U.S.
Department
**Federal
Railroad
Administration**

# ACOUSTIC DETECTION OF ROLLER BEARING DEFECTS: PHASE II, FIELD TEST

Office of Research and
Development
Washington, D.C. 20590

DOT/FRA/ORD-00/06.II

August 2003
Final Report

| REPORT DOCUMENTATION PAGE | Form approved<br>OMB No. 0704-0188 |
|---|---|

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0702-0288), Washington, D.C. 20503

| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | August 2003 | FRA, Nov.-Dec. 1996 |

| 4. TITLE AND SUBTITLE | 5. FUNDING NUMBERS |
|---|---|
| Acoustic Detection of Railcar Roller Bearing Defects:<br>Phase II, Field Test Report | DTFR53-93-C-00001, Task Order 111 |
| **6. AUTHOR(S)** | |
| Gerald B. Anderson, James E. Cline, Transportation Technology Center, Inc. and Richard L. Smith, North-South-East-West (NSEW) | |

| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) | 8. PERFORMING ORGANIZATION REPORT NUMBERS |
|---|---|
| Transportation Technology Center, Inc.<br>P.O. Box 11130<br>Pueblo, CO 81001 | |

| 9. SPONSORING/MONITORING AGENGY NAME(S) AND ADDRESS(ES) | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER |
|---|---|
| U.S. Department of Transportation Federal Railroad Administration<br>Office of Research and Development<br>1120 Vermont Avenue, NW<br>Washington, D.C. 20590 | DOT/FRA/ORD-00/06.II |

**11. SUPPLEMENTARY NOTES**

| 12a. DISTRIBUTION/AVAILABILITY STATEMENT | 12b. DISTRIBUTION CODE |
|---|---|
| This document is available through National Technical Information Service, Springfield, VA 22161 | |

**13. ABSTRACT**

The Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR) Research and Test Department, conducted a series of simulated revenue service tests with a train of eight cars containing wheel sets with specific roller bearing defects and wheel sets with good bearings. Testing was completed to record acoustic emissions of the bearings as they passed an array of microphones mounted along the track. Tests were conducted at the Transportation Technology Center in November and December 1996. Data collected was processed, filtered only to improve data quality, and distributed on compact disks to all program participants. The database was established to encourage development of advanced roller bearing inspection systems for railroad implementation. Participants included several potential developers of detector systems. The bearing defect types tested include raceway spalls (inner and outer ring, single or in multiples), roller defects, water etching, and loose inner rings (spun cones). This report describes the test methodology, instrumentation, and operation, as well as providing a description of the database content.

| 14. SUBJECT TERMS | 15. NUMBER OF PAGES |
|---|---|
| Acoustic railroad bearing detection, tapered railroad roller bearings, railroad bearing defects, spalls, water etching, loose inner rings, roller defects | 50 |
| | **16. PRICE CODE** |

| 17. SECURITY CLASSIFICATION | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | SAR |

NSN 7540-01-280-5500

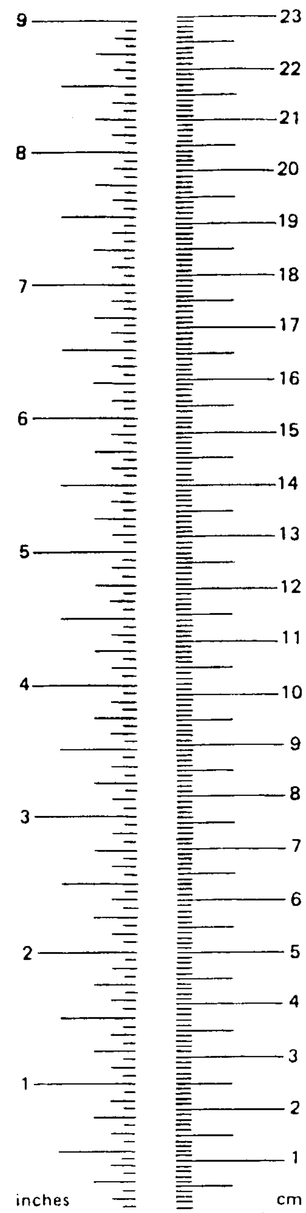
Standard Form 298 (Rec. 2-89)
Prescribed by ANSI/NISO Std. 239.18
298-102

# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

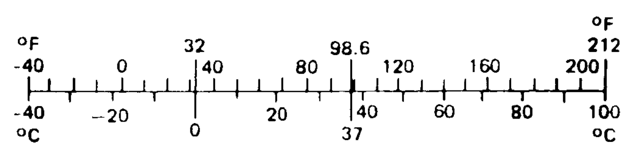
| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.50 | centimeters | cm |
| ft | feet | 30.00 | centimeters | cm |
| yd | yards | 0.90 | meters | m |
| mi | miles | 1.60 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.50 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.80 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.60 | square kilometers | $km^2$ |
| | acres | 0.40 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28.00 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.90 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5.00 | milliliters | ml |
| Tbsp | tablespoons | 15.00 | milliliters | ml |
| fl oz | fluid ounces | 30.00 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.80 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

* 1 in. = 2.54 cm (exactly)




## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.40 | inches | in |
| m | meters | 3.30 | feet | ft |
| m | meters | 1.10 | yards | yd |
| km | kilometers | 0.60 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centim. | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.20 | square yards | $yd^2$ |
| $km^2$ | square kilom. | 0.40 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.50 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.10 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 36.00 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.30 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32 | Fahrenheit temperature | °F |



## Acknowledgements

Those who contributed to making the field test a success are gratefully appreciated and acknowledged. First of all, we thank those TTCI staffers who assembled the bearings and put the test train together: Allen Armstrong, John Peachee, Ray Martin, and Joe Chamberlin. A special thanks to the train crew and test controller: Dean Holcomb, Bob Thuyns, and Gordon Columber. From the TTCI instrumentation crew, a special thanks to Richard Graff, Dave Williams, and Carl Bachhuber. And thanks to the engineering and computer support provided by Jim Bilodeau.

In addition to those directly involved in the test, the authors offer special thanks to the Federal Railroad Administration for making this program a reality, including Gerard Deily, Contracting Officers Technical Representative, and Monique Stewart, Task Order Technical Monitor.

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# EXECUTIVE SUMMARY

This research project solicited participation by industry and academia to stimulate the development of improved wayside defective railroad roller bearing detection techniques. A series of laboratory and field tests were conducted using defective and good railroad roller bearings to generate practical bearing acoustic emission databases. These databases will be available for the development of analytical techniques to "recognize" bearing defects from wayside sensor systems, and to produce working detector systems based on specific acoustic emissions.

This report describes the field tests of the Improved Freight Car Roller Bearing Wayside Inspection Program conducted by Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR) at the Federal Railroad Administration's (FRA) Transportation Technology Center (TTC) in Pueblo, Colorado. The program is funded by the FRA under Task Order No. 111, Contract DTFR53-93-C-00001, with in-kind support from the AAR. This report also provides a brief synopsis of the data collected. A thorough description of the acoustic instrumentation used to collect the data is provided along with the minimal filtering and processing performed on the data prior to distribution. The data was carefully checked before testing ended to ensure that all defective bearing conditions were represented in the database without error to the best knowledge of the authors. The database was distributed to the participants in binary format on two compact disks (CDs).

Objectives of the field test included: (1) determine if acoustic techniques can be reliably used in a wayside operation to identify the same specific bearing defects that were used in the laboratory test, (2) identify improvements in acoustic signal processing techniques, and (3) identify improvements in current wayside acoustic sensor arrays and/or improved array designs to enhance system performance. These objectives were accomplished by distributing the field test data of defective bearing acoustic emissions to program participants who will work with this data to develop improved wayside detector systems.

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# 1.0 INTRODUCTION

This report documents Phase II, the field test for wayside acoustic bearing development of the Improved Freight Car Roller Bearing Wayside Inspection Program conducted by Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR). The program was funded by the Federal Railroad Administration (FRA) under Task Order No. 111, with in-kind support from the AAR.

## 1.1 Objectives

Based upon the current understanding of the capabilities of present wayside acoustic roller bearing inspection technology, the following research objectives were determined for the field testing phase of the program.

Building on the success of the laboratory investigation (Phase I) of acoustic roller bearing defect detection, determine if acoustic techniques can be reliably used in a wayside operation to identify the same specific defects that were used in the laboratory test bearing specimens. Specifically, defects and objectives as identified in the AAR *Manual of Standards and Recommended Practices,* Section H-II, Rule 1.15 were:

1. Spun cone or loose components, in the absence of spalling of the raceway surfaces, for a bearing operating in the fully loaded or light car condition.
2. Broken roller element condition for a bearing operating in the fully loaded or light-car condition.
3. AAR condemnable cone spall defect for a bearing operating in the fully loaded or light-car condition.
4. AAR condemnable multiple connecting cone spall defect for a bearing operating in the fully loaded or light-car condition.
5. AAR condemnable cup spall defect for a bearing operating in the fully loaded or light-car condition.
6. AAR condemnable multiple connecting cup spall defect for a bearing operating in the fully loaded or light-car condition.
7. AAR condemnable water etching defects for a bearing operating in the fully loaded or light-car condition.
8. Identify improvements in acoustic signal processing currently in use and improved signal processing techniques.  Although many of the improvements may have been determined from the laboratory testing, the wayside acoustic processing will bring additional challenges to the inspection system function.
9. Identify improvements in current wayside acoustic sensor arrays and/or improved array designs to enhance system performance (reliability and repeatability).

## 1.2 Background

A meeting was held June 15, 1994, at what was then the AAR's Chicago Technical Center to initiate and review objectives of the Improved Freight Car Roller Bearing Wayside Inspection Program, sponsored by the AAR and the FRA. The objective of the meeting was to solicit participation by industry and academia to stimulate the development of improved wayside defective roller bearing detection techniques. Over 45 participants from industry, academia, and the national laboratories attended the meeting (Appendix A is a list of all participants).

The planned means of accomplishing the objective was for the AAR to conduct a series of controlled laboratory and on-track tests to aid in the development of improved wayside defective railroad roller bearing detection. The controlled laboratory tests were conducted on the AAR's bearing test machines at the Transportation Technology Center (TTC), Pueblo, Colorado. A set of data from each of the good and defective bearings tested was made available to program participants for their bearing detection process development.

Using many of the same defective bearings, the AAR conducted an on-track test series at the TTC, to provide an opportunity to develop improved detection techniques under controlled, simulated revenue service conditions. The tests were conducted in November 1996, using a combination of eight empty and loaded freight cars of different capacity with a mix of good, remanufactured, and defective bearings. This research program has and will continue to provide an indispensable database for developing and refining signal processing techniques for the identification of defective roller bearings on freight cars.

## 2.0 TEST SPECIMENS

### 2.1 Test Train Make-up

The test train consisted of one locomotive followed by eight 70- and 100-ton capacity freight cars, four loaded and four empty (see Figure 1).

