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IMPROVED ROLLER BEARING WAYSIDE DETECTION RESEARCH
Phase III System Evaluation Test

DOT/FRA/ORD-

July 24, 2000
Draft Report

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16. Abstract

TTCI conducted a series of simulated revenue service tests with a train of 8 cars containing wheel sets with specific roller bearing defects and wheel sets with good bearings. The purpose of the test was the evaluation of improved wayside acoustic bearing detection systems. The tests were conducted at the Transportation Technology Center in July 1999. The only supplier of a prototype ABD system for evaluation was TTCI, although several other suppliers participated by collecting onboard or wayside data, which may lead to other developments. The ABD was developed under the auspices of AAR's Track Performance Monitoring Strategic Initiative, funded by AAR's member railroads.

The bearing defect types tested include raceway spalls (inner and outer ring, AAR condemnable and/or repairable), roller defects, water etching, and loose backing rings, inner ring back face wear, and loose inner rings (spun cones). This report describes the test methodology and presents a general evaluation of the state of acoustic bearing detection based on the proprietary TTCI detector.

The test was conducted as a blind test, with bearing defect types and locations unknown to the participants. Results were determined based on the blind test concept using expert knowledge. Subsequently, the defect types and location were revealed and an expert system model was made using that information. Both results are presented in this report.

17. Key Words Wayside Acoustic Bearing Detection, Roller Bearing Defects, Raceway Spalls, Roller Defects, Water Etching, Loose Bearing Components, Spun Cones.		**18. Distribution Statement** This document is available through National Technical Information Service Springfield, VA 22161	
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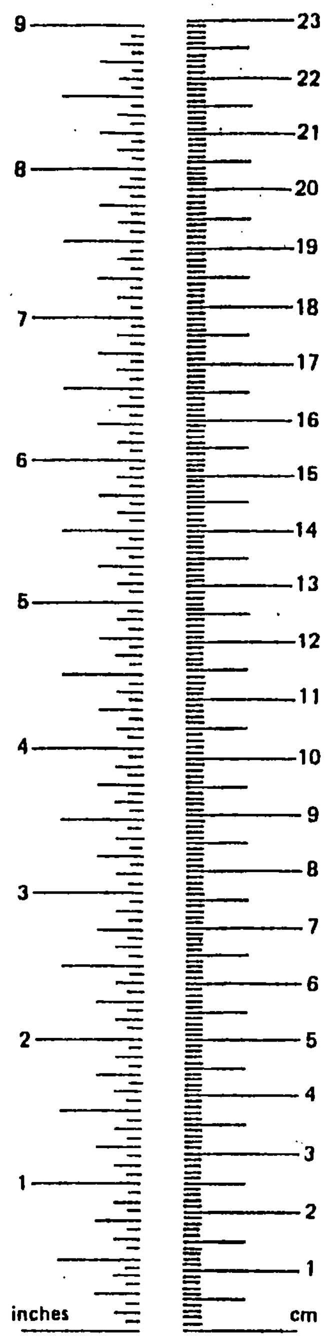
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

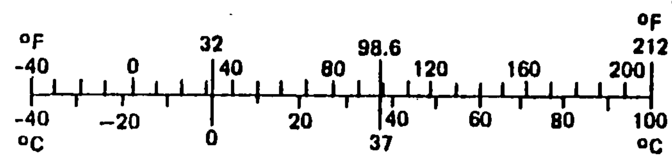
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.50	centimeters	cm
ft	feet	30.00	centimeters	cm
yd	yards	0.90	meters	m
mi	miles	1.60	kilometers	km
		AREA		
in^2	square inches	6.50	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.80	square meters	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



EXECUTIVE SUMMARY

Phase III of the Improved Freight Car Roller Bearing Inspection Program (Task Order 122) was conducted by Transportation Technology Center, Inc. (TTCI) at the Federal Railroad Administration's (FRA) Transportation Technology Center (TTC), Pueblo, Colorado. The FRA funded the evaluation program, with in-kind support from TTCI and the railroad industry. The only supplier of an acoustic bearing detector for evaluation was TTCI, although several other suppliers participated by collecting onboard or wayside data, which is discussed in this report and may lead to other developments. The proprietary TTCI Acoustic Bearing Detector was initially developed under the AAR Strategic Research Program funded by AAR's member railroads.

Phase III was a general performance evaluation test of acoustic detection technologies. This was accomplished by operating a defective bearing test train, while proprietary developmental systems attempted to "discover" the defects. The test was run blind; that is, the detector system operators were not privy to defect types or locations. Several different test car consists were operated with varying bearing defect types in various sizes (Association of American railroad classes) of bearings.

In summary, the proprietary TTCI detector was able to produce data from which defective bearings could be distinguished. This was shown in two ways: (1) manual evaluation of the blind test results by TTCI researchers and (2) development of an expert system model, with the capability to differentiate between acceptable and defective bearings. Generally, all types of bearing defects used in the tests were distinguishable through use of the model. This was not the case with the manual analysis of the blind results. The detector was shown to have extraneous noise in its data that complicated the defect recognition process, and it was not able to recognize all defects on all train passes. The expert system model was able to distinguish about 40 percent of the condemnable defects during an average train pass using a mid-range defect threshold. False detector selections at this threshold were minimal (5%). More defects were captured at lower thresholds, but with a significantly higher false rate.

Further training and development can be expected to improve this detector's performance. The manual analysis of blind results was done on a total bearing basis, not by individual bearing passes. Of the total condemnable bearings in use during the test, just over 60 percent were selected as defective by TTCI researchers. The selections were made over multiple train passes.

Generally, the Phase III tests revealed that a defective bearing will not produce a consistent pattern of acoustic emission at all times, and on occasion its acoustic emission may be masked by other noise sources such as wheel flats, locomotive engines, or wheel/rail interaction. Specifically, it was determined that a defective bearing on the far side of the axle away from the detector does not significantly interfere with the detection of the near bearing. Further, a significant wheel flat in close proximity to a defective bearing will interfere with the detection of that bearing to some extent, but does not mask it entirely. The use of wheel flat detectors in conjunction with an acoustic bearing detector would be recommended as best practice for an operating railroad.

