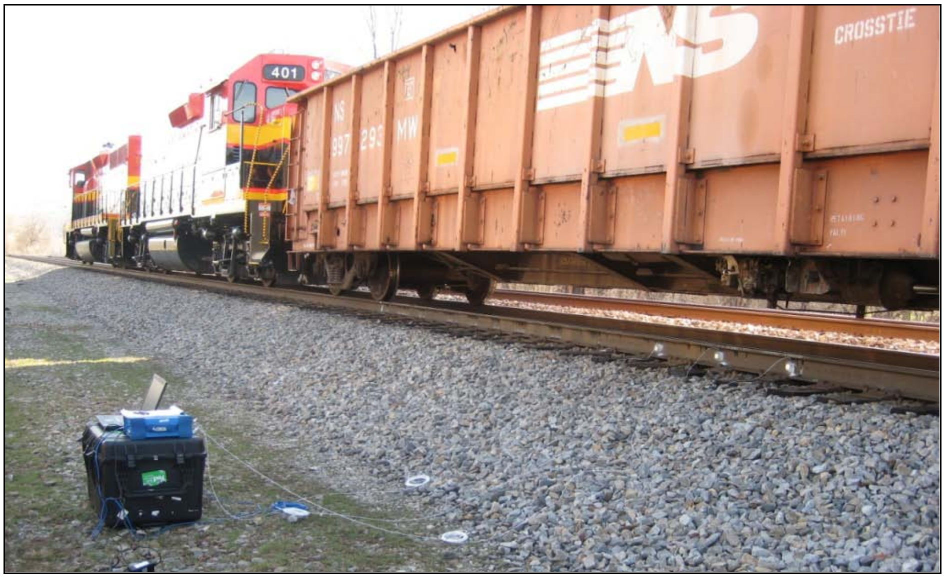


FIGURE 15 Test consist at the test zone.

3.3 Field Test

The test was conducted on March 19, 2010. The test matrix was developed for different test speeds and rail top conditions in Stage I of the project. The test matrix was adjusted to suit for the test logistics and availability of the track window. The actual test matrix is given in TABLE 3. The tests runs were designed in pairs so that for each test speed, the test consist would pass the test zone in both forward and backward directions. However, the relative short test section did not allow very good control of speeds, especially at higher speeds due to limited distance for acceleration. The test speeds varied within 2 mph in most of the paired test runs. The test speeds listed in the table were read off the speedometer onboard NS32. However, they are not constant since the test consist could have been accelerating when it passed the test zone. This should not be a problem for the data analysis in Stage III of the project since only several seconds of data will be examined. Precise speeds can be determined using recorded signals.

Both the onboard and wayside data collection systems were started at approximately 30 seconds before the defective bearing arrived at the wayside accelerometers. The systems recorded the acceleration signals continuously for up to 60 seconds to ensure the defective bearing signals were recorded. For the wayside data, it is anticipate that data of several seconds when the defective bearing was in the vicinity of the accelerometers would be analyzed in Stage III. The data from the two systems will be aligned during the data analysis process to ensure the signals from the same timeframe will be analyzed.

After two trial runs, a total of 24 test runs were carried out within an approximately 4-hour track window, thanks to excellent coordination by NS. During the first 20 runs, the rail top was dry and clean. For the test runs 21 and 22 the rail top was modified by fine sand. For the last two test runs the rail top was modified by regular motor engine oil. These rail top modifications are expected to affect the defective bearing signals transmitted through the wheel-rail contact patch, which will be examined in the data analysis stage.

3.4 Sample Test Data

Data assurance checks during the field test and post test evaluation of the data showed that the test configuration, test procedure, and test data were all valid. Sample time history data from the onboard data collection system for test run 4F is shown in FIGURE 16. The blue (dark) signal trace is the acceleration of the defective bearing and the green (light) trace is the good bearing. The bearing defect signals can clearly be seen from the time history. The time history represents 0.5 seconds of data. There are 36 spikes in the data set, depicting 72 to 74 Hz of repeating frequency generated by bearing rollers hitting the defect on the bearing cup. This frequency corresponds correctly to the car speed of 40 mph for this particular run.

Sample data for the same timeframe collected by one of the three accelerometers at wayside is given in FIGURE 17. As expected, the bearing defective signals are not obvious from the time history. This is where the research needs to be focused. More sophisticated data analysis algorithms will be needed to demodulate the signals in order to derive useful information for bearing defect detection.

TABLE 3 Actual Test Matrix

Run #	Run ID	Speed	Rail Condition	Direction
1	1-F	39	Clean	East
2	1-R	44	Clean	West
3	2-F	49	Clean	East
4	2-R	47	Clean	West
5	3-F	40	Clean	East
6	3-R	43	Clean	West
7	4-F	41	Clean	East
8	4-R	42	Clean	West
9	5-F	37	Clean	East
10	5-R	46	Clean	West
11	6-F	41	Clean	East
12	6-R	37	Clean	West
13	7-F	32	Clean	East
14	7-R	32	Clean	West
15	8-F	27	Clean	East
16	8-R	27	Clean	West
17	9-F	20	Clean	East
18	9-R	22	Clean	West
19	10-F	41	Clean	East
20	10-R	42	Clean	West
21	11-F	41	Sand	East
22	11-R	42	Sand	West
23	12-F	32	Oil	East
24	12-R	32	Oil	West