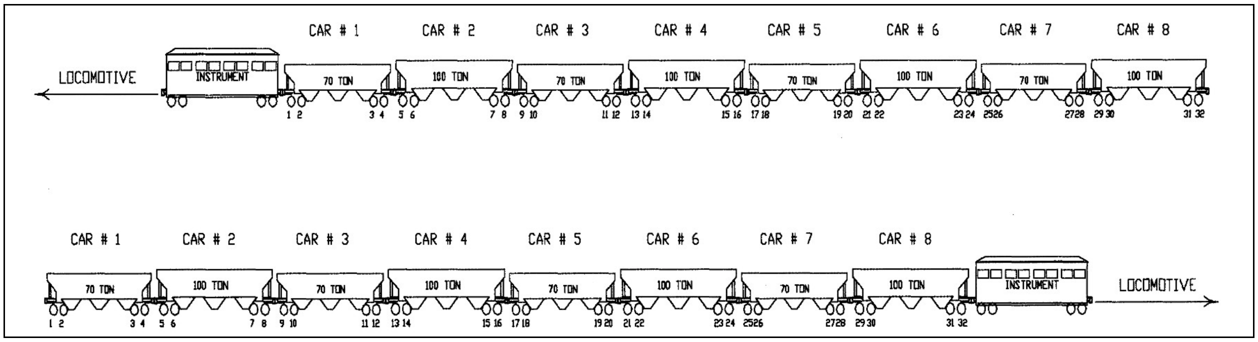


**Figure 1. Test Train**

Wheel sets and/or trucks were switched between freight cars once during the testing to place defective bearings under different car loads. There was an AAR test/instrumentation car in the consist as well to provide onboard monitoring of defective bearings and other support services. Each car was weighed on a car scale before testing. Table 1 lists the car numbers and their weights.

The test train was operated past the wayside instrumentation from both directions. Both train directions are shown in Figure 1. Note that in the lower illustration, the direction of movement and the location of the instrumentation car and locomotive have changed. The other cars are not turned. The side of the cars with the defective bearings were always toward the south, the side of the wayside instrumentation.

For the purpose of presenting different combinations of bearings to the wayside sensor array(s), 70- and 100-ton cars, empty and loaded, were distributed in the train in a pseudo-random manner. There were "good" bearings distributed between the defective bearings for the same purpose. Table 2 lists the locations of the defective bearings in the test consist for the first half and Table 3 for the second half of the test. Each figure shows the onboard instrumentation that was used to monitor the defective bearings. Photographs of each defective bearing, from leading end of first car sequentially down to the train, are in Appendix B.

**Table 1.  Car Numbers and Weights**

| Car Number | A-End Weight | B-End Weight | Total Weight (lbs.) | Car Capacity |
|---|---|---|---|---|
| DOTX 205 | 80467 | 80063 | 160530 | Inst. Car |
| TTX 479303 | 68182 | 78015 | 146197 | 70-Ton loaded |
| AAR 704 | 133034 | 133018 | 266052 | 100-Ton loaded |
| DOTX 307 | 78819 | 86739 | 165558 | 70-Ton loaded |
| AAR 703 | 132885 | 133687 | 266572 | 100-Ton loaded |
| TTWX 981423 | 34106 | 35891 | 69997 | 70-Ton empty |
| AAR 707 | 39285 | 48459 | 87744 | 100-Ton loaded |
| RTTX 152423 | 35046 | 35664 | 70710 | 70-Ton empty |
| AAR 705 | 32103 | 33632 | 65735 | 100-Ton empty |

**Table 2.  Defective Bearing Location & Onboard Instrumentation**

| First Half—Wayside Bearing Defect Detection Consist Table | | | | | |
|---|---|---|---|---|---|
| Car | BEARING | DEFECT | TEMP | ACCEL | CONE SLIP |
| | 1 | Single Cup Spall | | | |
| No. 1 | 2 | Remanufactured | | | |
| 70T | 3 | Single Cone Spall | | | |
| LOAD | 4 | Remanufactured | | | |
| | 5 | Single Cup Spall | | | |
| No. 2 | 6 | Remanufactured | | | |
| 100T | 7 | Single Cone Spall | | | |
| LOAD | 8 | Remanufactured | | | |
| | 9 | Broken Roller | X | | |
| No. 3 | 10 | Remanufactured | | | |
| 70T | 11 | Water Etched | X | | |
| | 12 | Remanufactured | | | |
| | 13 | Remanufactured | | | |
| No. 4 | 14 | Spun Cone | X | X | X |
| 100T | 15 | Spun Cone | X | X | X |
| LOAD | 16 | Remanufactured | | | |
| | 17 | Remanufactured | | | |
| No. 5 | 18 | Spun Cone | X | X | X |
| 70T | 19 | Spun Cone | X | X | X |
| EMPTY | 20 | Remanufactured | | | |
| | 21 | Remanufactured | | | |
| No. 6 | 22 | Water Etched | X | | |
| 100T | 23 | Remanufactured | | | |
| EMPTY | 24 | Broken Roller | X | | |
| | 25 | Remanufactured | | | |
| No. 7 | 26 | Multiple Cone Spall | | | |
| 70T | 27 | Mystery | | | |
| EMPTY | 28 | Multiple Cup Spall | | | |
| | 29 | Remanufactured | | | |
| No. 8 | 30 | Multiple Cone Spall | | | |
| 100T | 31 | Mystery | X | | |
| EMPTY | 32 | Multiple Cup Spall | | | |

**Table 3. Defective Bearing Location and Onboard Instrumentation**

| Second Half—Wayside Bearing Defect Detection Consist Table | | | | | |
|---|---|---|---|---|---|
| Car | BEARING | DEFECT | TEMP | ACCEL | CONE SLIP |
| | 4 | Remanufactured | | | |
| No. 1 | 3 | Single Cone Spall | | | |
| 70T | 2 | Remanufactured | | | |
| LOAD | 1 | Single Cup Spall | | | |
| | 8 | Remanufactured | | | |
| No. 2 | 7 | Single Cone Spall | | | |
| 100T | 6 | Remanufactured | | | |
| | 12 | Remanufactured | | | |
| No. 3 | 11 | Water Etched | X | | |
| 70T | 10 | Remanufactured | | | |
| LOAD | 9 | Broken Roller | X | | |
| | 16 | Remanufactured | | | |
| No. 4 | 15 | Spun Cone | X | X | X |
| 100T | 14 | Spun Cone | X | X | X |
| LOAD | 13 | Remanufactured | | | |
| | 20 | Remanufactured | | | |
| No. 5 | 19 | Spun Cone | X | X | X |
| 70T | 18 | Spun Cone | X | X | X |
| EMPTY | 17 | Remanufactured | | | |
| | 24 | Broken Roller | X | | |
| No. 6 | 23 | Remanufactured | | | |
| 100T | 22 | Water Etched | X | | |
| EMPTY | 21 | Remanufactured | | | |
| | 28 | Multiple Cup Spall | | | |
| No. 7 | 27 | Mystery | | | |
| 70T | 26 | Multiple Cone Spall | | | |
| EMPTY | 25 | Remanufactured | | | |
| | 32 | Multiple Cup Spall | | | |
| No. 8 | 31 | Mystery | X | | |
| 100T | 30 | Multiple Cone Spall | | | |
| EMPTY | 29 | Remanufactured | | | |

## 2.2 Test Site

Testing was conducted at TTC on the Railroad Test Track (RTT) at the existing Hot Bearing Detector (HBD) test farm (Station 14). This location is equipped with two bungalows with 100 VAC power and telephone services. The track section at Station 14 is tangent with a grade of 0.26 percent. Figure 2 shows the test site.

**Figure 2. Wayside Test Site**

# 3.0 INSTRUMENTATION AND DATA COLLECTION

## 3.1 Data Sensors

The AAR, under this joint program, provided a microphone array to collect the wayside acoustic emissions of the passing test train. The data from this array comprised, in large part, the data distributed to the program participants. The 12-microphone array, Figure 3, was set back from the test track (measured from gage face of rail) approximately 38 inches, with a spacing between microphones of 35 inches. The microphones were mounted horizontally, as shown, and based at a compromise height of 35 inches (for 33- and 36-inch wheels) from top of rail at the same height as the centerline of the roller bearings. Each microphone was protected from wind noise by a wind sock. The microphones have a frequency response of 1 Hz to 40 kHz. The low frequency response of the microphones caused a problem by responding to the aerodynamic bow wave in front of the locomotive. This was seen in the data as a large DC offset with a rather slow recovery. High-pass filtering was added to some microphone channels during the testing to alleviate this problem. For the remainder of the channels, the data was digitally filtered after the test.

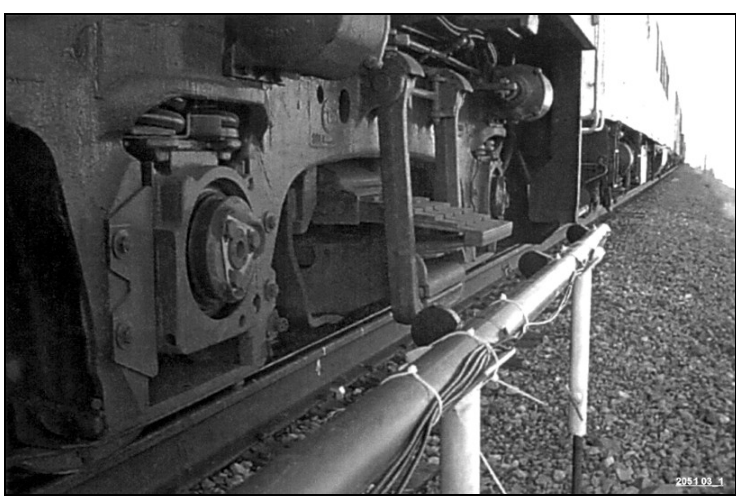

**Figure 3. Microphone Array**

Wheel presence detectors, operating by electromagnetics, were used to indicate axle speed and to position the wheels in time relative to the location of the microphones.

In addition to the wayside acoustic array, onboard bearing sensors were used to monitor temperature on those defective bearings whose performance at test speeds and loads was deemed critical. The critical bearing defects included spun cones and damaged rollers, because industry research has shown that these defects are the most likely to lead to rapid bearing burn off. Sensing was done for safety purposes and was not included in the data set CD.

The spun cone bearings were also equipped with the cone motion sensor system that was used in the laboratory tests for measuring cone rotation. This sensing system consisted of small rare earth magnets attached to the axle, as a fixed reference, and to the bearing cone back face. "Hall Effect" (physical phenomena) sensors located off the axle and in the bearing seal case were used to trigger timers to reference cone motion to that of the axle. Identical values represented no relative cone to axle rotation. Differential readings indicate relative motion as well as the amount of cone slip.

Train speed was recorded from onboard the test car within 1 mph, and train presence/speed pulses were recorded at wayside. An existing HBD system on the RTT (Servo 9000) was also used to monitor bearing temperatures and as a comparative performance measure for the onboard safety sensors.