Task Order 122 was initiated to solicit participation by industry and academia to stimulate the development of improved wayside defective bearing detection techniques. The program began by soliciting participation by industry and academia to stimulate the development of improved wayside defective bearing detection techniques. As a means toward providing the necessary database to enable this development, 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 would then be available for the development of analytical techniques to "recognize" bearing defects from a wayside sensor system, and to produce a working detector system based on the advanced analytical techniques.

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LIST OF EXHIBITS

1.0 INTRODUCTION

Phase III field tests of the Improved Roller Bearing Wayside Inspection Program were conducted by the Transportation Technology Center, Inc. (TTCI) at the Federal Railroad Administration, (FRA), Transportation Technology Center (TTC), Pueblo, Colorado, in July 1999. The program was funded by FRA, under Task Order No. 122, with in-kind support through the Association of American Railroads (AAR) and the railroad industry.

Based upon the current understanding of the capabilities of improved wayside acoustic roller bearing inspection technology (Phase I and II), the following research objectives were determined for this phase of the field-testing program:

- Determine if proposed acoustic systems can be used reliably in a simulated revenue service operation to identify typical bearing defects identified previously in this program. Specifically, these defects are:
  - Spun cone or loose components, in the absence or the presence of spalling of the raceway surfaces, for a bearing operating a fully loaded or light-car condition.
  - Damaged roller element condition for a bearing operating in a fully loaded or light-car condition (i.e., spalled roller, brinelled roller, water-etched roller, or seamed roller).
  - AAR condemnable cone spall defect for a bearing operating in a fully loaded or light-car condition.
  - AAR condemnable multiple connecting cone spall defect for a bearing operating in a fully loaded or light-car condition.
  - AAR condemnable cup spall defect for a bearing operating in a fully loaded or light-car condition.

- AAR condemnable multiple connecting cup spall defect for a bearing operating in a fully loaded or light-car condition.
- AAR condemnable water-etching defects for a bearing operating in a fully loaded or light-car condition.

- Evaluate the performance of improved bearing defect inspection/detection systems.
- Identify improvements in preliminary wayside acoustic detection systems to enhance system performance (reliability and repeatability).

In addition to the above objectives, this test program also introduced several other detection anomalies to test whether the anomalies would either confuse the bearing detection systems or be detected themselves. These included wheel tread defects, loose backing rings, bearings with excess lateral clearance, and bearing defects on the opposite side of the vehicle from the detector.

Safety of test personnel and facilities dictated the actual train speeds and car loadings used in the field test. Defective roller bearing performance was monitored continuously in the field testing to prevent any bearing related failures or derailments. The most critical bearings were monitored before and after the higher speed test runs for excessive temperature.

A program review meeting to invite participation in the Phase III test program and to review the draft test plan was held in January 1998 in Colorado Springs, Colo. Any comments received then and thereafter were incorporated into the draft test plan, which was submitted to the FRA. The meeting included representatives from the FRA, AAR/TTCI, AAR affiliated universities, and the railroad bearing and wayside detection supply industries (Appendix A).

It was expected after the field test of Phase II in late 1996 that several companies would develop improved wayside bearing detection systems to be evaluated during Phase III testing. However, by 1998, it appeared that only two companies were developing such systems for test — TTCI and Vipac, Ltd. of Australia. Vipac declined to participate in the Phase III test, leaving TTCI as the only participating detector developer. The program was held in abeyance for the remainder of 1998 and early 1999, while a Public Notice was posted in several trade magazines looking for additional participants. Approval was given in spring 1999 to proceed with Phase III, as planned.

2.0 TEST SPECIMENS

2.1 TEST ROLLER BEARINGS

Exhibit 2-1 shows the bearings used in this test; a description of the defect is given. Appendix B is a compact disk (CD), with a table of contents, of photographs of all defects by bearing number. As Exhibit 2-1 shows, the bearings covered a broad range of the defect types and defect severity. Many of the defects fell outside of the severity for the program, meaning that some defects were not condemnable under the AAR bearing reconditioning standards (*Manual of Standards and Recommended Practices,* Section H-II, Feb. 1, 2000). The test was not only intended to evaluate the performance of their detection systems for large or severe defects (i.e. AAR condemnable), but to allow developers to test the sensitivity of their systems and their detection thresholds.

Different defective test bearings than those used in Phases I and II were used in this evaluation test. The test bearings included both AAR 110-ton capacity Class "F" (6½ x 12) and 70-ton capacity Class "E" (6 x 11) bearings, and a few AAR 125-ton capacity Class "G" (7 x 12) bearings. The defect types as described in Section 1.0 were represented individually or in combination. All the specific defects and their location in the test train throughout the test were unknown to the participants. Therefore, the entire program was a blind test.

Exhibit 2-1. Test Bearings

Bearing No.	Capacity	Defect Description
B24*	100 ton	Roller defect, medium water etch all
B33*	70 ton	Cup barline spall
B101*	70 ton	Cup brinell, IB spall, WE cones
B102*	70 ton	2 repaired OB cone spalls, cup WE
B103*	70 ton	Cup WE & spalls, OB cone WE & spall
B105	70 ton	2 repaired OB cone spalls, cup WE
B107	100 ton	Cup brinells
B114	100 ton	1 cone spall – unrepaired
B116	100 ton	Oversize bore
B119	100 ton	Excessive lateral clearance
B120	100 ton	Oversize bore
B123	100 ton	Possible loose backing ring
B124	100 ton	WE cup, WE cones, WE rollers
B201	125 ton	Water etch cup and cones
B202 *	125 ton	Repairable cup spall, 4 cone spalls
B203 *	100 ton	Cup spalls & water etch, spalled rollers, cone water etch
B205 *	100 ton	Cup brinells, cone barline spall (IB), 8 cone spalls (OB)
B207 *	100 ton	Roller spalls & WE (IB & OB), cone WE, cup WE & brinell
B208 *	100 ton	Cup spalls & WE, IB con barline spalls(4), OB cone WE
B210	100 ton	Cup brinell
B211 *	70 ton	2 cup barline spalls
B212 *	70 ton	Cup cond. Brinells, 1 OB cone spall
B214 *	70 ton	OB roller spalls, cone WE (IB & OB), OB cone barline spall
B215	100 ton	Oversize bore
B216	100 ton	OB cone WE & spalls
B217 *	100 ton	OB roller spall & WE, OB cone WE
B218	100 ton	Cone spall – OB
W30LBR B988	70 ton	Confirmed IB loose backing ring
W31LBR B902 *	100 ton	IB loose backing ring, IB roller WE, OB cone & roller WE, cup WE & barline spall
B996	100 ton	Cone OB spalls
B998	70 ton	Cone 1B repairable spall Cone OB single condemnable spall
B999	70 ton	Cone 1B, 2 small spalls, repairable CuoB, repaired spall
W32LBR B903	100 ton	Confirmed IB loose backing ring
W52SC B989*	70 ton	Grooved journal for spun cone
W54SC *	100 ton	Grooved journal for spun cone