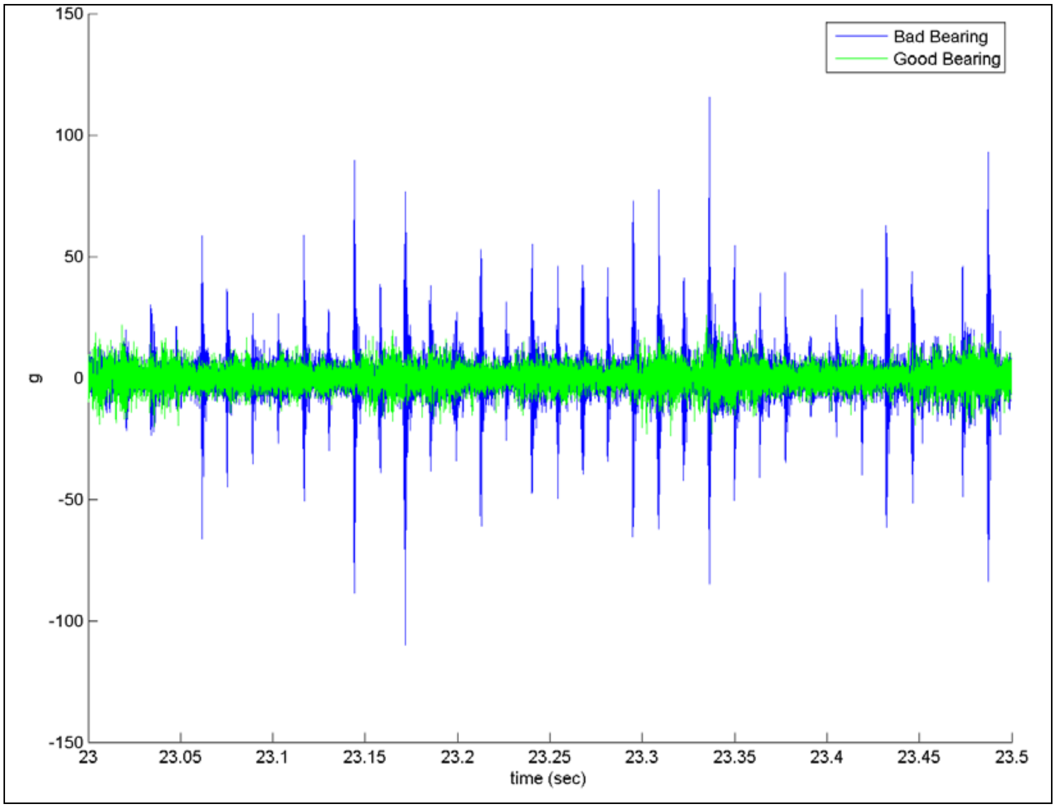


FIGURE 16 Sample time history data from onboard data collection system.

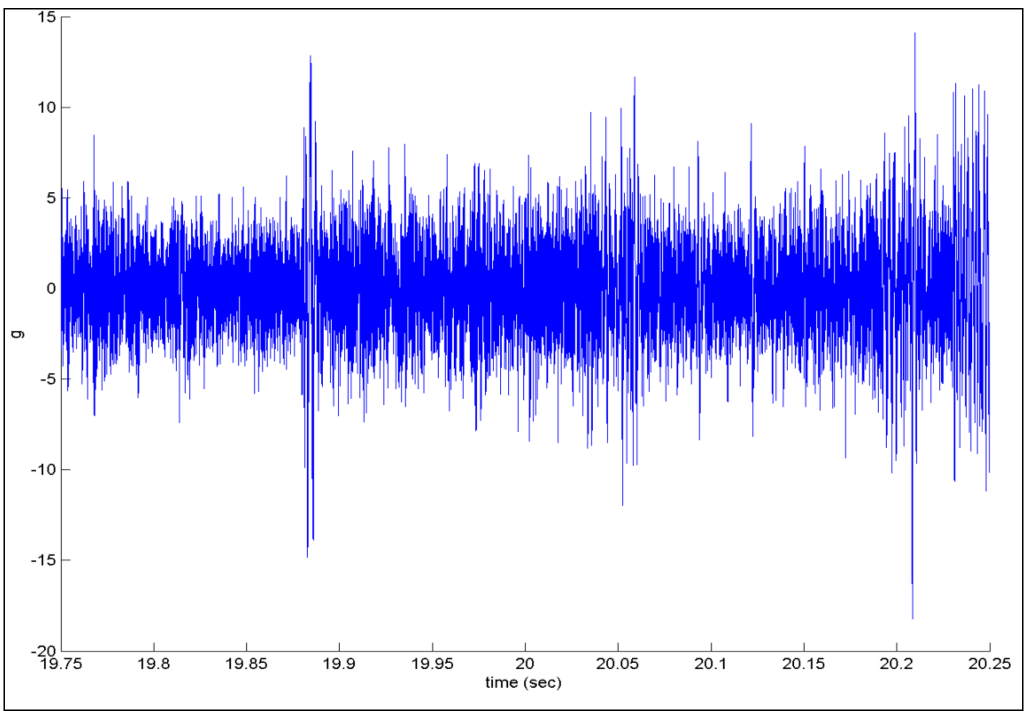


FIGURE 17 Sample time history data from wayside data collection system.

The power spectral density for the same piece of data is plotted in FIGURE 18. The dark blue line is the PSD for the defective bearing. It indicates that the bearing defect vibrations generated the highest power in the frequency range between 7 and 10 kHz. Some power concentration can also be seen around 13 kHz. These frequencies provide useful references for data analysis in the next stage.