### 3.2 Data Collection System

The wayside acoustic and wheel presence data was collected in parallel by fast digital computer and on analog tape. The tape was used as backup for the digital computer. A sample rate of 125 kHz per channel was chosen for the microphones to fully support the highest expected useful frequency content of the data. The sample rate was based on frequency evaluation of the laboratory data. An analog filter for anti-aliasing was used between the microphones and the digital computer with an appropriate filter cut-off frequency. As stated previously, a high-pass filter, set to approximately 8 Hz was installed between some of the microphones and the computer during the testing. All data was digitally filtered in the post-test data processing. Figure 4 shows the wayside instrumentation.

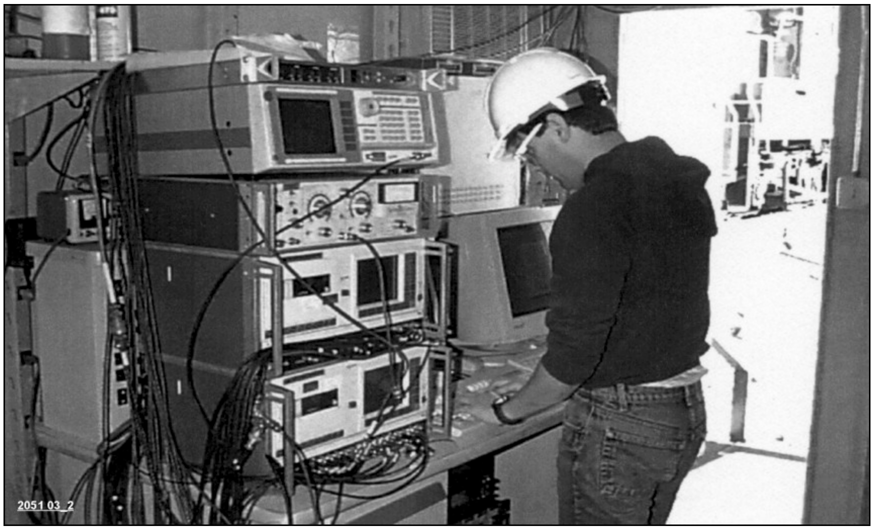


**Figure 4. Wayside Instrumentation Setup**

Data was sampled and stored in RAM (memory) on the computer during each test run. After each run, this data was written to a hard drive in a packed binary format. Subsequently, this data was re-formatted to standard binary for processing.

In addition to the data collected under this program, several of the program participants brought their own instrumentation and data collection equipment. Data collection was proprietary to each participant, but the list of those involved is included here for information:

1. Harmon Industries - wayside acoustic data
2. Salient Systems/Battelle Labs - wayside acoustic data
3. Vipac Inc. - wayside acoustic data
4. SAIC - wayside thermal data
5. GRS - onboard thermal data
6. Elexor Associates - onboard thermal data
7. Brenco - onboard bearing data
8. Timken - onboard bearing data
9. NSEW - wayside acoustic data

## 4.0 TEST PROCEDURES

### 4.1 General Procedures

The test was divided into two halves. Many identical test runs were made in both halves, but the test consist and defective bearings were rearranged between the halves. In this manner, the defective bearings were moved from lightly loaded to heavily loaded axles and vice-versa.

A test run consisted of backing the train a sufficient distance to achieve the desired speed past the wayside instrumentation. After backing, the consist was accelerated to the desired speed and run past the wayside instrumentation. For test runs at 70 miles per hour (mph), a complete lap around the RTT was made.

The train was braked to a stop after almost all runs. The test train was operated in three different modes past the instrumentation. In most cases, locomotive power was applied and speed was held constant. The train was also operated in coast mode, where speed was allowed to diminish slightly as locomotive power was put to idle.

The third mode was braking. Here the train was accelerated to the desired speed, then before reaching the wayside instrumentation, a train air brake application was made. The amount of the brake application was typically half service.

During a test run, the wayside instrumentation was operated for a period before train arrival and shortly after departure to ensure complete capture of the acoustic information. Data files were then trimmed to remove excess "zero" information during post test data processing.

In addition to the wayside instrumentation, the critical bearing temperatures and cone movement in the spun cone bearings were monitored from the instrumentation car during all train movements. Onboard data was also collected during each test run for post-test review.

## 5.0 TEST RESULTS

Table 4 lists the test run numbers and other pertinent information for the first half of the test. Table 5 shows data from the second half.

**Table 4. Test Run Information—First half**

| Run No. | Date | Time | Speed | Mode |
|---|---|---|---|---|
| 1a | 11/18/96 | 13:05 | 25 | Power CW* |
| 1b | 11/18/96 | 13:34 | 25 | Power CW |
| 2a | 11/18/96 | 13:50 | 30 | Power CW |
| 3a | 11/18/96 | 14:15 | 40 | Power CW |
| 2b | 11/18/96 | 14:48 | 30 | Power CW |
| 4a | 11/18/96 | 15:23 | 50 | Power CW |
| 5a | 11/18/96 | 16:08 | 55 | Power CW |
| 6a | 11/18/96 | 16:28 | 60 | Power CW |
| 7a | 11/18/96 | 16:55 | 70 | Power CW |
| 1c | 11/19/96 | 09:40 | 25 | Power CW |
| 8a | 11/19/96 | 10:15 | 30 | Power CW |
| 9a | 11/19/96 | 10:26 | 30 | Power CW |
| 10a | 11/19/96 | 10:46 | 50 | Power CW |
| 10b | 11/19/96 | 13:01 | 50 | Power CW |
| 11a | 11/19/96 | 13:26 | 30 | Coasting |
| 12a | 11/19/96 | 13:42 | 40 | Coasting |
| 13a | 11/19/96 | 13:54 | 50 | Coasting |
| 14a | 11/19/96 | 14:28 | 30 | Braking |
| 15a | 11/19/96 | 14:40 | 40 | Braking |
| 16a | 11/19/96 | 14:54 | 50 | Braking |
| 17a | 11/20/96 | 09:43 | 25 | Power CCW** |
| 18a | 11/20/96 | 09:55 | 30 | Power CCW |
| 19a | 11/20/96 | 10:05 | 40 | Power CCW |
| 20a | 11/20/96 | 10:36 | 50 | Power CCW |
| 21a | 11/20/96 | 10:53 | 55 | Power CCW |
| 22a | 11/20/96 | 13:02 | 60 | Power CCW |
| 23a | 11/20/96 | 13:13 | 70 | Power CCW |
| 23b | 11/20/96 | 13:34 | 70 | Power CCW |
| 24a | 11/20/96 | 14:44 | 30 | Power CCW |

*Clockwise **Counterclockwise

**Table 5. Test Run Information—Second half**

| Run No. | Date | Time | Speed | Mode |
|---|---|---|---|---|
| 27a | 11/25/96 | 11:22 | 25 | Power CCW |
| 28a | 11/25/96 | 11:41 | 30 | Power CCW |
| 29a | 11/25/96 | 13:33 | 40 | Power CCW |
| 30a | 11/25/96 | 14:13 | 50 | Power CCW |
| 31a | 11/25/96 | 14:35 | 55 | Power CCW |
| 32a | 11/25/96 | 14:53 | 60 | Power CCW |
| 33a | 11/25/96 | 15:42 | 70 | Power CCW |
| 33b | 11/25/96 | 15:58 | 70 | Power CCW |
| 34a | 11/25/96 | 16:21 | 30 | Power CCW |
| 36a | 11/25/96 | 16:47 | 50 | Power CCW |
| 43a | 11/26/96 | 09:32 | 25 | Power CCW |
| 45a | 11/26/96 | 09:46 | 40 | Power CCW |
| 46a | 11/26/96 | 10:05 | 50 | Power CCW |
| 48a | 11/26/96 | 10:47 | 60 | Power CCW |
| 49a | 11/26/96 | 11:08 | 70 | Power CCW |
| 41a | 11/26/96 | 11:32 | 40 | Braking CCW |
| 42a | 11/26/96 | 13:25 | 50 | Braking CCW |
| 48b | 11/26/96 | 13:43 | 60 | Power CCW |
| 49b | 11/26/96 | 13:59 | 70 | Power CCW |
| 41b | 11/26/96 | 14:18 | 40 | Braking CCW |

Upon completion of the test runs, the digital data was checked for integrity by plotting select test run time histories at various operating speeds. Based on an analysis of these plots, a method was determined for trimming the files for excess data taken either before the train reached the microphone array or after it had passed. A program was written to process each of the test files, to trim them and to multiply the binary values for engineering units. These processed files were then plotted to check for spurious data points, offsets, and other obvious digitization errors. When the data was reviewed, and the quantity of data realized, a selection was made of the "best" or cleanest data files for inclusion in the CDs for release to the program participants.

Ultimately, 19 test runs were included in the two CDs that were produced in April of 1997. These test runs encompassed the full range of train speeds and operating conditions. The run numbers and other information are shown in Table 6.

**Table 6. Test Run Data Included in CDs**

| Run No. | Train Speed | Operating Mode | Consist Configuration |
|---|---|---|---|
| 12a | 40 | Power CW | 1 |
| 13a | 50 | Coasting CW | 1 |
| 14a | 30 | Braking CW | 1 |
| 15a | 40 | Braking CW | 1 |
| 16a | 50 | Braking CW | 1 |
| 18a | 30 | Power CCW | 1 |
| 19a | 40 | Power CCW | 1 |
| 20a | 50 | Power CCW | 1 |
| 21a | 55 | Power CCW | 1 |
| 22a | 60 | Power CCW | 1 |
| 23b | 70 | Power CCW | 1 |
| 24a | 30 | Power CCW | 1 |
| 34a | 30 | Power CCW | 2 |
| 36a | 50 | Power CCW | 2 |
| 41a | 40 | Braking CCW | 2 |
| 42a | 50 | Braking CCW | 2 |
| 45a | 40 | Power CCW | 2 |
| 48a | 60 | Power CCW | 2 |
| 49a | 70 | Power CCW | 2 |

Table 7 provides the statistics made from the laboratory data. A similar approach was initially tried for the wayside data. After examining statistics from a few runs, the signal processing methods better revealed the character and usefulness of the file.

**Table 7. Typical Statistical Table—Lab Data (volts)**

| File | Mean | Var | StDev | Skew | Kurtosis | Min | Max |
|---|---|---|---|---|---|---|---|
| 30hst90 | -0.002 | 1.809 | 1.345 | 0.134 | -1.411 | -1.968 | 2.151 |
| 30hsc90 | 0.216 | 125.589 | 11.207 | -0.027 | 1.302 | -57.976 | 70.898 |

| File | Range | C.V. | Counts | LMean | UMean | LVar | UVar |
|---|---|---|---|---|---|---|---|
| 30hst90 | 4.120 | -558.104 | 65536.000 | -0.013 | 0.008 | 1.789 | 1.829 |
| 30hsc90 | 128.874 | 51.926 | 65536.000 | 0.130 | 0.302 | 124.240 | 126.960 |

Figure 5 shows a series of typical plots made for a single test run. In addition to the plots made, statistical analyses were performed for each of the data channels for each test run, as a means of determining offsets and other data variations.