*Condemnable defects

2.2 TEST TRAIN

The test train generally consisted of one locomotive followed by eight freight cars, mostly 70- and 100-ton capacity cars with one 125-ton car in the test consist. The test had five consists for three days of testing. Day one had a 100-ton car consist; day two had a 70-ton consist used in two configurations; and day three had the same 100-ton consist as day one but with different bearings, and it was used on two configurations. Thus five consists were achieved. Configuration changes consisted of turning the train with respect to the wayside detector systems. Each car was weighed on a car scale prior to testing. The table in Exhibit 2-2 lists the car numbers and their weights.

Exhibit 2-2. Car numbers and Weights

Car Number	A-End Weight	B-End Weight	Total Weight (lbs)	Car Capacity
TTX 160539	70922	51855	122777	70 ton loaded
TTWX 970094	34433	34426	68859	70 ton empty
TTWX 981423	34516	34463	68979	70 ton empty
DOTX 307	78921	86543	165464	70 ton loaded
LTTX 200468	26937	29849	56786	70 ton empty
AAR 700	132500	132300	264800	100 ton loaded
LN 195192	131400	131140	262540	100 ton loaded
UP41373	131500	131300	262800	100 ton loaded
LN 196386	136330	135050	271380	100 ton loaded
AAR 703	132850	134450	267300	100 ton loaded
AAR 701	123450	129500	252950	100 ton loaded
FAST 390				125 ton loaded

Exhibit 2-3 is a list of the various test car consists used on each test day. Exhibits 2-4 through 2-8 are lists of consists by car number with defect bearing location information. These exhibits provide important information on the test train make-up.

Exhibit 2-3. List of Consists by Date

Test Date	Consist Number	Consist Type	Consist Length
July 26, 1999	6	100 ton & 125 ton	8 cars + loco
July 27, 1999	7	70 ton	5 cars + loco
July 27, 1999	8	70 ton	5 cars + loco
July 29, 1999	9	100 ton & 125 ton	8 cars + loco
July 29, 1999	10	100 ton & 125 ton	8 cars + loco

Exhibit 2-4. List for Test Consist 6

Car No.	Car Cap.	Leading End	Car Type	Bearing Defect Loc.	Bearing Code No.
AAR203			Loco. 4-axle		
UP41373	100 ton	"A"	Hopper 4-axle	L2	B107
"				L3	W32LBR
LN195192	100 ton	"A"	Hopper 4-axle	L2	B119
"				L3	B120
"				L4	B996
AAR700	100 ton	"A"	Hopper 4-axle	R2	B210
"				R3	B205
LN196386	100 ton		Hopper 4-axle	None	
AAR 706	100 ton	"A"	Hopper 4-axle	L2	B24
"				L3	B203
"				R4	Flat Wheel
AAR701	100 ton	"B"	Hopper 4-axle	R2	W54SC
"				R4	B114
AAR703	100 ton	"A"	Hopper 4-axle	L2	B116
"				L3	B207
FAST390	125 ton	"B"	Hopper 4-axle	R1	B201
"				R3	B202

Exhibit 2-5. List for Test Consist 7

Car No.	Car Cap.	Leading End	Car Type	Bearing Defect Loc.	Bearing Code No.
AAR203			Loco. 4-axle		
LTTX200468	70 ton	"B"	Flat 4-axle	R2	B103
"				R3	B105
TTWX981423	70 ton	"B"	Flat 4-axle	R1	B211
"				R3	W51SC
TTWX970094	70 ton	"A"	Flat 4-axle	L2	B33
"				L3	B212
"				L4	B998
"				R4	B999
TTX160539	70 ton	"A"	Flat 4-axle	L2	B101
"				L4	B102
DOTX307	70 ton	"A"	Flat 4-axle	L2	W30LBR
"				L3	B214

Exhibit 2-6. List for Test Consist 8

Car No.	Car Cap.	Leading End	Car Type	Bearing Defect Loc.	Bearing Code No.
AAR203			Loco. 4-axle		
DOTX307	70 ton	"B"	Flat 4-axle	L2	W30LBR
"				L3	B214
TTX160539	70 ton	"B"	Flat 4-axle	L2	B101
"				L4	B102
TTWX970094	70 ton	"B"	Flat 4-axle	L2	B33
"				L3	B212
"				L4	B998
"				R4	B999
TTWX981423	70 ton	"A"	Flat 4-axle	R1	B211
"				R3	W51SC
LTTX200468	70 ton	"A"	Flat 4-axle	R2	B103
"				R3	B105

Exhibit 2-7. List for Test Consist 9

Car No.	Car Cap.	Leading End	Car Type	Bearing Defect Loc.	Bearing Code No.
AAR203			Loco. 4-axle		
UP41373	100 ton	"A"	Hopper 4-axle	L2	B215
"				L3	B218
LN195192	100 ton	"A"	Hopper 4-axle	R2	B124
"				L3	B123
"				L4	B996
AAR700	100 ton	"A"	Hopper 4-axle	L2	B217
"				R3	B205
LN196386	100 ton	"A"	Hopper 4-axle	R1	B203
AAR 706	100 ton	"A"	Hopper 4-axle	L2	B207
"				L3	B216
"				R4	Flat Wheel
AAR701	100 ton	"B"	Hopper 4-axle	R2	W54SC
"				R4	W31LBR
AAR703	100 ton	"A"	Hopper 4-axle	L2	B116
"				L3	B208
FAST390	125 ton	"B"	Hopper 4-axle	R1	B201
"				R3	B202