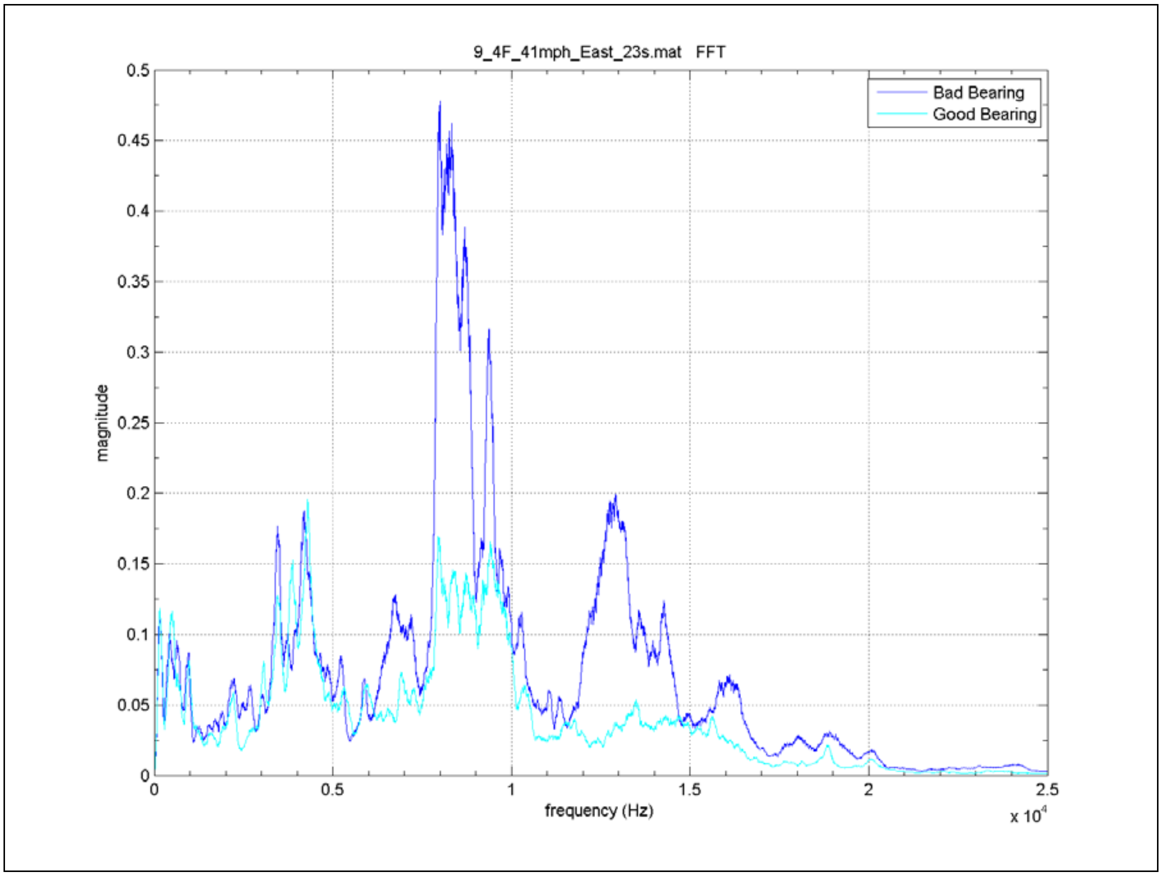


FIGURE 18 PSD for defective bearing from onboard data for test run 4F.

4. DATA ANALYSIS

4.1 Data Analysis Approach

High frequency (HF) vibration envelope detection is known to be the most effective method for detecting defects in rolling element bearings. 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's inner or outer races. The magnitude, and hence the detectability, of the HF vibration levels will depend on many factors including the force on the bearing and the shaft rotation speed.

The first step of envelope detection is high-pass filtering of the raw vibration data to retain only the HF components. The next step is to envelop the data by rectifying and low-pass filtering of the data. And finally, it involves estimation of the power spectrum using FFT spectral analysis. A defect will reveal its presence by an apparent spectral component at the roller passing, or impact, frequency and its harmonics.

To prove if the bearing defect vibration is transmitted through the wheel to the rail, 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 is expected that the onboard data would easily yield 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 should be similar to the defect frequency component from the onboard data.

4.2 Onboard Data Analysis

As discussed previously, during the field test, one accelerometer was installed on the bearing adaptor directly above the defective bearing. Therefore, it is not important which segment of data is analyzed since the accelerometer always followed the bearing. However, for consistency of analysis, the time segment when the defective bearing was above the sensors on the rail has been extracted and used in the 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.

It can readily be seen from the time history shown in FIGURE 16 that the defective bearing signals stand out clearly from the background noise. The bearing signal line becomes even clearer after the band-pass filtering and envelope detection. FIGURE 19 shows the enveloped PSD for the same data segment. It clearly depicts a cup (bearing outer race) defect with an average characteristic frequency of 73.5 Hz. The harmonics are not exact multiples of 73.5 but are within the resolution for the data segment analyzed. This corresponds to the car speed and expected repeating frequency discussed in section 3.4.

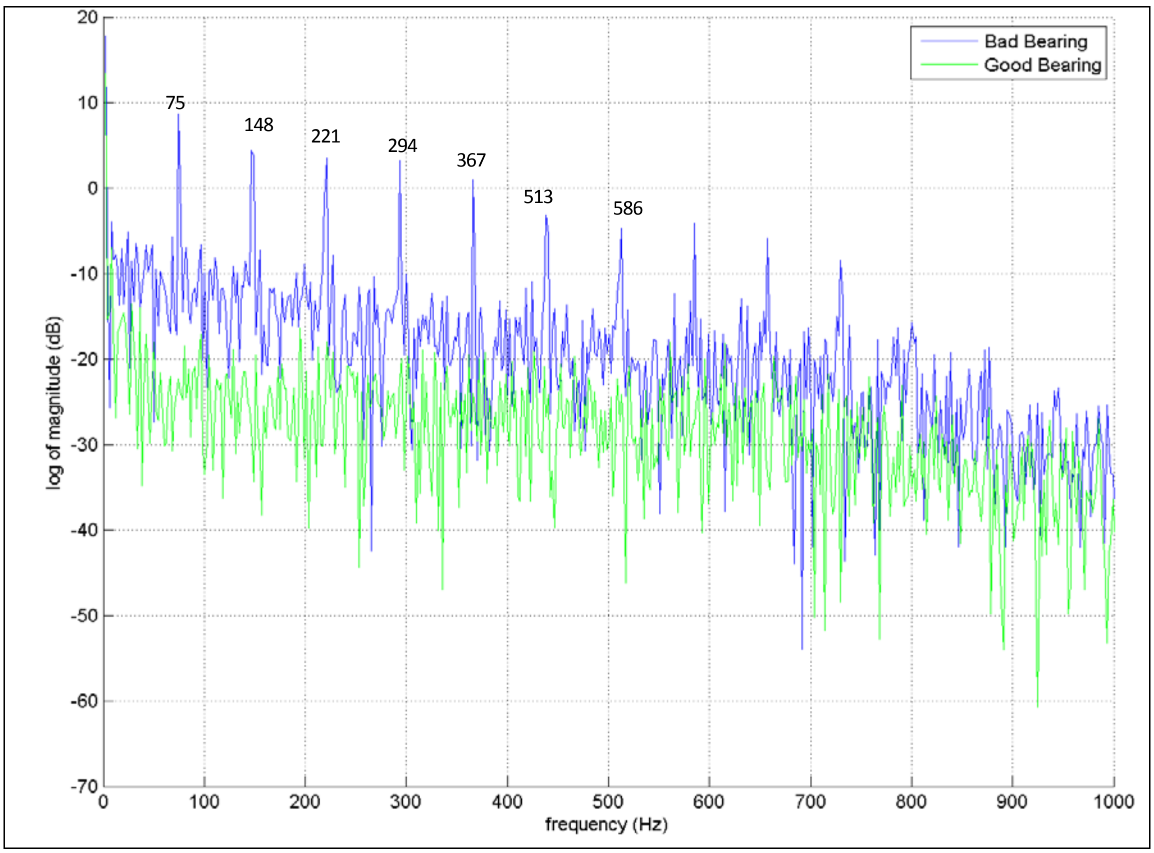


FIGURE 19 Enveloped PSD for defective bearing from onboard data of test run 4F.

4.3 Wayside Data Analysis

The wayside data differs from the onboard data in several respects. The useful time segment was when the wheel with the defective bearing traversed the track location instrumented with accelerometers, or the test zone. Wheel/rail interface noises entered into the accelerometer with full strength. The defective bearing signals were expected to be attenuated by the transmission path from the bearing, to the axle, the wheel and then the rail.