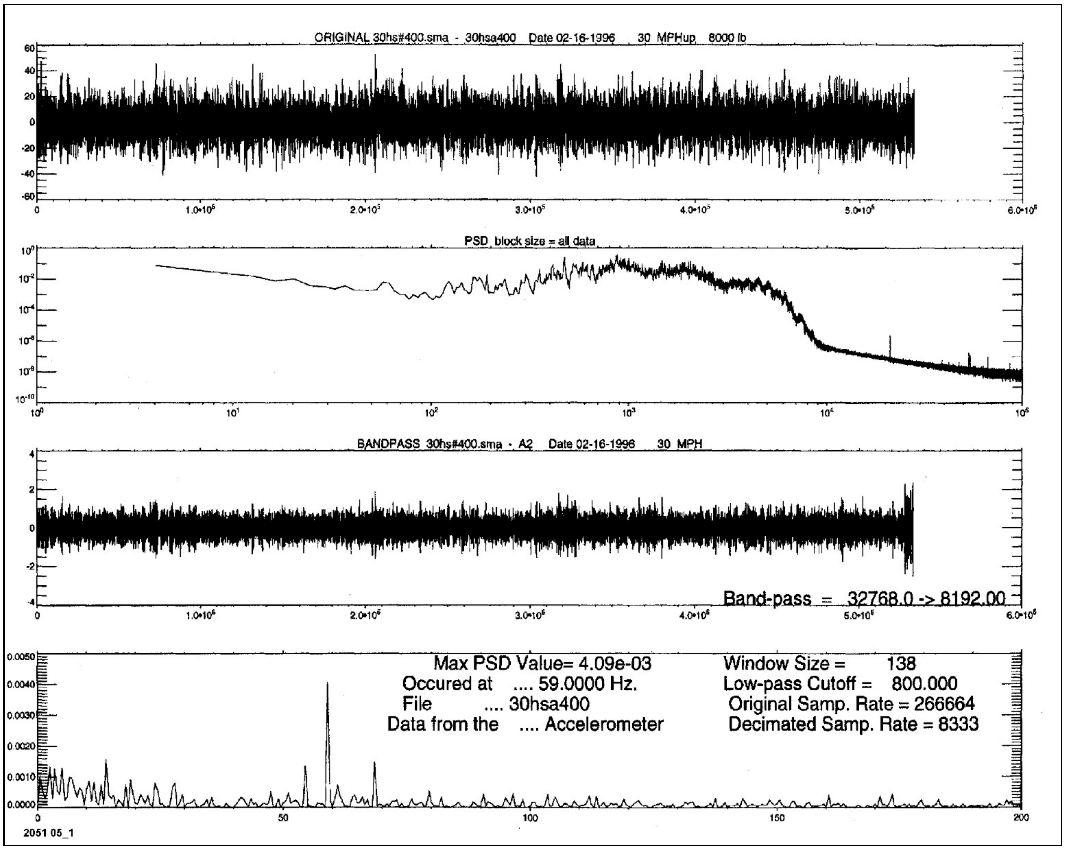


**Figure 5. Typical Test Run Data Plot**

Early in the first half of the test on November 18, 1996, a large pressure wave was shown to be preceding the lead locomotive, and to a lesser extent at the leading edge of each hopper car that trailed a flat car. The effect of these pressure or "bow" waves is exaggerated in Figure 6. The air pressure in the wave caused a large offset to each of the 12 microphones as it passed. The frequency content of the wave was less than 2 Hz.

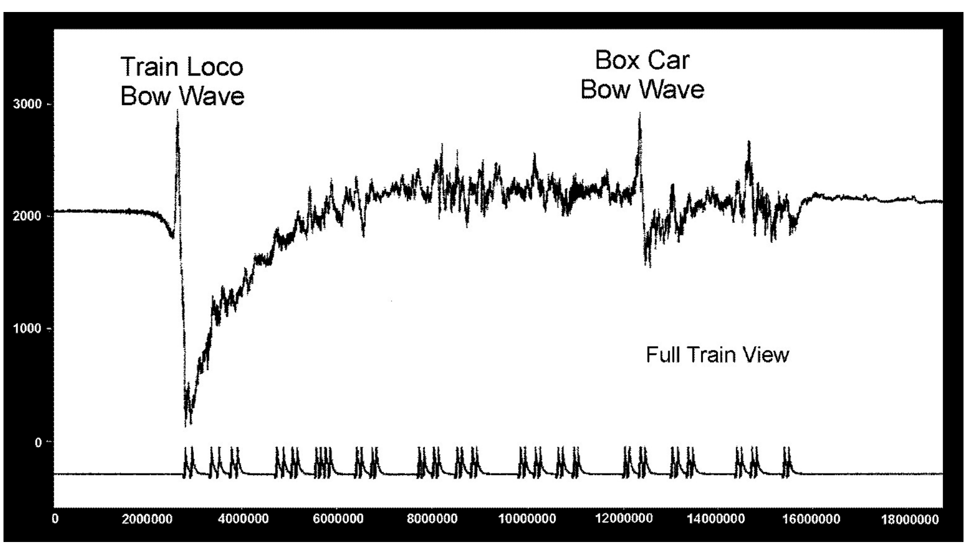


**Figure 6. Exaggerated Illustration of Bow Wave Effect**

To reduce the effect of the bow waves on the test data, filtering was obtained for some of the microphones to do high frequency passing (above 8 Hz), and thus to filter out the low frequency offset. There were not enough channels of filtering to accommodate all the microphones, so the bow wave effect was digitally filtered as part of the post test data processing. This effect was overlooked in test preparations.

# 6.0 DISCUSSION

## 6.1 Acoustic Data

Acoustic data from 49 test runs at speeds ranging from 25 to 70 mph were gathered from the wayside microphones. With 12 microphones and 2 wheel sensors, there was enough recorded data collected to fill several CDs.

Two CDs, which represented the full range of test conditions, were recorded for release to the program participants. Each CD contains 500 megabytes of acoustic time-based bearing data along with bearing defect photographs and other test operational information. The CDs contain 14 binary files for every test run included. Each file name has been encoded so that running speed and other operating conditions can be interpreted from the alphanumeric title. Each file also has a unique 3-digit extension that indicates from which microphone and/or wheel sensor the data was received. Table 8 lists the test runs and the size of the associated stored files on the two CDs.

**Table 8. CD File Sizes and Names**

| Run No. | File Name | Samples per File | Sample Rate (kHz) | CD No. |
|---|---|---|---|---|
| 12a | 12AC1S40 | 1206620 | 1.25 | 1 |
| 13a | 13AC1S50 | 953575 | 1.25 | 1 |
| 14a | 14AB1S30 | 1520561 | 1.25 | 1 |
| 15a | 15AB1S40 | 1166823 | 1.25 | 1 |
| 16a | 16AB1S50 | 987238 | 1.25 | 1 |
| 18a | 18AP1N30 | 1645071 | 1.25 | 1 |
| 19a | 19AP1N40 | 1174448 | 1.25 | 1 |
| 20a | 20AP1N50 | 1016290 | 1.25 | 1 |
| 21a | 21AP1N55 | 866557 | 1.25 | 1 |
| 22a | 22AP1N60 | 800016 | 1.25 | 1 |
| 24a | 24AP1N30 | 1651274 | 1.25 | 2 |
| 34a | 34AP2N30 | 1699602 | 1.25 | 2 |
| 36a | 36AP2N50 | 1012640 | 1.25 | 2 |
| 41a | 41AP2N40 | 1328932 | 1.25 | 2 |
| 42a | 42AP2N50 | 1129141 | 1.25 | 2 |
| 45a | 45AP2N40 | 1242085 | 1.25 | 2 |
| 48a | 48AP2N60 | 837721 | 1.25 | 2 |
| 49a | 49AP2N70 | 749145 | 1.25 | 2 |

In addition to the acoustic data, each CD also contains photographs of the defective test bearings. Two of the bearings are shown in detail in Figures 7 and 8. The bearings have large spalls on the cup and cone raceways, respectively. The bearing with the cone spalls (Figure 8) is also one of the test bearings operating with a spun cone. The frequency content of the types of defects shown in these two figures is given in Figures 9 through 11.

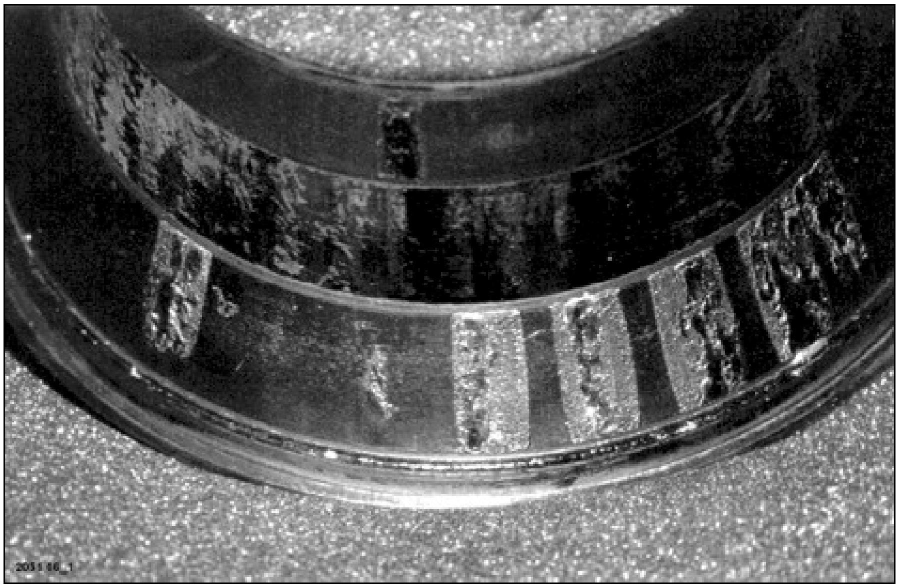

**Figure 7. Large Cup Defect in Bearing on Axle 4 of Run 24**

The acoustic signature from Run No. 24a (first half - consist given in Table 2) is shown in Figures 9 through 11. Figure 9 shows a plot of the numeric data from microphone 1 as stored on the CD (i.e., disk file 24AP1N30.001). This time based display contains over 1.65 million real data points. The first time derivative of the data is displayed in Figure 10. This data has essentially the same frequency content as the previous plot, but contain no bias offset on the vertical axis. The purpose of the following discussion is to illustrate that the raw acoustic data contained in the CDs contains good bearing defect data when properly processed. It is presented here to verify basic data integrity and its use in the development of systems for defect recognition.