Exhibit 2-8. List for Test Consist 10

Car No.	Car Cap.	Leading End	Car Type	Bearing Defect Loc.	Bearing Code No.
AAR203			Loco. 4-axle		
FAST390	125 ton	"A"	Hopper 4-axle	R1	B201
"				R3	B202
AAR703	100 ton	"B"	Hopper 4-axle	L2	B116
"				L3	B208
AAR701	100 ton	"A"	Hopper 4-axle	R2	W54SC
"				R4	W31LBR
AAR706	100 ton	"B"	Hopper 4-axle	L2	B207
"	100 ton		Hopper 4-axle	L3	B216
"				R4	Flat wheel
LN196386	100 ton	"B"	Hopper 4-axle	R1	B203
AAR700	100 ton	"B"	Hopper 4-axle	L2	B217
"				R3	B205
LN195192	100 ton	"B"	Hopper 4-axle	R2	B124
"				L3	B123
UP41373	100 ton	"B"	Hopper 4-axle	L2	B215
"				L3	B218

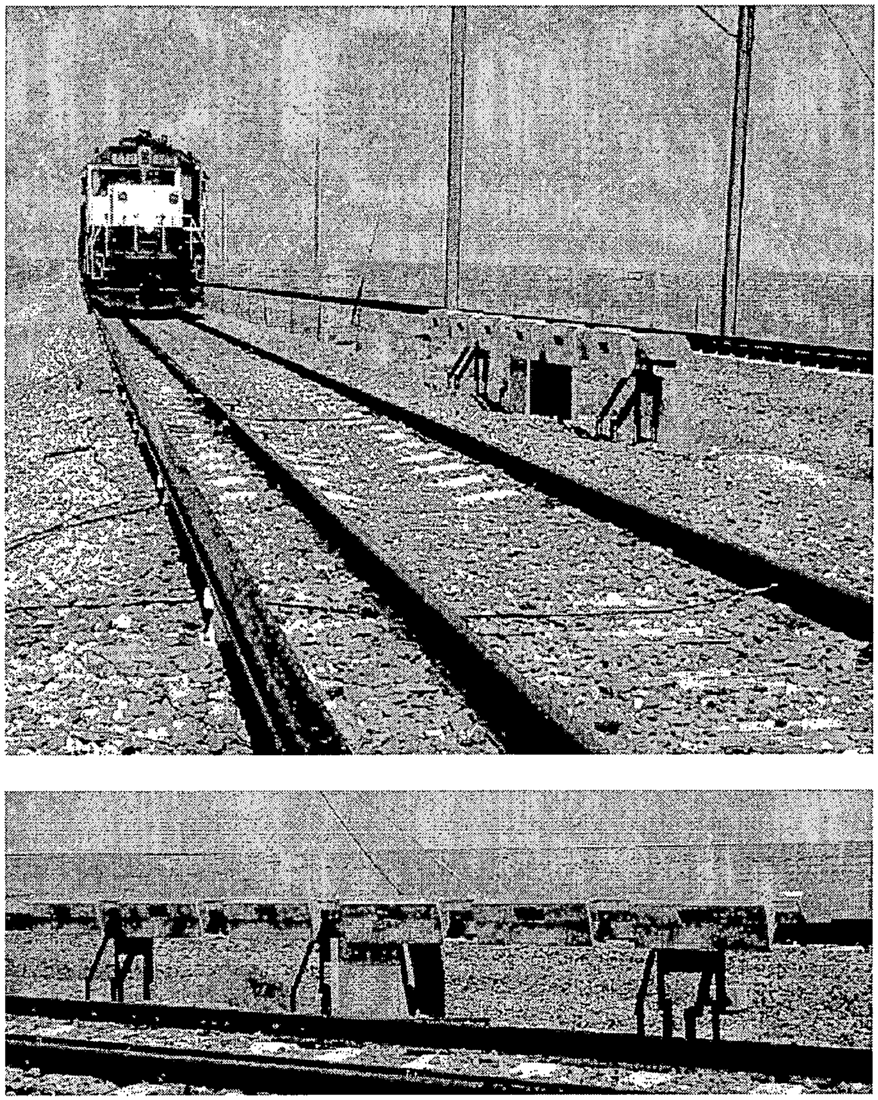
3.0 DETECTOR TEST SYSTEMS

3.1 TRANSPORTATION TECHNOLOGY CENTER, INC.

The one wayside bearing detection system evaluated in this program was developed by TTCI under contract to the AAR as part of its strategic research program. The system is, therefore, a research system under development. The system consists of three sections: (1) a trackside microphone enclosure package, (2) wheel detectors, and (3) a computer system for data collection and analysis.

Exhibit 3-1 shows the trackside microphone enclosure, and Exhibit 3-2 shows the track mounted wheel sensors. In addition to the wheel detectors clamped to the rail, a traditional island track circuit was used to alert the system for train presence. The wheel detectors, typically used in hot bearing detection systems, were used to calculate vehicle speed, wheel (bearing) position relative to the microphones, and to estimate bearing class from axle spacing. These wheel detectors are magnetic probes that respond to the proximity of the wheel flanges passing over the sensor element.

The TTCI bearing detection computer system is actually comprised of two computers, an earlier version using analog pre-processing and then analog to digital (A/D) conversion of signals, and a newer all-digital system with high speed A/D and no pre-processing. The best data was taken with the newer all digital system. That data will be presented in this report exclusively. Although the system is generally shown in photographs here, details of the machine and its operation are proprietary.



FRA Test Train & TTC Wayside Array Detector

Exhibit 3-1. Test Train and TTCI Microphone Array

Exhibit 3-2. Wheel Sensor

3.2 OTHER PARTICIPANTS

In addition to the TTCI wayside acoustic bearing detector (ABD) system, Encore Electronics, and North-South-East-West (NSEW) tested a wheel monitor development to aid in the measurement of wheel presence, speed, and wheel diameter (more information on these companies in Section 5). NSEW also took bearing data using a wayside microphone. Science Applications International Corporation (SAIC) participated in these tests with a data collection package for onboard bearing vibration measurement. The SAIC effort was funded by the FRA and will not be reported here. TTCI also collected onboard bearing vibration data, as part of an effort to study onboard bearing detection under the auspices of the AAR research program.

4.0 TEST PROCEDURES

4.1 PRE-TEST PREPARATIONS

To gather data from the participant's wayside acoustic sensor(s), sensor and peripheral support utilities were installed near the test track location. TTCI did not provide instrumentation for other participants. Power and other support structures were provided for participants who installed their own sensors and /or data collection/processing systems.