There were three wayside channels. Two of them were redundant for the purpose of this project. Data recorded by the three channels is the same except that there is a slight time delay as has been discussed in section 2.1.3. In this report, data from channel 1 is selected for the subsequent analysis.

FIGURE 20 shows the entire wayside time history of channel one for test run 4F. For this test run the test train traveled east bound. The hauling locomotive entered the test zone first, followed by the slave locomotive, test car and NS's research car NS32. The first spike in the time history mark the first wheel of the leading locomotive and the two humps towards the end of the plot are NS32 front and rear tracks. Using the test train configuration shown in FIGURE 14, it is determined that the defective bearing was in the test zone in the time frame of 19.75 – 20.25 seconds. The time history plot for this specific time segment has been given previously in FIGURE 17.

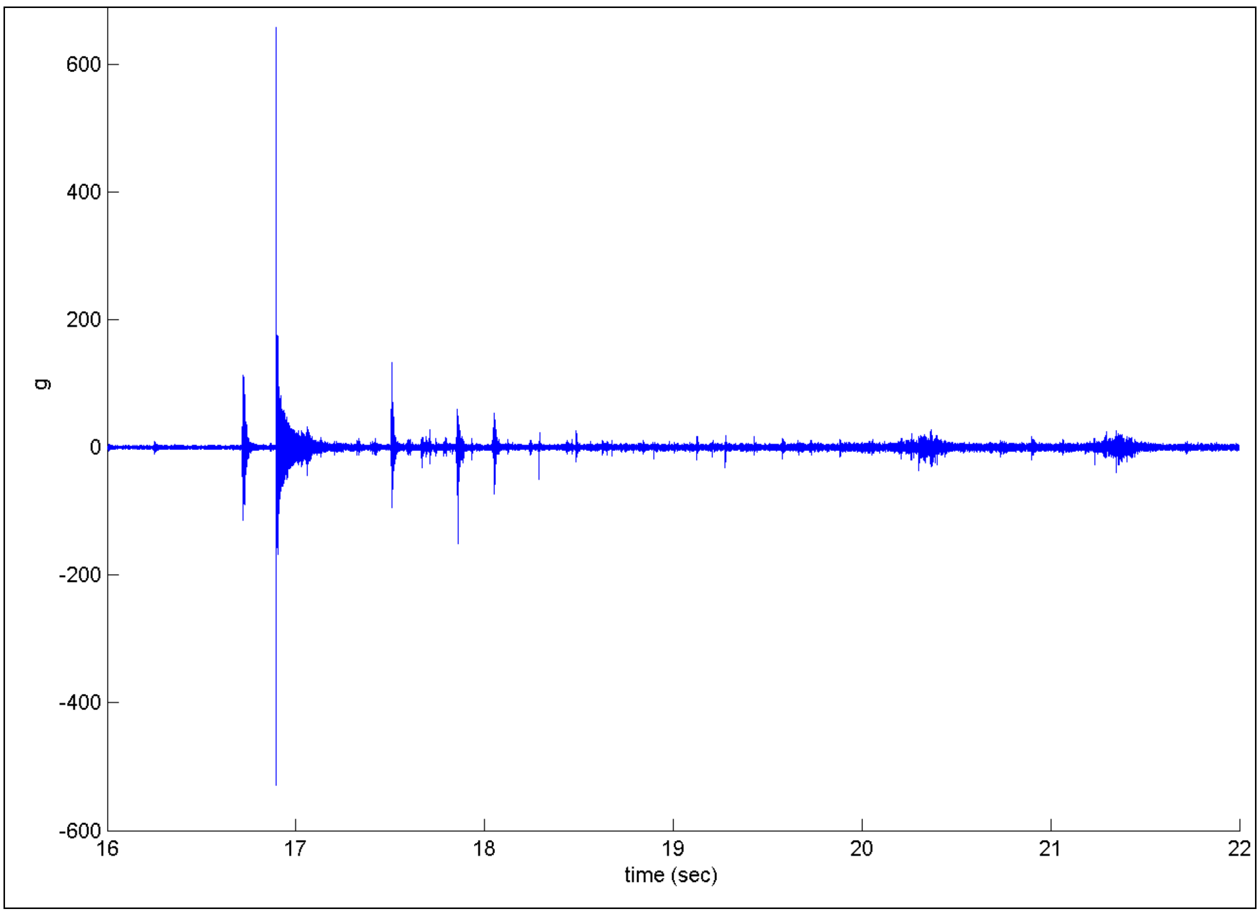


FIGURE 20 Entire time history for channel 1 of wayside data from test run 4F.

The same type of band-pass filter used for onboard analyses was applied to the wayside data. Envelope detection was then used to demodulate the bearing signals. After multiple iterations of different bandwidths, it was found that the bandwidth from 7-9 kHz yielded the best results. FIGURE 21 shows the results for test run

4F. The bearing defect signals appeared in the wayside data stream. However, background noises were found to coexist in the same bandwidth. As a result, the bearing signal lines in the enveloped PSD plots are not as clear as those in the onboard data.

Similar analysis was done for each test run. The results did not seem to differ significantly. This seems to suggest that the background noise severely masked the defective bearing signals which have been significantly weakened after having traveled from their path from the bearing to the rail.