**Figure 8. Large Cone Defect in Bearing from Axle 19 of Test Run 24**

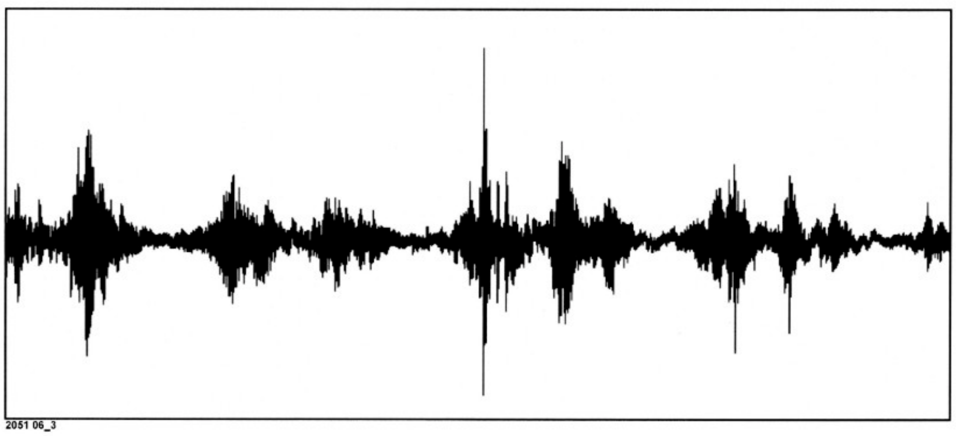


**Figure 9. Raw Acoustic Microphone Output from "Run 24AP1N30.001"**

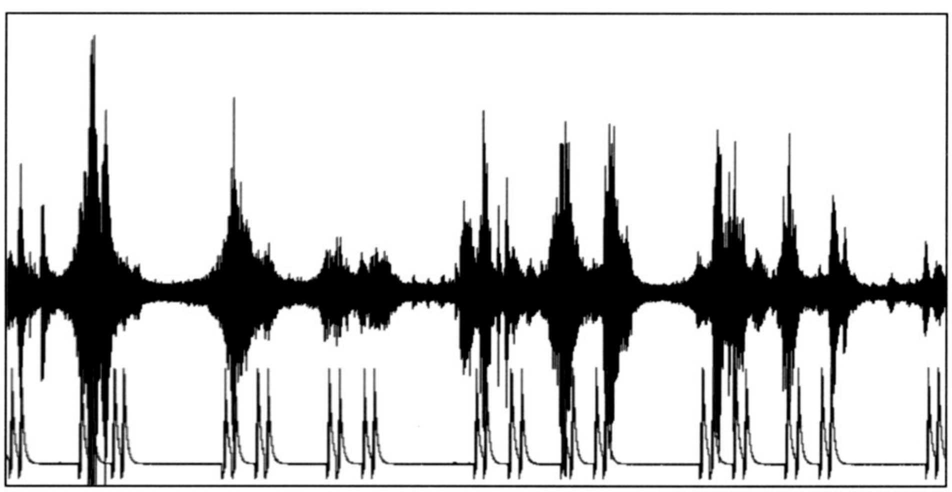


**Figure 10. First Derivative of Acoustic Microphone Output from "Run 24AP1N30.001" with Wheel Gate Signatures attached below.** Spikes in Wheel Signature are near the Bearing Locations during the Test Run. Numbers below the Two-Time Traces indicate the Center of each of the Test Cars for the Run.

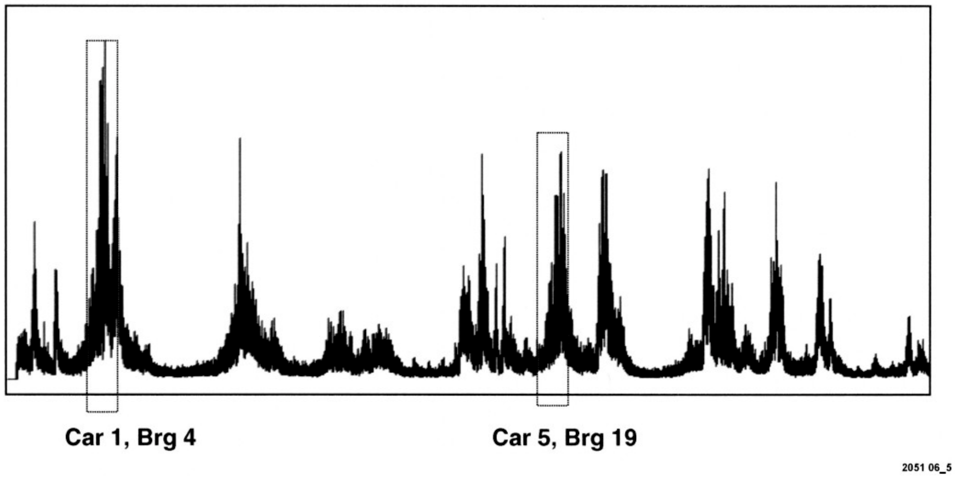


**Figure 11. CD Data File 24AP1N30.001 after Envelope Detection Processing is Applied**
(Dotted boxed portions of the above signals are discussed more thoroughly in *Technology Digest* 96-004 issued February 1996)

The frequency content of the time signatures ranges from 3 Hz to over 40 kHz. At the base of Figure 10 is the wheel presence detector, which provides a sharp spike for every one of the 32 passing wheels (bearings). The wheel spikes provide time based reference points that can be used to identify the acoustic signal position (and thus the character) of any passing test bearing after it passed. The center of each test car is also shown by a number.

Figure 11 shows the time data from Figure 10 after it has been detected by the envelope. This process extracts a smooth outline tracing of the upper portion of the time based signature and ignores the negative part of the signal. Details of the envelope detection process and its potential for defect diagnostics have been discussed thoroughly in *Technology Digest* 96-004 issued by TTCI February 1996. The bearing defects shown in Figures 7 and 8 generated the acoustic outputs that have been boxed in with dotted lines in Figure 4.

Figure 12 provides an expanded view of the microphone envelope signal from the fourth bearing on car 1. The signature comes from the severely spalled cup raceway, Figure 8.

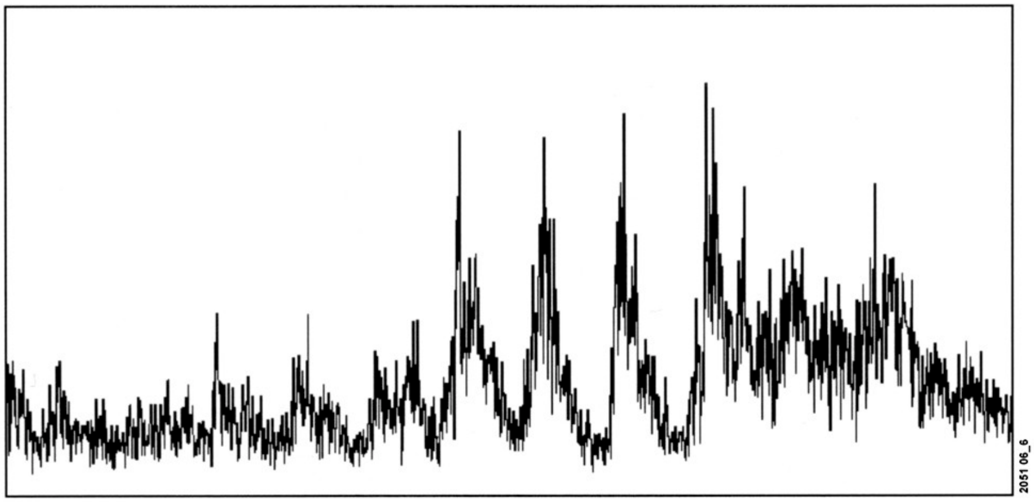


**Figure 12. Expanded CD Data File 24AP1N30.001 Signature from the up Defective Bearing on Axle 4 of Car 1** (See dotted boxed portion of Figure 11)

Figure 13 shows a low-frequency spectrum of the time based signature displayed in Figure 12. The spectrum has two dominant peaks. The one at 3.8 Hz corresponds to the anticipated rotational rate of the bearing (4.6 Hz) at 30 mph. The 3.8 Hz peak is within the expected frequency range since a single microphone can only provide enough time based data from typical wayside passes to resolve any peak within 1 Hz. The second peak at 49 Hz comes directly from the cup defect repetition rate at 30 mph.

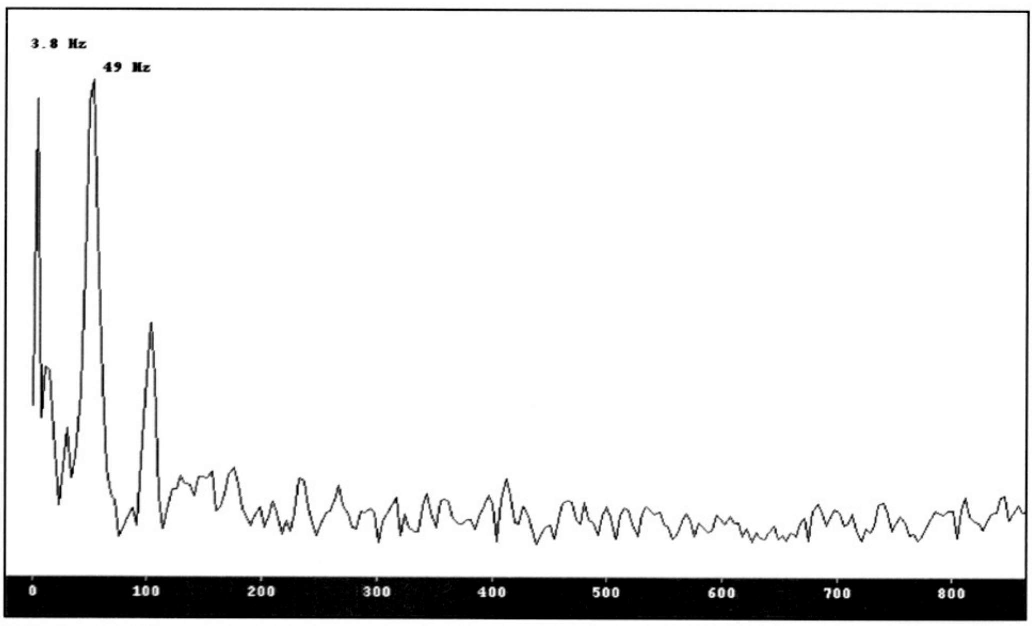


**Figure 13. Spectrum of Above Enlarged Trace from Cup Defective Bearing on Axle 4. The 49 Hz Peak Corresponds to the Cup Defect**

Figure 14 is an expanded view of the data from bearing 19 on car 5.  This bearing contains the severely damaged cone shown in Figure 8.  Figure 15 shows the low-frequency content of the time signature in Figure 14.  It contains two or three dominant peaks.  As before, the peak at 3.8 Hz corresponds to the rotational rate (4.6 Hz) of the bearing at the 30 mph running speed.  The second peak at 61 Hz comes directly from the cone defect repetition rate at the same speed.  In this spectra there is also a minor peak at 15 Hz.  Since this bearing also contains a spun cone defect, this anomalous peak may be associated with that defect, as well as other possible internal component damage.