4.2 TEST SITE

Testing was conducted on the Transit Test Track (TTT) at TTC. The actual test site on the TTT was adjacent to the existing hot bearing detector (HBD) test farm (Station 14). This location is equipped with two bungalows with 110 VAC power and telephone services. The bungalows were not used; power and telephone services were.

4.3 TEST TRAIN MAKE-UP

There were five consists numbered 6 through 10 used in the course of this test. Their car make-up is shown in Section 2.0, Exhibits 2-3 through 2-7. The test train typically consisted of one locomotive followed by six to eight freight cars (some loaded, some empty). There were both 70- and 100-ton capacity cars and one 125-ton capacity car.

Exhibit 4-1 shows the make-up of one of the test trains. Wheel sets and/or trucks were switched between cars to place defective bearings under different loads. Each car was weighed on a certified scale either before or after testing (see Section 2.0, Exhibit 2-2). The test train was operated past the wayside instrumentation from both directions.

Exhibit 4-1. Test Train Make-up

4.4 TEST DATA RUNS

Exhibit 4-2 lists each test run made, along with other pertinent data such as time of day, ambient conditions, desired train speeds, and car consist identification.

Exhibit 4-2. List of Test Runs

Run No.	Date	Time	Consist No.	Train Speed	Comments
TCR	7-26-99	1333	6	25	Wind NE 16 mph
P1	7-26-99	1410	6	30	
R1	7-26-99	1428	6	30	
R2	7-26-99	1453	6	40	
R3	7-26-99	1519	6	50	
R4	7-26-99	1545	6	55	
R5	7-26-99	1612	6	60	
R6	7-26-99	1641	6	30	Wind S 17-22 mph
R7	7-26-99	1702	6	50	
R8	7-26-99	1723	6	40	
TCR	7-27-99	1100	7	25	
R9	7-27-99	1320	7	30	Wind S 12-15 mph
R10	7-27-99	1339	7	40	
R11	7-27-99	1355	7	50	
R12	7-27-99	1412	7	55	
R13	7-27-99	1433	7	60	
R14	7-27-99	1520	7	30	
R15	7-27-99	1533	7	40	
R16	7-27-99	1554	7	50	Wind S 10 mph
R17	7-27-99	1637	8	30	Wind S 10 mph
R18	7-27-99	1657	8	40	Lapped TTT
R19	7-27-99	1720	8	50	
TCR	7-29-99	0903	9	25	
P2	7-29-99	0948	9	30	
R20	7-29-99	1003	9	30	
R21	7-29-99	1016	8	40	Wind calm
R22	7-29-99	1030	9	50	
R23	7-29-99	1055	9	55	
R24	7-29-99	1116	9	60	
R25	7-29-99	1255	9	30	Lapped TTT
R26	7-29-99	1310	9	40	
R27	7-29-99	1330	9	50	
R28	7-29-99	1425	10	30	
P3	7-29-99	1443	10	40	Wind calm
R29	7-29-99	1457	10	40	
R30	7-29-99	1516	10	50	

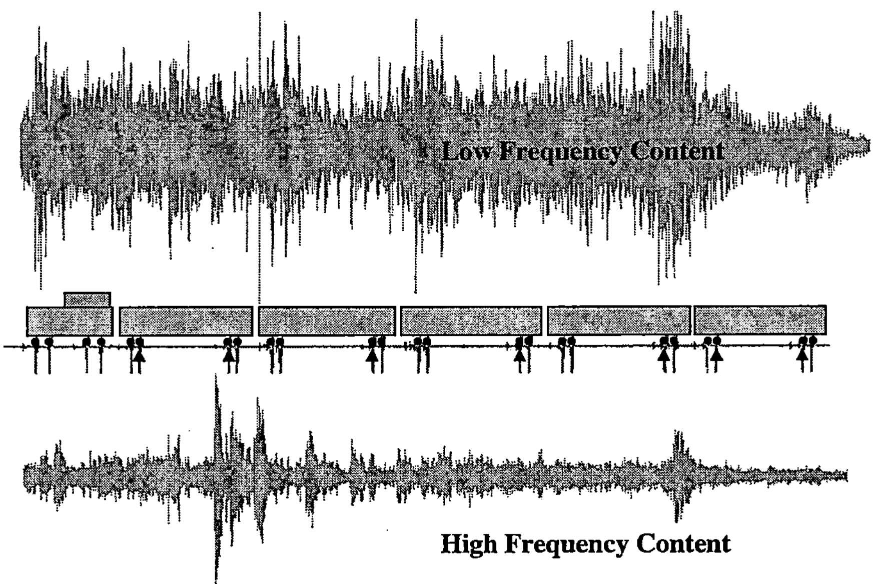
Note: R means test run, P means preliminary run, TCR means track conditioning run.

5.0 RESULTS

5.1 TTCI ABD SYSTEM

The following summary of results contains photographs, tabulations, and mathematical models as a summary analysis of the collected acoustic data from the TTCI wayside detector. Also included are images from the microphone recordings that were taken during some of the train runs. In general, the microphone time histories reveal some minor difficulties with the microphones themselves as well as the computer system used in recording all of the FRA Phase III test data. The time histories illustrated here reveal that various noise anomalies were recorded along with the digitized acoustic responses from the test train roller bearings. From a diagnostic standpoint, the noises were undesirable. In addition to noise being recorded, there were unanticipated offsets in the recording channels and the two A/D cards within the computers. Subsequent to these tests, TTCI has upgraded both the microphones and the computer data acquisition cards so that the major difficulties of recording have been eliminated, but that will not be reflected in the data presented here.

A typical raw microphone time history for a passing train is given in Exhibit 5-1. Data has been broken down into the low-frequency content of the signal (above) and the high frequency (below). The graphic depicting the consist properly positions the wheel sets with respect to the signal, and the small vertical arrows give the position of defective bearings in this particular consist.



Sample TTC Microphone Measurements from FRA July 99 Acoustic Wayside Test

Exhibit 5-1. Typical Microphone Time History

Exhibit 5-2 shows an example of the multiple microphone signals from the test, the small delay encountered between channels, and the larger delay encountered between A/D boards in the computer.