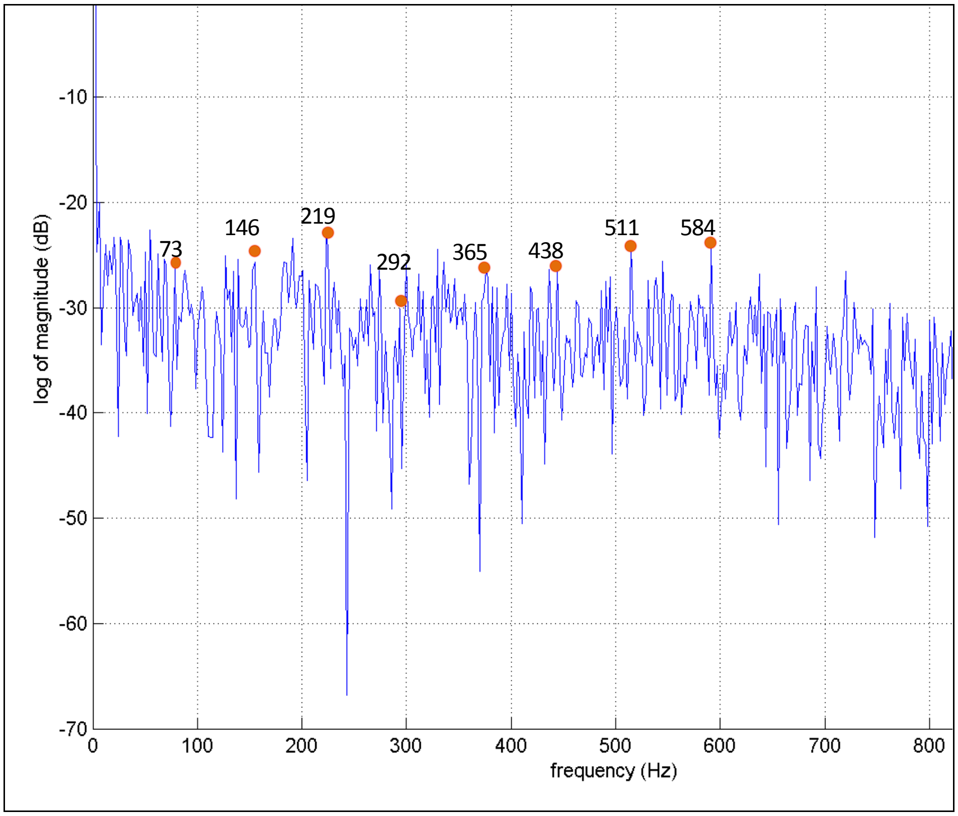
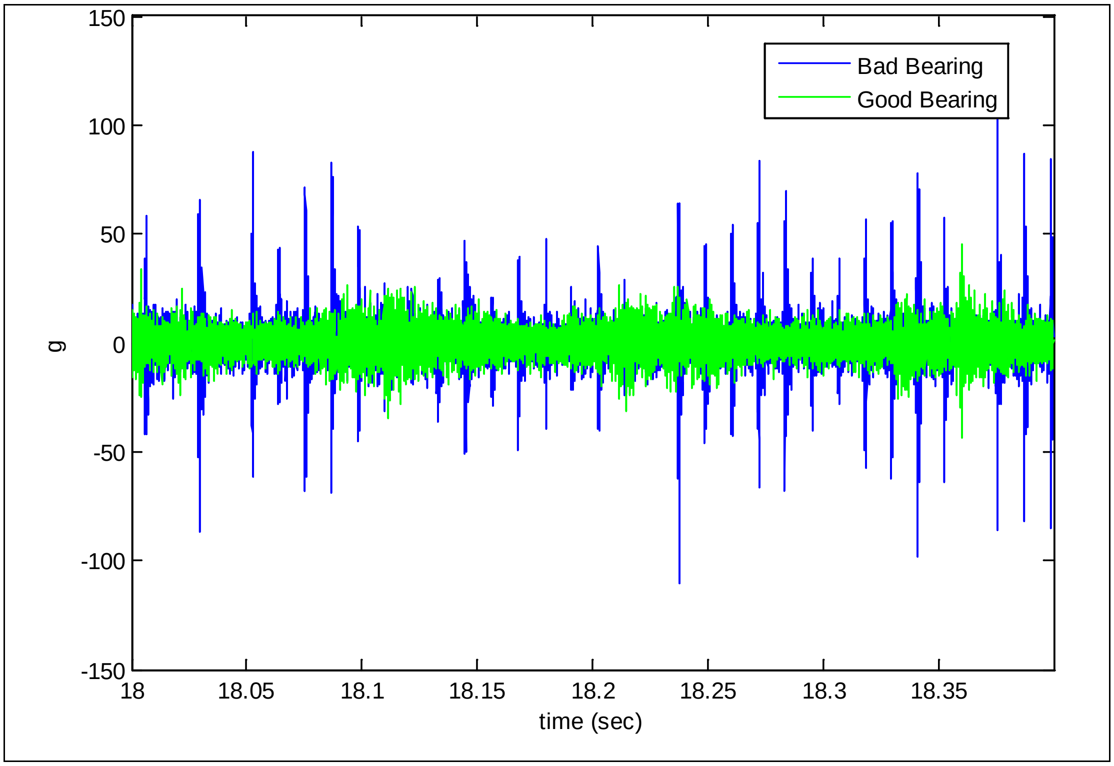


FIGURE 21 Enveloped PSD for wayside data from test run 4F.