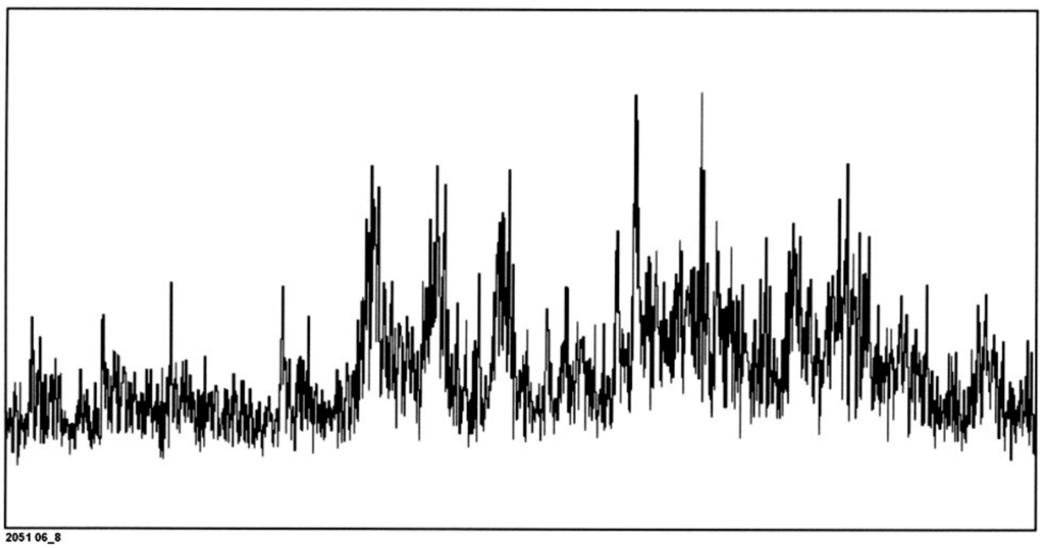


**Figure 14. Expanded CD Data File 24AP1N30 Signature from the Cone Defective Bearing on Axle 19 of Car 5 (**See boxed portion of Figure 11)

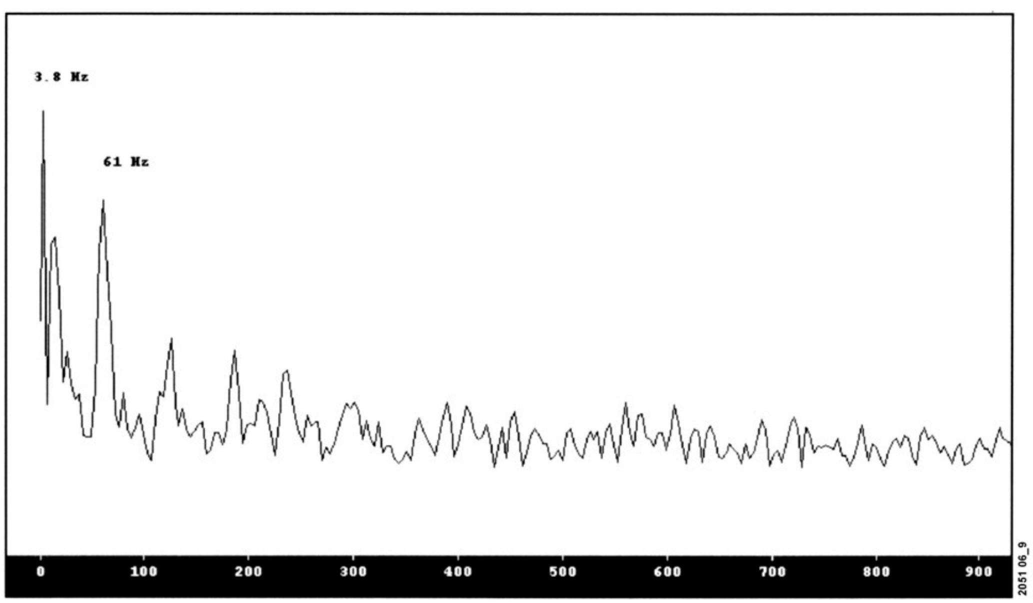


**Figure 15. Spectrum of above Enlarged Trace from Cone Defective Bearing on Axle 19**
The 61 Hz Peak corresponds to the Cone Defect Repetition Rate (Frequency) at the 30 mph Running Speed

Figures 16 and 17 show a variety of signal characteristics collected form axles (bearings) 11, 15, 17, 18, and 19 in consist two. The train running speeds were 50 mph 60 mph. The interesting feature is that all the defective bearings emitted high frequency sounds, above 15 kHz. These vibrations were observed in several microphones in the wayside array. Since several microphones were in a linear array, it is also possible to review signals from any single bearing as it approached (or receded) from any of the centrally located microphones. Doppler shifts from loud approaching (or receding) bearings were observed.

Note to Figure 16: Sound of Bearing 18 from 17's microphone point of reference is on approach (i.e. Doppler shifted frequency higher). Also from Bearing 19's microphone point of reference, the sound of Bearing 18 is receding (i.e. Doppler shifted frequency lower). Distance from Bearing 18 to Bearing 17 is 10 feet and distance from 19 to 18 is about 40 feet, so the observed level of 18's sound in Bearing 19"s record is lower than it is in the spectral record of 17. The source of the sharp peak at 32 KHz on the right side of each spectrum in unknown.

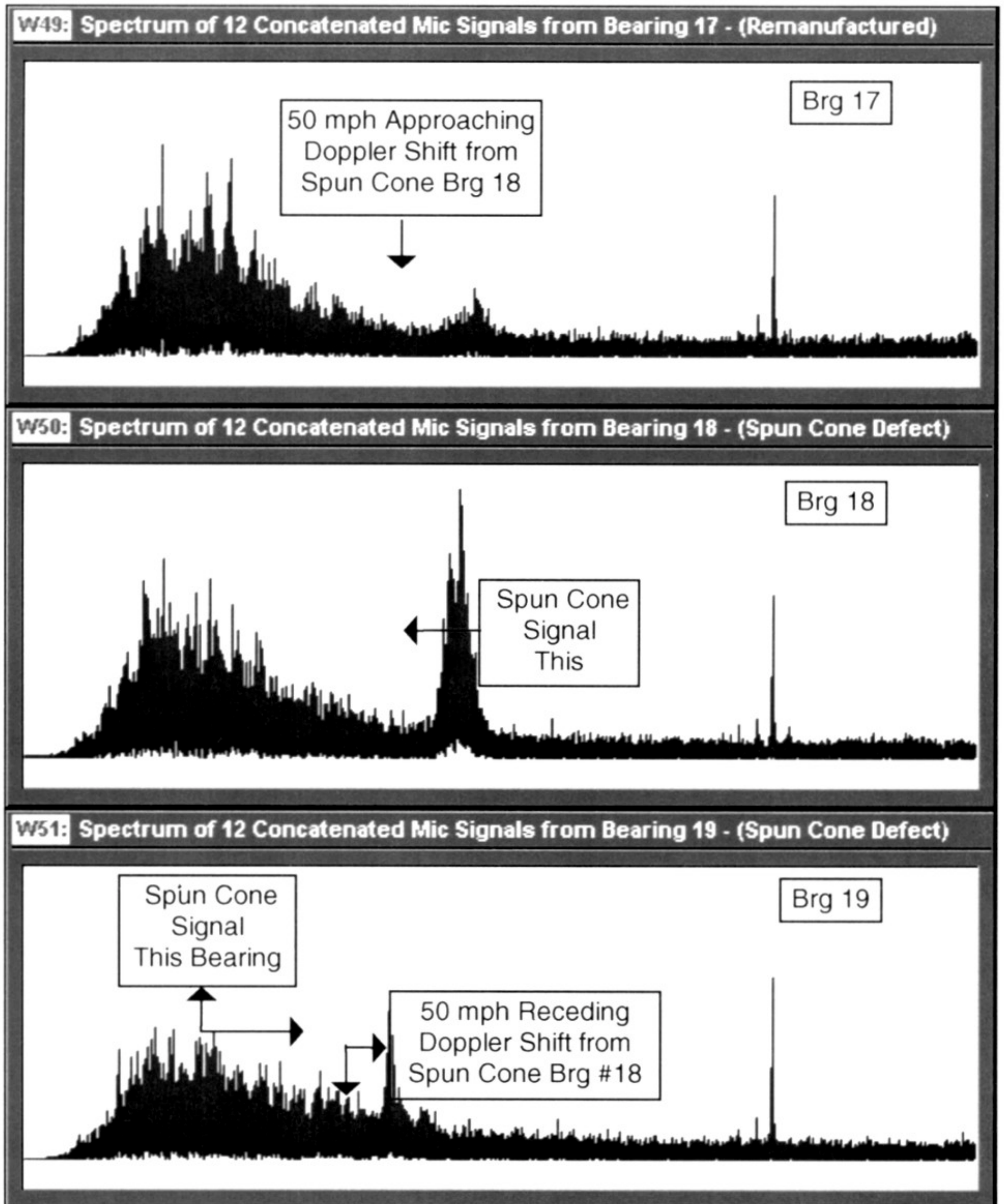


**Figure 16. Spectral Plots from 12 Microphone Matrix Signatures for 3 Bearings**
Note High Amplitude 18 KHz Signature, Doppler Shifts, and Microphone Spill-Over of Sounds to Adjacent Bearing's Reference Points of View During Run

Note to Figure 17: Signal at 40 KHz has a greater amplitude than shown since the microphones attenuated signals above 30 KHz. Peak spacing in the 3 to 6 KHz range is about 640 Hz which is the same as the side bands on either side of the 32 KHz signal. The source of the sharp peak at 32 KHz to the right of center has not been established.