Although there were problems identified in the recording system used in the tests done in July 1999, the collected data still provided the opportunity to demonstrate (but to a degraded extent) that a designated bearing's acoustic output is directly related to the presence of an internal defect.

The data from the test was processed in two distinct ways, first based on the test being conducted blind (i.e. defects unknown). The second data processing was done subsequent to the defects locations being revealed (after sharing blind test results with the FRA representative Gunars Spons, FRA's on-site Contract Officer's Representative, in August 1999), and involved the development of an analytical or expert system model based on the known and catalogued defect types, severity, and locations.

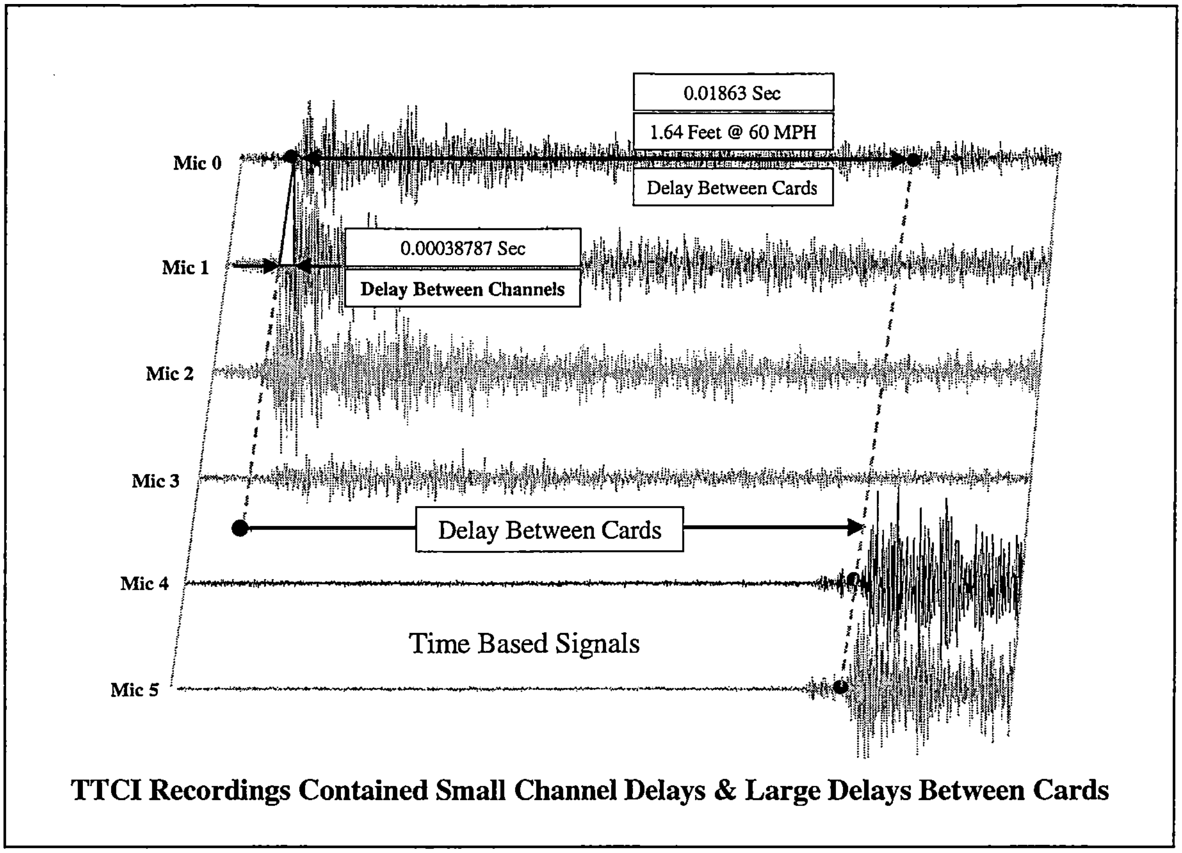


Exhibit 5-2. Example of Multiple Microphone Signal Delays

The results of the blind test were analyzed by a manual method using expert knowledge or expertise. The data files were prepared using a statistical approach, where certain proprietary features were extracted for each bearing file accumulated by the TTCI detector. The features for the bearings were compared with each other to look for features that stood out, in a manner that was typical of a bearing defect. This is where expertise was used based on knowledge gleaned from past testing and bearing analysis experience of the TTCI researchers. Files from multiple runs were used in this comparison. Ultimately, for each test train consist, a list of probable defects was compiled, and this was shared with a FRA representative in August 1999.

Exhibit 5-3 is a table of selections made from the blind data. The selections are given in three categories: (1) condemnable bearings near the detector, (2) non-condemnable bearings near the detector, and (3) condemnable defects away from the detector (opposite end of axle from detector).

Exhibit 5-3. Blind Bearing Selections

	Condemnable Bearings Near Detector	Non-Condemnable Bearings- Near Detector	Condemnable Bearings Away from Detector
Total Possible	22	16	15
Number Selected	13.5	6.5	2
Percentage Selected	61.4%	40.6%	13.3%

The data in Exhibit 5-3 shows that a reasonable number of the condemnable bearing defects were discovered using expertise and without prior information (just over 60%), while non-condemnable bearings were harder to find (about 40%). Since non-condemnable defects are less severe, the lower percentage of correct selections was expected. It should be noted that the "Total Possible" data row contains some duplicate bearing defects, since some defects were not removed when train consist changes were made (see Consist Lists in Exhibits 2-4 through 2-8). The half numbers were used in the "Number Selected" row when researchers were split in their decision of the probable defect selection.

The last column in the table presents selections made on condemnable bearings that were on the far side of the car away from the detector. In this case, the detector is actually focusing on the near bearing (opposite end of the axle from the defect), and this was an attempt to see if the defect would interfere with the reading of the near bearing. In all cases, a good remanufactured bearing was placed on the axle opposite a defect. Since only 13 percent of the defects were supposedly detected, it appears that interference is slight.

Other blind selections were made that are not represented in Exhibit 5-3. These were bearings of unknown but assumed acceptable condition that were selected by the TTCI researchers. Since the condition of the bearings was unknown, no general statements or reasons for these selections can be made. In some cases, the selected bearings were adjacent to a defect, and it is generally assumed this sound may have been interpreted as belonging to the adjacent bearing.