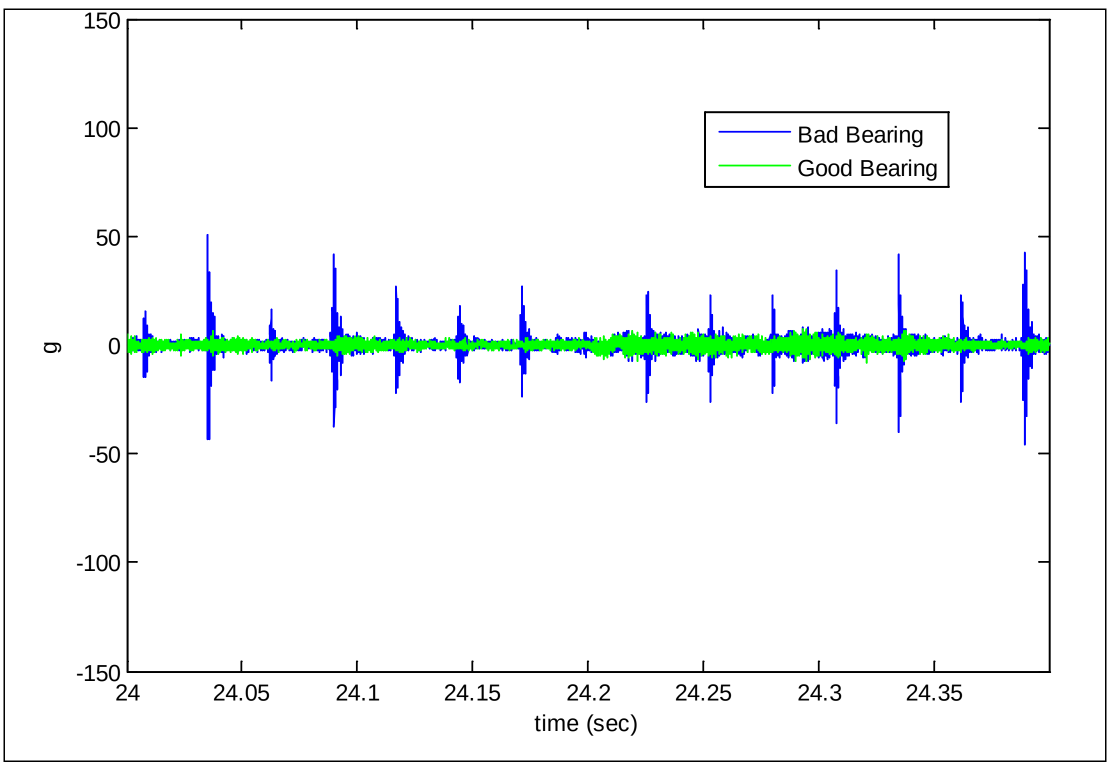
4.4 Effect of Train Speed

The effects of car speeds are obvious as expected. FIGURE 22 shows the comparison of the time history from on two onboard accelerometers for test runs 2F and 9F. The nominal speeds for the two test runs are 49 mph and 22 mph, respectively. From the acceleration time history, it is readily seen that the signals are stronger at higher speed. It is also noted that the strength of the background noise, i.e., the acceleration signals of the good bearing in this case, increased proportionally.

The effects of speed were also manifested in the acceleration signals from the wayside accelerometers. These can be seen from the acceleration signals shown in FIGURE 23. Test run 2F at the speed of 49 mph yielded much stronger signals than test run 9F at the speed of 22 mph. However, these signals have very different characteristics from those of the onboard accelerometers. The background noises from the wheel-rail contact interface and others sources dominate in the wayside signals. Increasing speed did not seem to improve the detectability of the defect since the background noises also increased by similar magnitudes.