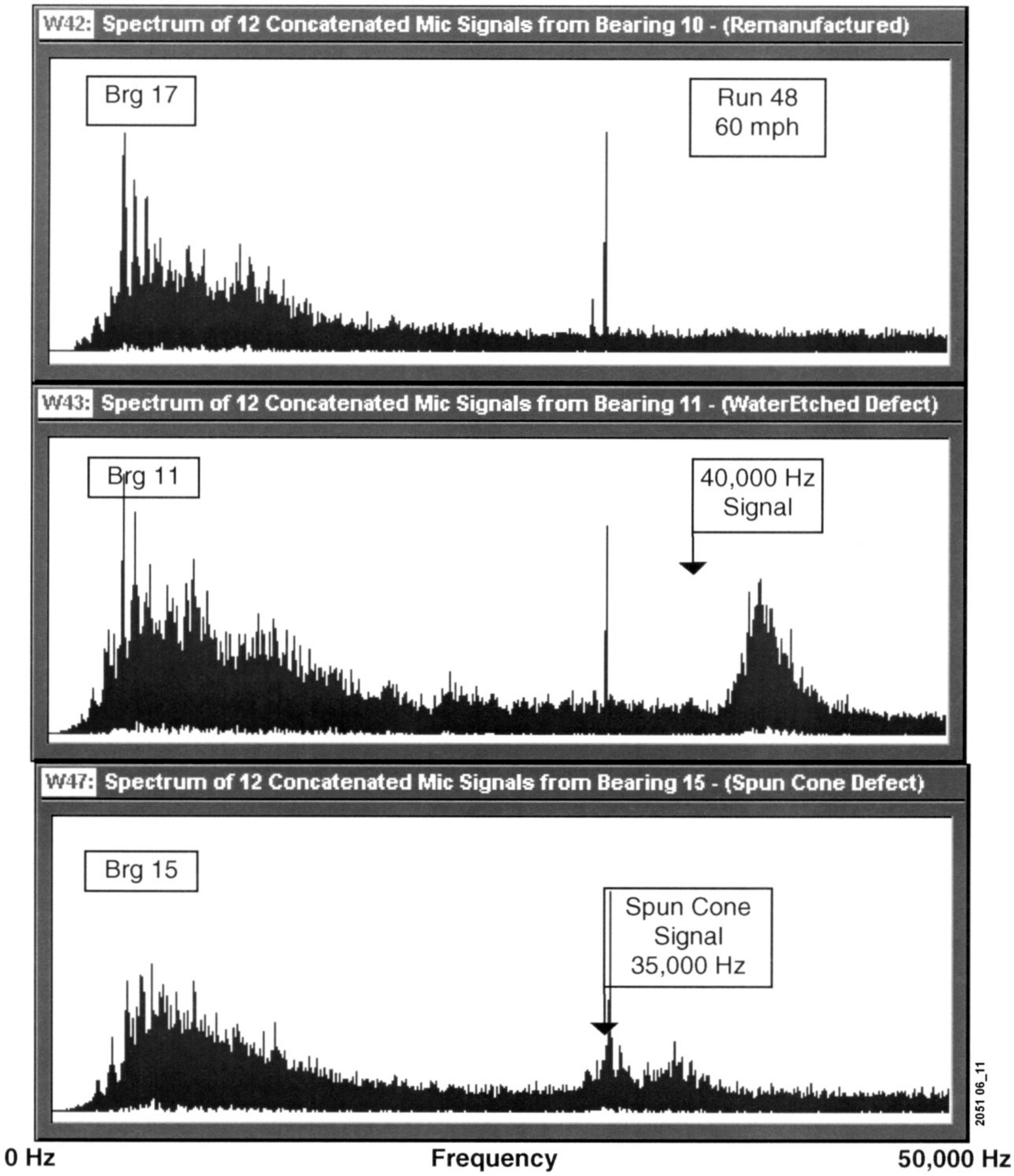


**Figure 17. Spectral Plots from 12 Microphone Matrix Signatures for 3 Bearings**
Note Significant High Frequency 35-40 KHz Peaks in Defective Bearings

Figure 16 is a composite of three spectra. The spectra shown here are higher in resolution than previously discussed. The increase in resolution is possible since the data from each spectrum comes from a composite of signals collected from 12 microphones positioned along the track. The composite signal is a long timeframe concatenation of 12 separate time slices taken from the 12 microphone files stored on a CD from a single test run.

Due to the greater noise from bearing 18 relative to its neighbors, each spectrum of Figure 16 contains the full acoustic response from the spun cone. Time slices from the array can be selected so as to be centered on any bearing as it passes through the array. Any set of slices selected for tracking a single bearing are either just before (or just after) another bearing in the train. As a result, the acoustic energy from one bearing's output can spill over into an adjacent bearing's timeframe, if the defective bearing signal is loud enough.

Figure 16 shows the spill over effect of bearing 18 noise and its associated Doppler shift as it passes through the wayside microphone array. The signal from bearing 18 is higher in frequency as it approaches and then drops in frequency as it passes its neighboring bearing's reference frame. In addition, bearing 19 has its own spun cone output, which is identified as a separate frequency peak in the last spectrum in the figure. These large high-frequency amplitudes range from 15 kHz to nearly 20 kHz. Notice that although the high-frequency peaks displayed in this example are clearly generated by two separate bearings with the spun cone defect, this result is not universal. In other words, every test bearing with a spun cone defect did not generate observable high-frequency signatures during every pass.

Figure 17 is another composite of three spectra that shows the acoustic character from three additional test bearings. As before, the displayed spectra are derived from time slices taken from all 12 microphones in the sampling array, and cover the range of frequencies from 0 to 50 kHz. The top portion of the display comes from a bearing which has no internal defects. It is one of the re-manufactured test bearings. The middle plot is derived from a bearing with internal water etched surfaces, and the lower tracing is from a bearing containing an inherent spun cone.

The features of the above discussed spectra are all potential diagnostics for identifying the types of defective bearings reviewed. Only a few of the rich frequency based characteristics of the data contained in the two CDs are presented here. This discussion is a simplified overview of many acoustic signature subtleties that are available to those who are interested in digging further into the data on the CDs for diagnostic purposes.

## 7.0 CONCLUSIONS

The following conclusions resulted from the test program:

- Envelope detected acoustic signatures (even from a single microphone) contain frequencies that are generated by defective internal bearing components.
- Spectrum of envelope detected acoustic signatures collected from wayside microphones contain peaks at (or near) the expected rotational frequencies of defective bearing components.
- Many of the same laboratory test bearing defects were used in the field test and identified as such, which was a goal in the test program.
- High frequency diagnostic information (i.e. 5 kHz to 40 kHz) is contained in the recorded wayside data and available from the CD files produced in this program.
- Adjacent microphones with the 35-inch spacing used in the test program pick up approaching (and/or receding) bearing signals when they are loud enough.
- Doppler shifts in approaching or receding bearings are present and affect frequency based analyses.
- Train speed relates directly to the rotation rate of the wheels (bearings), and must be determined precisely from the passing wheel gate signals before accurate frequency based analyses can be performed on the bearings.
- Knowledge of wheel size (bearing class/size) is also needed to accurately establish the rotational frequencies of the passing bearings at any train speed.
- Emitted bearing sound levels increase with train speed.
- Sound levels generated by the test bearings are dependent on car (bearing) load.
- Data contained in the two CDs has been thoroughly checked and is an excellent database for the development of improved acoustic bearing detection systems.

## 8.0 RECOMMENDATIONS

Based on the field tests, the following recommendations are made:

- The field test has provided a consistent and unique database for the development of wayside acoustic bearing detection technologies. However, an actual system, when developed, will need to be performance-tested under service conditions, such as long trains, diverse environmental conditions, typical North American train operations, diverse car fleets, etc.
- The field test has produced much usable bearing defect signature data; however, there are many variations in bearing defect sizes and patterns not included in this test. Any future testing should include other bearing defect sizes and configurations to broaden the database.
- Care was taken during the field test to preclude additional acoustic emissions from contaminating this developmental database. Other acoustic sources might typically include wheel tread defects, air hose leaks, high winds, ground borne vibrations, or urban noises. Future testing should include such emitters to fully test the discriminating capabilities of a bearing acoustic detector.
- Any acoustic bearing detection system design should consider gathering such additional vehicle information as wheel load, wheel rotational speed, and train speed.

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## APPENDIX A

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# Appendix B

## Defective Bearing Tables and Photographs

| | | | | |
|---|---|---|---|---|
| | | **BEARING #1** | **CLASS E "SPUN CONE" SERIAL # 29814** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | Single 1/8 inch repaired spall | Fig. B23, B24 |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #3** | **CLASS E "SINGLE CONE SPALL" SERIAL # 84372** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | Single line spall manufactured by grinding | Fig. B9 |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #5** | **CLASS F "SINGLE CUP SPALL" SERIAL # 87958** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | Spalls, 1 severe, 3 less than or equal to ½" | Fig. B30 |
| | | Not Under-Load | Water etched, single ½" spall | Fig. B29 |
| | Field Side | Loaded Zone | Single line spall | Fig. B31 |
| | | Not Under-Load | No Defects Observed | |
| | | | | |

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| | | **BEARING #7** | **CLASS F E "SINGLE CONE SPALL" SERIAL # 34593** | |
| CONE | Inside | Race | Single ½" line spall manufactured by grinding | Fig. B11 |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | Single small repaired spall | Fig. B10 |
| | Field Side | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #9** | **CLASS E "BROKEN ROLLER" SERIAL # 83622** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | Single ½" flat manufactured by grinding | Fig. B14 |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #11** | **CLASS E "WATER ETCH" SERIAL # X-167** | |
| CONE | Inside | Race | Three very small spalls | Fig. B22 |
| | | Rollers | Three each have very small spalls | |
| | Field Side | Race | Water etched | Fig. B20 |
| | | Rollers | Water etched | Fig. B21 |
| CUP | Inside | Loaded Zone | Water etched with very small spalls | Fig. B19 |
| | | Not Under-Load | Small repaired spalls | |
| | Field Side | Loaded Zone | Small repaired spalls | Fig. B18 |
| | | Not Under-Load | Small repaired spalls | |
| | | | | |

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| | | **BEARING #14** | **CLASS F "SPUN CONE" SERIAL # 10915** | |
| CONE | Inside | Race | Single 1/16 inch repaired spall | Fig. B12 |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #15** | **CLASS F "SPUN CONE" SERIAL # 61405** | |
| CONE | Inside | Race | Repaired non-condemnable, six each | Fig. B4 |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | Six large spalls | Fig. B1 |
| | | Rollers | Steel flakes in grease | Fig. B23 |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | | Spacer Ring | Worn | Fig. B5 |
| | | **BEARING #18** | **CLASS E "SPUN CONE" SERIAL # 18A** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | Small Repaired Spall | Fig. B43 |
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|---|---|---|---|---|
| | | **BEARING #19** | **CLASS E "SPUN CONE" SERIAL # 83333** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #22** | **CLASS F "WATER ETCH" SERIAL # 85882** | |
| CONE | Inside | Race | Minor water etching | Fig. B13 |
| | | Rollers | Minor water etching | |
| | Field Side | Race | Minor water etching | Fig. B41, B42 |
| | | Rollers | Minor water etching | Fig. B40 |
| CUP | Inside | Loaded Zone | Minor water etching | Fig. B39 |
| | | Not Under-Load | Minor water etching | |
| | Field Side | Loaded Zone | Minor water etching | Fig. B38 |
| | | Not Under-Load | Minor water etching | |
| | | | | |
| | | **BEARING #24** | **CLASS F "Broken Roller" SERIAL # 39164** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | Single defect manufactured by grinding | Fig. B37 |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | Very shallow repaired spalls | |
| | | Not Under-Load | No Defects Observed | |
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| | | **BEARING #26** | **CLASS E "MULTIPLE CONE SPALL" SERIAL # 54871** | |
| CONE | Inside | Race | Multiple spalls | Fig. B44 |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #27** | **CLASS E "MYSTERY" SERIAL # 18-T** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | Several spalls | Fig. B36 |
| | Field Side | Race | Three small line spalls | Fig. B34, B35 |
| | | Rollers | No Defects Observed, rollers are brown | |
| CUP | Inside | Loaded Zone | Many small dents | Fig. B32 |
| | | Not Under-Load | Many small dents | |
| | Field Side | Loaded Zone | Brinnell | Fig. B33 |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #28** | **CLASS E "MULTIPLE CUP SPALL" SERIAL # 54900** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | Water etched | Fig. B28 |
| | | Not Under-Load | Single spall | Fig. B27 |
| | Field Side | Loaded Zone | Multiple Spalls | Fig. B26 |
| | | Not Under-Load | Multiple Spalls | Fig. B25 |
| | | | | |