An analytical or expert system model was developed after the blind picks were made. Ultimately, the detector must be capable of selecting defects without manual intervention. Prior to this test, no database using the TTCI detector was available to construct such a model. The model produces numeric values (dimensionless) that are directly related to a passing bearing's condition.

The computed model's values are intended to be scaled over the 0 to 1 range, with values closest to one indicating the presence of a bearing defect. The expert system model discussed here represents a complex mathematical approach. The results from the model are presented in both graphic and tabular form. The tabulations list the defects in descending rank order. The diagnostic graphic places defective bearings at the top of the model's plot.

An expert system model is defined using several diagnostically important acoustic parameters from the collected database. The model makes use of the parameters to compute a numeric value from the database information for every bearing that passed the TTCI wayside detector during testing. A graphic display in Exhibit 5-4 shows every computed point from the model for each consist in a two-dimensional plot.

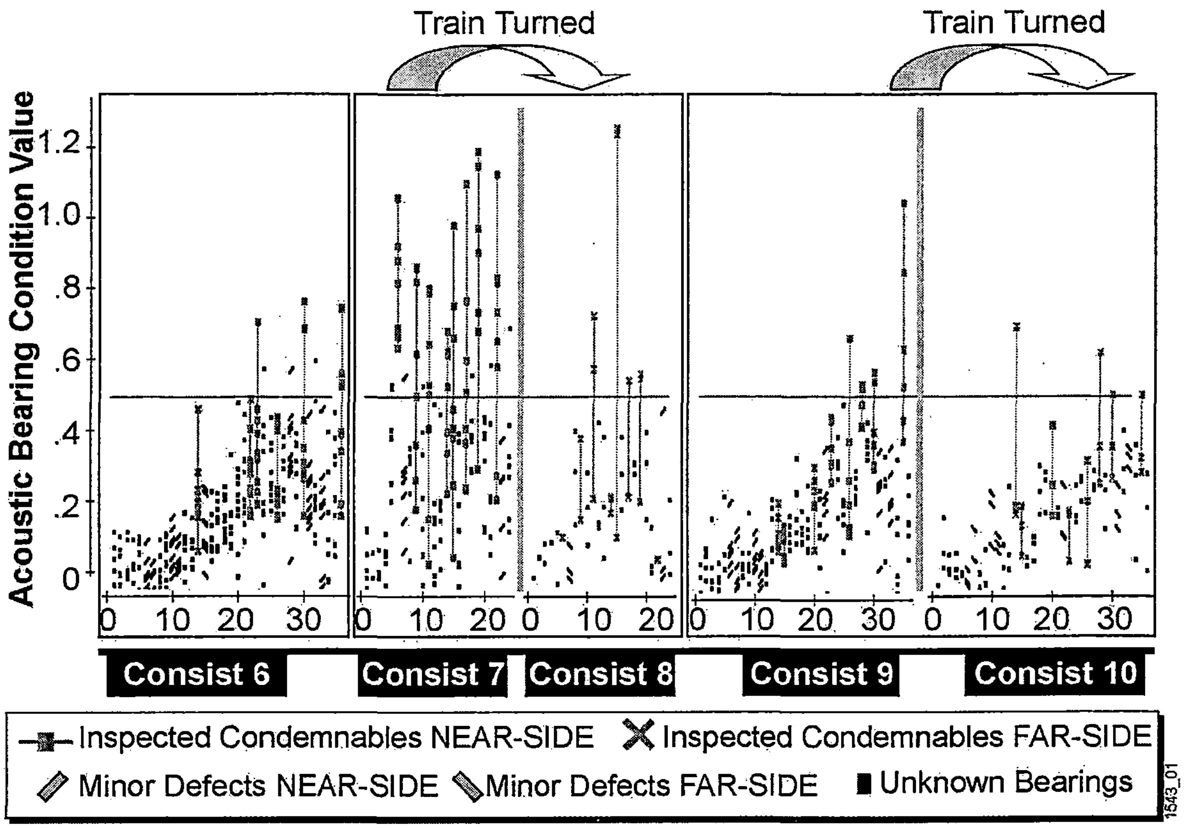


Exhibit 5-4. Graphical Output for Expert Model Results

The expert system model output shown in Exhibit 5-4 contains the entire result from the detector for all test runs with all five consists. It shows that consists 8 and 10 were run with the train direction reversed and defective bearings on the opposite side from the detector. Few defects were detected from those two consists compared to the previous consist before the train was reversed. The figure also illustrates that this expert system does select only defective bearings with a few exceptions.

Exhibit 5-4 also illustrates that not all defects will be "heard" or recognized each time they pass the detector. Observe the numerous defects that have low ABC values, mixing with the good bearings. This analysis, complicated by the extraneous noise, mixes the defects with many of the unknown but assumed good bearings. A given threshold, shown by the dashed line here at an ABC value of 0.5, would not identify some defects. Besides illustrating a variation in detectable acoustic emissions between passes, it can also be assumed that this expert system is not fully developed and may produce better results with additional data points (meaning more in quantity and variety of defective bearings and car types).

Exhibit 5-5 lists information on the defective bearings, and how they were classified during the test. The defective bearings are classified into those that were condemnable by AAR standards (*Manual of Standards and Recommended Practices*, H-II, Feb. 1, 2000) and those that were non-condemnable (smaller). This table shows that the larger condemnable defects are generally classified higher than the non-condemnable, as expected. Using a threshold ABC value of 0.50 shows that many condemnable defects are above the threshold, while most non-condemnable defects are below the threshold. Among the condemnable defects, the table shows that some are harder to classify than others (see B203, B217, and the three spun cones). The critical spun cone wheel sets are above the threshold 13 times out of 30 passes.

The expert system model developed from this data is a complex one. In spite of the noise issues, this model is almost accurate enough to be useful in revenue service, as Exhibit 5-4 shows. It is expected that further training with more and varied bearing defects would improve this performance.