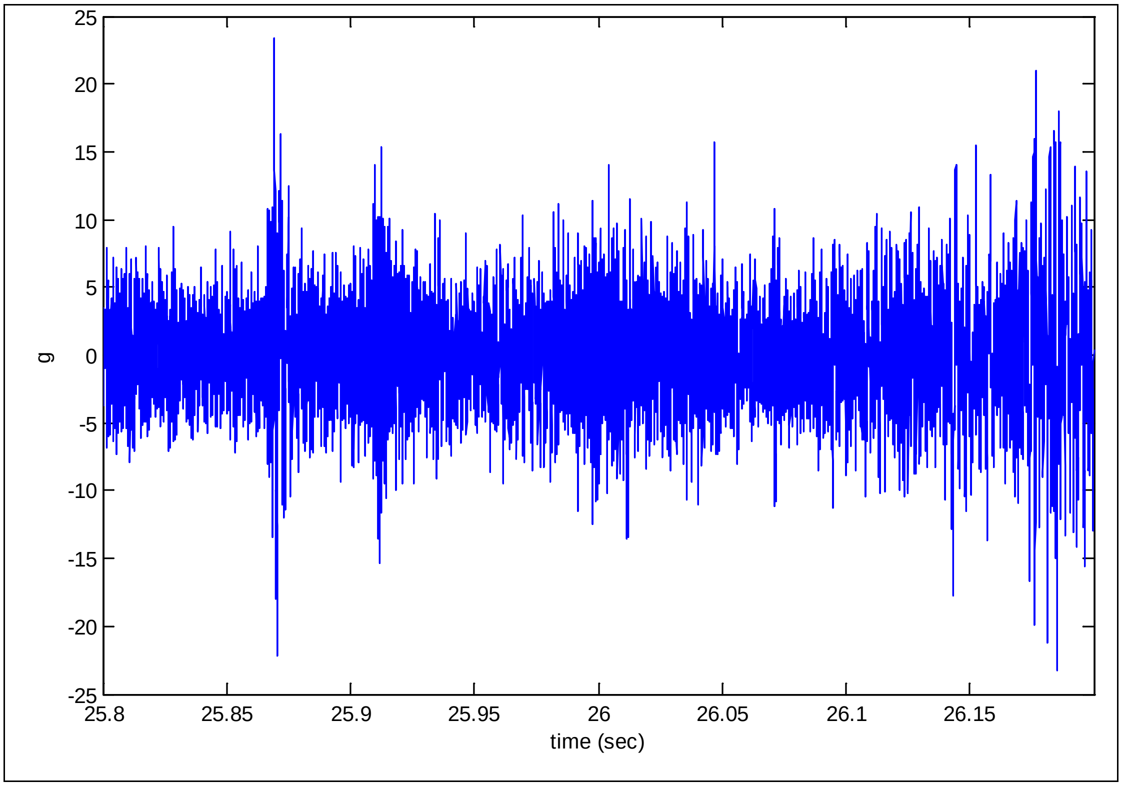


(a) Test Run 2F at Speed 49 mph

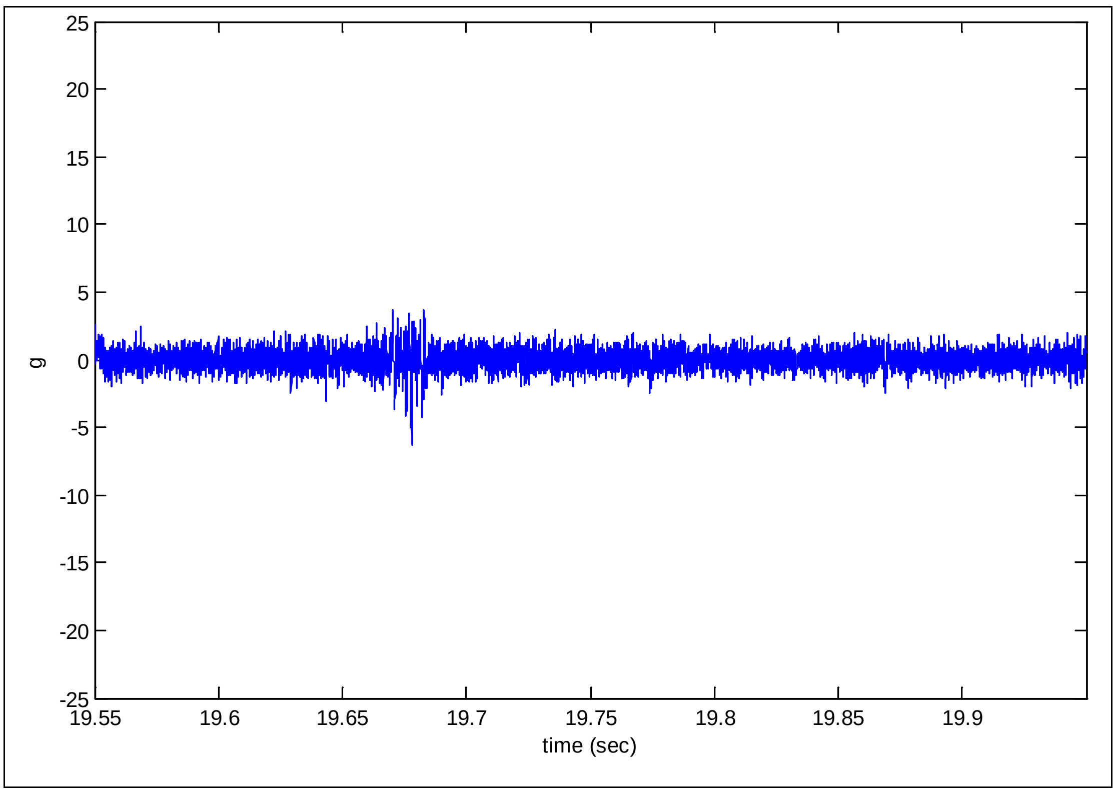


(b) Test Run 9F at Speed 22 mph

FIGURE 22 Comparison of time history of different speeds.



a) Test Run 2F at 49 mph



(b) Test Run 9F at 22 mph

FIGURE 23 Enveloped PSD for test run 6.

4.5 Effect of Rail Surface Contamination

The effect of rail surface contamination was also investigated. In test runs 11F and 11R, the test zone was spread with sand to modify contact conditions. FIGURE 24 shows the acceleration time history for test run 11F. This test run had approximately the same speed as test run 4F with a clean rail surface. The time history of test run 4F has been given in FIGURE 16. As expected and by comparing FIGURE 24 with FIGURE 16, sand on the rail showed little, if any, effect on the acceleration signals measured by the onboard accelerometers.

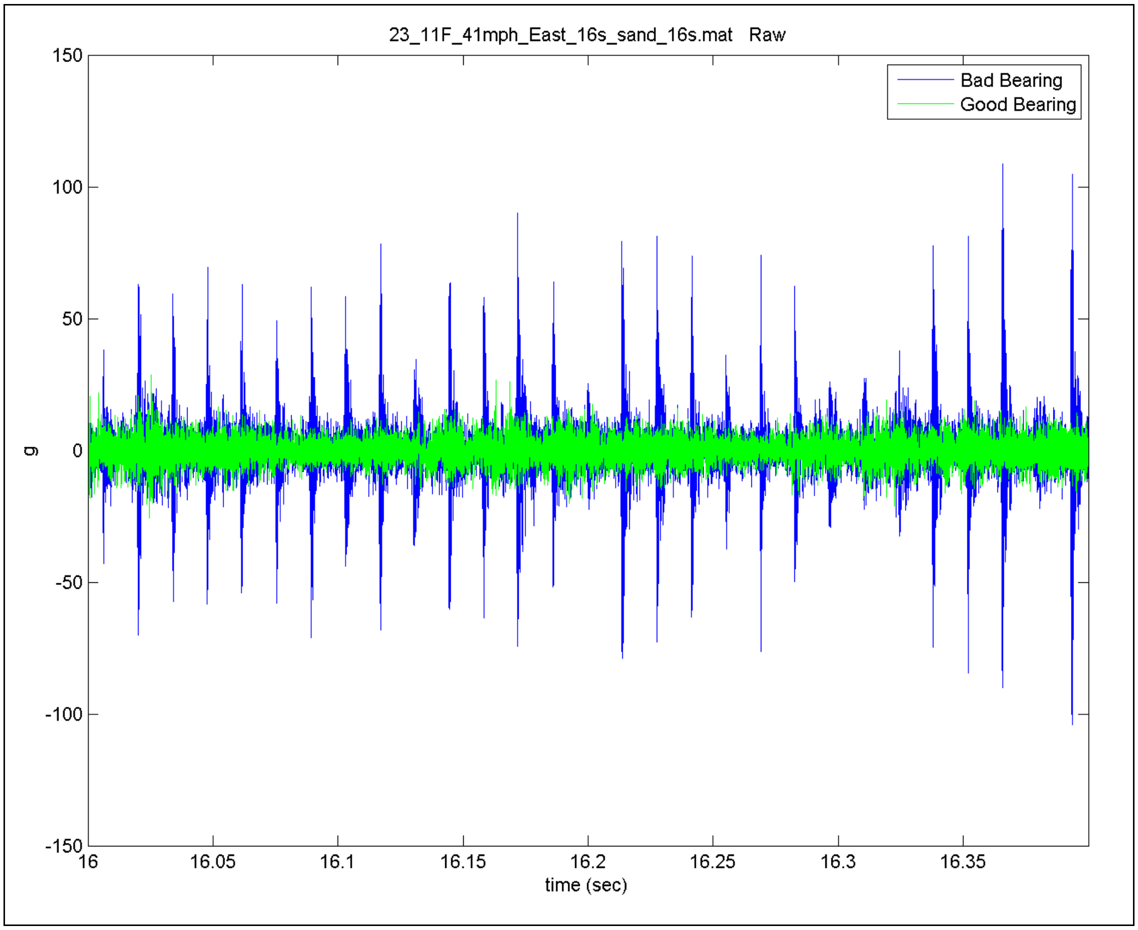


FIGURE 24 Onboard time history from test run 11F with sand on rail.

Examination of the acceleration data from the wayside accelerometers for the same two test runs revealed that sand on the rail did not seem to affect the wayside acceleration signals either. Comparison of the time history for this run (FIGURE 25) with that of test run 4F (FIGURE 17) shows the acceleration signals from both runs had approximately the same signal strength. The explanation could be that by the time the test wheel reached the test zone, the sand had been crushed and cleaned by the locomotives' wheels.

Regular engine oil (SAE 5W-30) was applied to the test zone in test runs 12F and 12 R. Comparison analysis of the data from these test runs with other runs of similar speeds did show noticeable effects. In theory, the oil film at contact interface can enhance signal transmissibility. However, in this case the contact interface was the small wheel and rail contact zone, which was highly stressed by the heavy wheel. Therefore, the oil film could not further enhance the signals.