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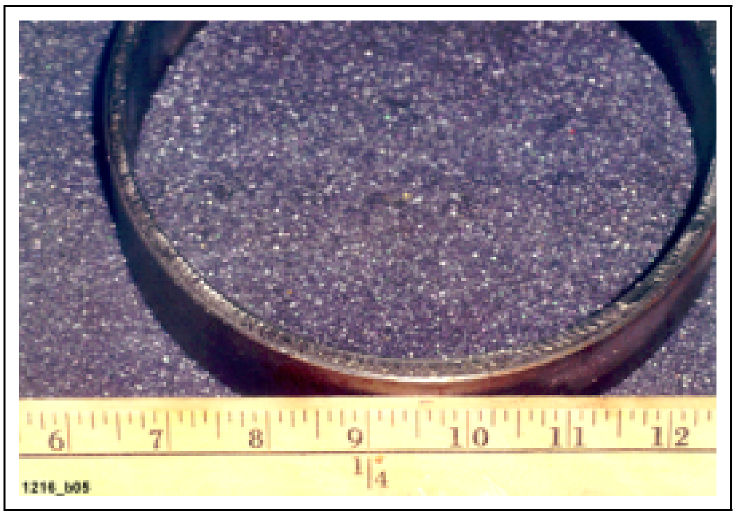
| | | **BEARING #30** | **CLASS F "MULTIPLE CONE SPALL" SERIAL # 31401** | |
| CONE | Inside | Race | Many small spalls | Fig. B6 |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | One line spall and other spalls | Fig. B7 |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #31** | **CLASS F "MYSTERY" SERIAL # 1041** | |
| CONE | Inside | Race | Multiple repaired spalls | Fig. B17 |
| | | Rollers | Broken | Fig. B17 |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | Multiple Spalls, color shows excessive heat | Fig. B16 |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | Multiple Spalls | Fig. B15 |
| | | Not Under-Load | No Defects Observed | |
| | | | | |
| | | **BEARING #32** | **CLASS F "MULTIPLE CUP SPALL" SERIAL # 34576** | |
| CONE | Inside | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| | Field Side | Race | No Defects Observed | |
| | | Rollers | No Defects Observed | |
| CUP | Inside | Loaded Zone | No Defects Observed | |
| | | Not Under-Load | No Defects Observed | |
| | Field Side | Loaded Zone | Multiple spalls, large | Fig. B8 |
| | | Not Under-Load | No Defects Observed | |
| | | | | |


**B1.**


**B2.**

**B3.**

**B4.**




**B5.**

**B6.**

**B7.**

**B8.**

**B9.**

**B10.**

**B11.**

**B12.**

**B13.**

**B14.**

**B15.**

**B16.**

**B17.**

**B18.**

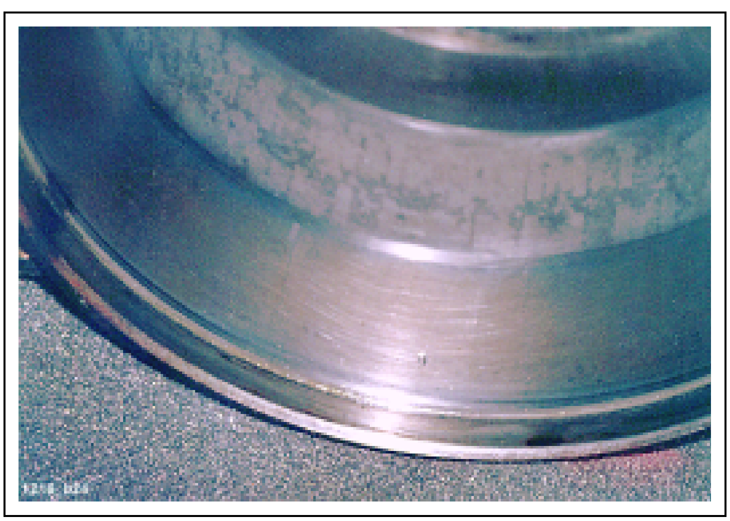
**B19.**

**B20.**

**B21.**

**B22.**

**B23.**



**B24.**

**B25.**

**B26.**

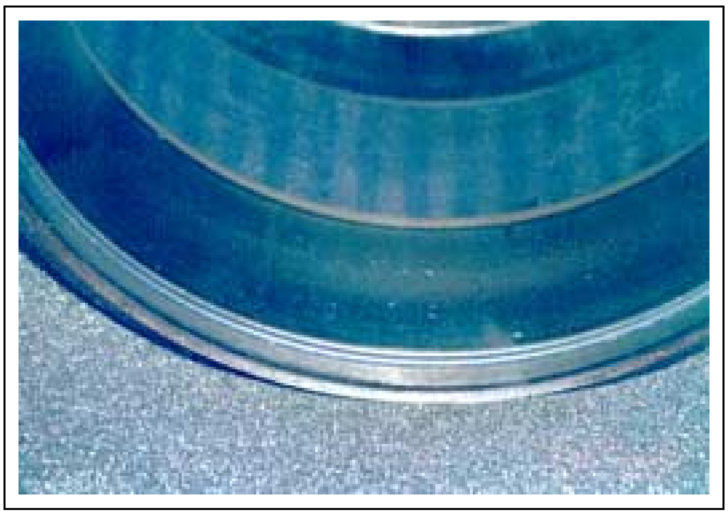
**B27.**

**B28.**

**B29.**

**B30.**

**B31.**



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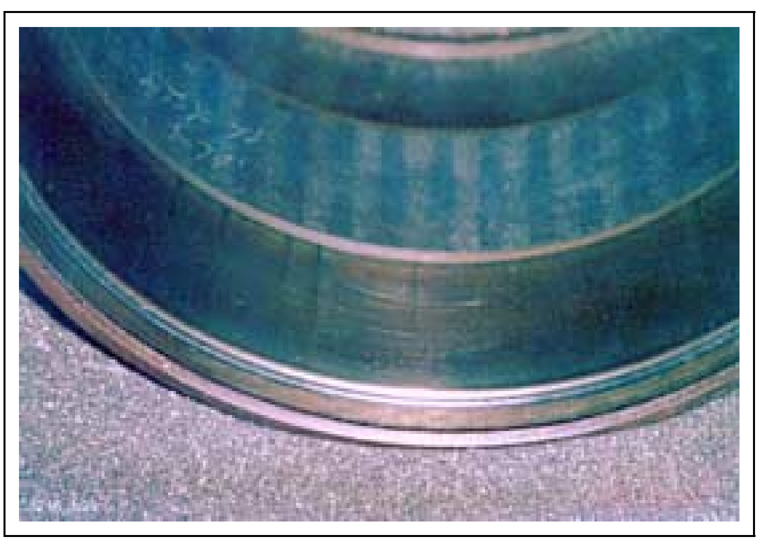


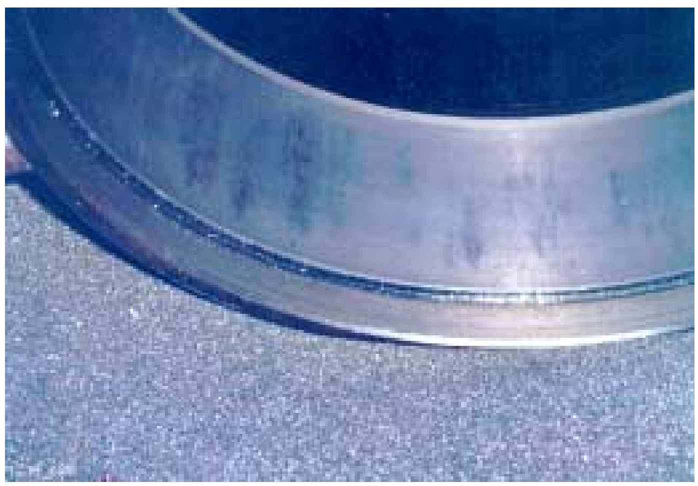
**B33.**

**B34.**

**B35.**

**B36.**

**B37.**



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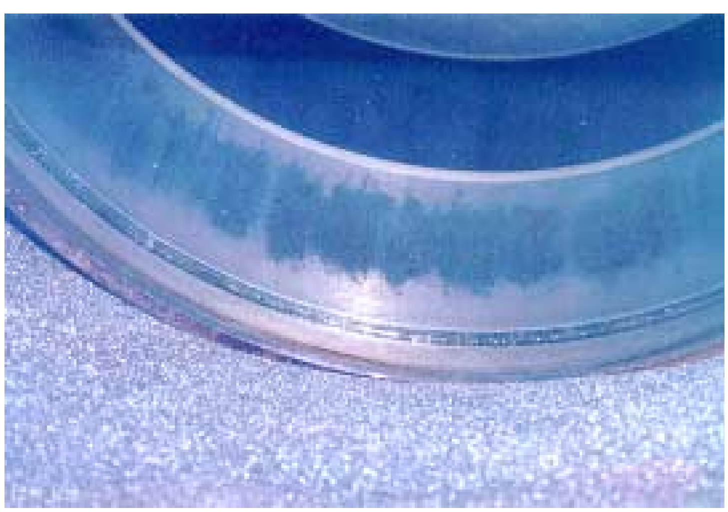
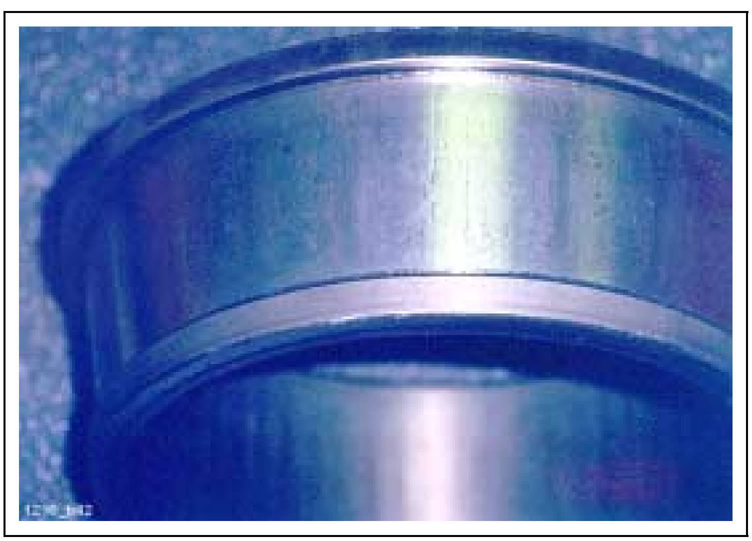


**B39.**

**B40.**

**B41.**



**B42.**

**B43.**

**B44.**