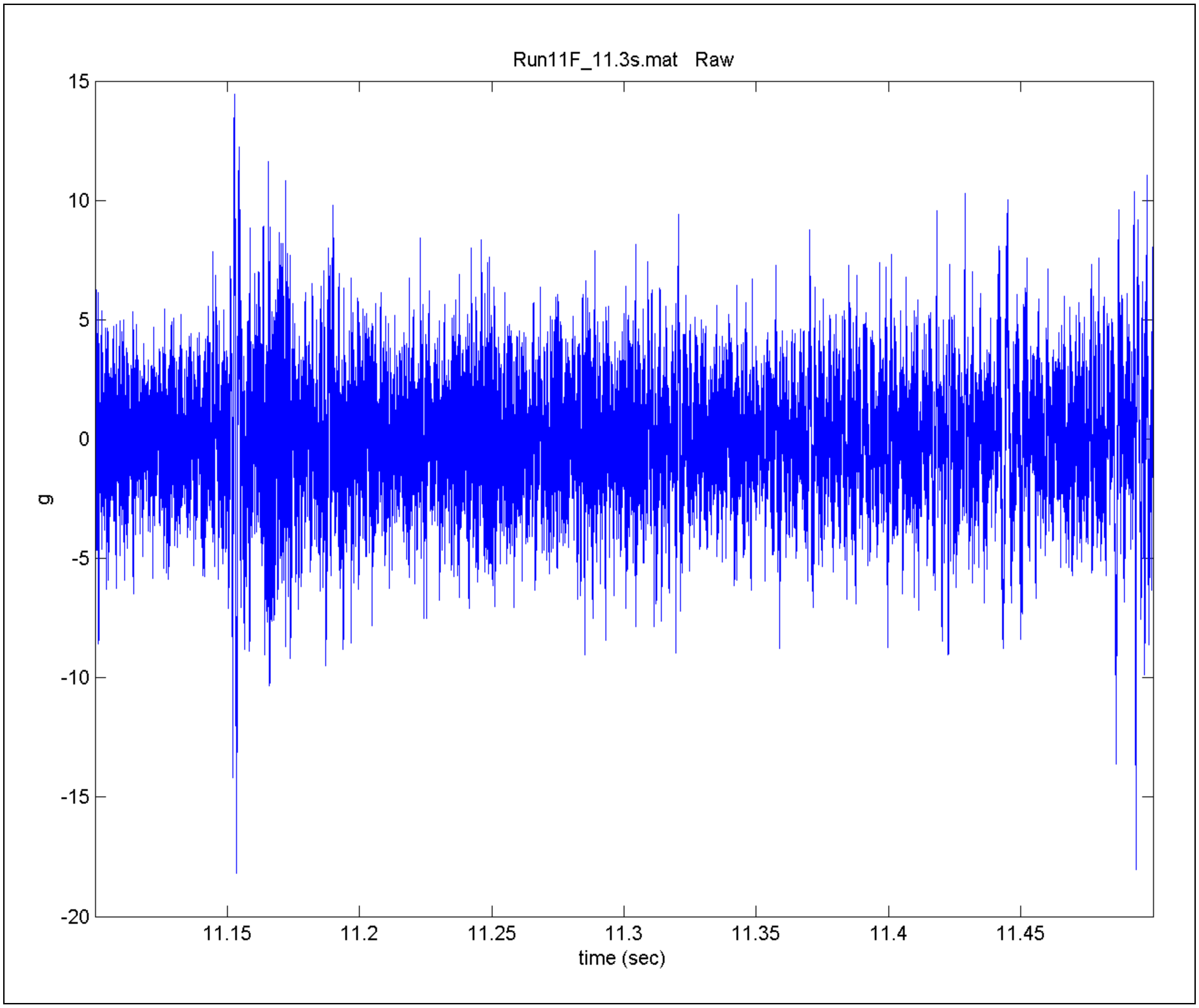


FIGURE 25 Wayside time history from test run 11F with sand on rail.

5. DISCUSSIONS AND CONCLUSIONS

This report described the effort to investigate the transmissibility of wheel bearing signals from the source to rail-mounted accelerometers, under real train operation conditions. Laboratory tests successfully demonstrated that the signals were detectable by these accelerometers, barring background noises. The laboratory tests further confirmed that the existence of a bearing on the axle intend for use in the field test.

The field test was successfully conducted in March 2010 on a NS track near Roanoke, VA. The test achieved all the objectives. The test consist included a hauling locomotive, a slave locomotive, a loaded gondola freight car as the test car, and the NS32 research car. The same accelerometers used and calibrated for the laboratory test in Stage I of the project were used during the field test. The accelerometers were instrumented both on the test car and on the rail at the test zone. Two data collection systems, one onboard the test consist and the other at wayside, collected data simultaneously when the test car passed the test zone. The test train passed the test zone at various speeds in both directions. Rail running surface was modified with sand and oil during four test runs to investigate their effect on the strength of the signals measured by the accelerometers both onboard and on the rail.

During the data analysis stage, a widely used envelope detection technique was employed to demodulate the signals of the known bearing defect. The signals are easily detectable by the onboard accelerometers which are close to the signal source. However, the signals do not seem to be prominent at wayside. There can be multiple factors that impeded the signal transmissibility. The most important one appears to be the noises from the wheel and rail contact interface. The frequency components of these noises happen to coincide with the bearing defect signals. Since these noises are closer to the wayside accelerometers than the bearing, their existence masked the bearing defect signals in the envelope detection analysis. Another important influencing factor is the transmission path of the bearing defect signals. For this particular case, the defect was on the bearing outer race (cup), which is fixed at the loading position. When the rotating rollers hit the defect, the impact force transfers down to the bearing inner race, and then to the axle. The path takes a 90° turn before reaching the wheel and continuing down to the rail and accelerometers. The leg from the axle to the wheel may have significantly damped the vertical component of the impact. The fact that the onboard accelerometer above the control bearing which is across the side frame from the defective bearing did not pick the defect bearing signals seems to support this assumption.

Increasing test speed strengthens signals. However, it does not improve the detectability of the bearing defect since it also enhances the adverse effects of the influencing factors discussed above. Contamination of the rail surface has little effect on the signals detected by the wayside accelerometers.

In summary, it appears that the signals transmitted through the transient mechanical path. However, the signals have been weakened upon arrival at the wayside accelerometers due to damping of the signal path. In addition, the background noises are found to coincide with the bearing signals. This has largely prevented a significant signal-to-noise ratio from being established for reliable defect detection.

The investigators of the project suggest that any future follow on efforts concentrate on detailed characterization of the background noise. These noises can then be excluded in the detection analysis. More sophisticated frequency domain analysis techniques, such as wavelet analysis can be employed. Time domain analysis should also be explored so that the complications of frequency domain can be ameliorated and more comprehensive signal clarification and characterization can be achieved.

6. REFERENCES

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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.

7. PRINCIPAL INVESTIGATOR PROFILE

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