Exhibit 5-5. Defective Bearing Analytical Model Results

BEARING NO.	BEARING PASSES WITH ABC VALUES IN RANGE SPECIFIED						BEARING
Condemnable	**>1.00**	**1.0 - 0.75**	**0.75 – 0.50**	**0.50 – 0.25**	**0.25 – 0**	**<0**	**TOTALS**
B101	2	4	3	1	1	0	11
B102	1	3	2	5	0	0	11
B103	3	5	2	1	0	0	11
B202	2	7	5	4	1	0	19
B203	0	0	1	13	5	0	19
B205	0	1	5	7	5	0	18
B207	0	3	1	12	3	0	19
B208	0	2	2	5	0	0	9
B211	2	2	2	5	0	0	11
B212	1	1	5	4	0	0	11
B214	2	4	3	2	0	0	11
B217	0	0	0	3	6	0	9
B24	0	1	4	5	0	0	10
B33	3	1	3	3	1	0	11
W31LBR	0	1	6	1	1	0	9
W51SC	0	3	4	2	2	0	11
W52SC	0	0	2	4	4	0	10
W54SC	0	0	4	4	1	0	9
Non-Condemnable							
B105	0	0	2	2	1	6	11
B107	0	0	0	2	5	2	9
B114	0	0	2	6	1	1	10
B116	0	0	0	4	5	0	9
B119	0	0	0	0	4	5	9
B120	0	0	0	1	7	1	9
B121	0	0	1	4	5	0	10
B123	0	0	0	2	6	1	9
B124	0	0	0	0	7	2	9
B201	0	0	0	7	7	5	19
B210	0	0	0	2	7	0	9
B215	0	0	0	1	5	3	9
B216	0	0	0	4	4	1	9
B218	0	0	0	1	7	1	9
W32LBR	0	0	0	0	3	6	9
W30LBR	0	0	1	1	4	5	11

Further attempts to extend this expert system analytical model led to the realization that the recorded acoustic data contained excessive amounts of noise in various forms. Additional analysis of the database provides evidence that the majority of the useful diagnostic information is extracted with analytical models like the one just reviewed. Alternate models will pick out other defective bearings from the test data, but only at the expense of missing some of those bearings that are known to be defective and have already been identified as defective.

At this point, it must be mentioned that the analytical model presented still identifies many defective bearings to a relatively high degree of accuracy and would be of use in revenue service even if the observed levels of captured noise were to occur in future wayside detectors. To be useful, future detector systems using this expert system model would have to restrict its operating condition judgements to bearings with outputs that provide computed values above 0.50.

Beyond the above conclusion, it should also be noted that more (or less) bearings could be called out by changing the cut-off level of detection (set here at 0.50), which is somewhat arbitrary. Each selected cut-off level would provide a higher (or lower) degree of detection accuracy. If a higher cut-off level were used to identify defective bearings, it would provide greater removal accuracy – but fewer bearings would be identified for removal in the long run.

5.2 ENCORE ELECTRONICS, INC.

Encore Electronics, Inc., Saratoga Springs, NY 12866 was founded in 1967. They design and manufacture test measurement equipment for research laboratories, process control and industrial automation. Their recent products range from basic signal amplifiers to full-vibration monitoring systems. They also customize engineering products for many customers. Some of the electronic products that they have built were taken from concept to completion in as little as a week. Encore maintains in-house engineering, circuit board layout, metal fabrication, and paint shop facilities.

5.2.1 Encore Wheel Size Monitor

There is need for a wheel size monitor, which can provide internal specifics about detected bearing defects. Knowledge of the wheel size allows a diagnostic system to compute the rotational rate of the passing wheel (ultimately the rotational rate of the bearing itself). Knowledge of the rotation rate along with the acoustic character of the bearing's sound provides the distinct component condition information needed to make an intelligent removal decision.

Exhibit 5-6 shows two photographs of the tested wheel size monitor under development by Encore and placed in test during the FRA/TTCI wayside test program. The photo on the left shows the sensor mounted on the rail in front of the test train. A close-up photo of the electronic prototype monitor is on the right side. The prototype shown has its electronics encased in plastic, but the final design will have all sensing elements and the electronic components encased in a welded steel package.

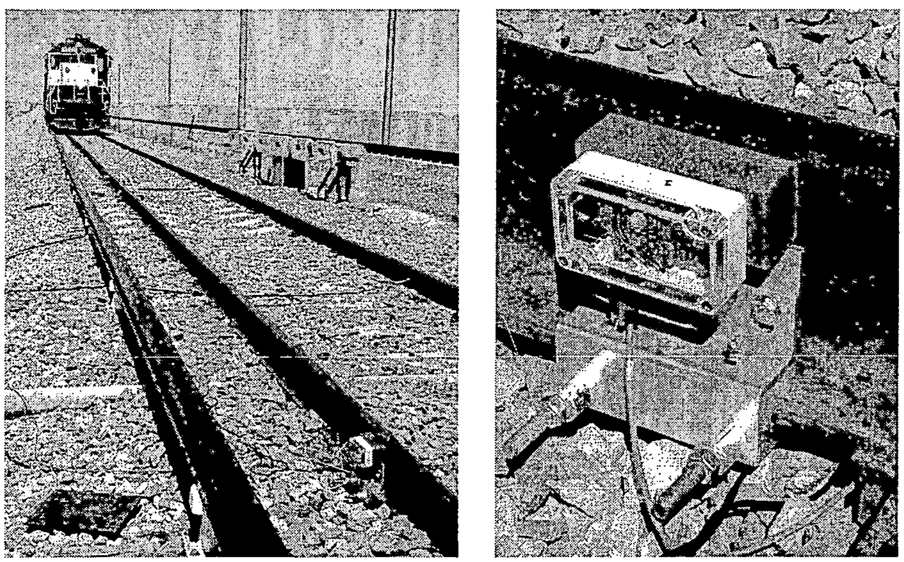
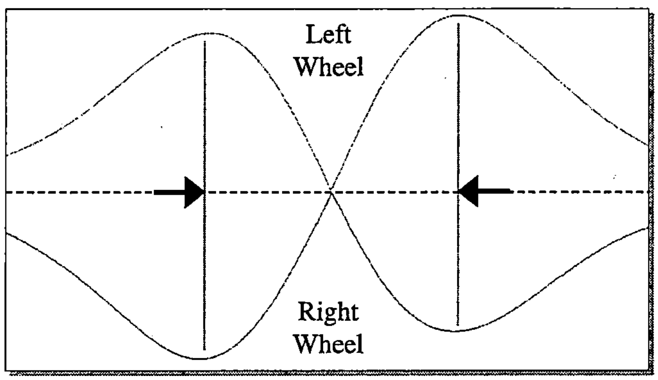
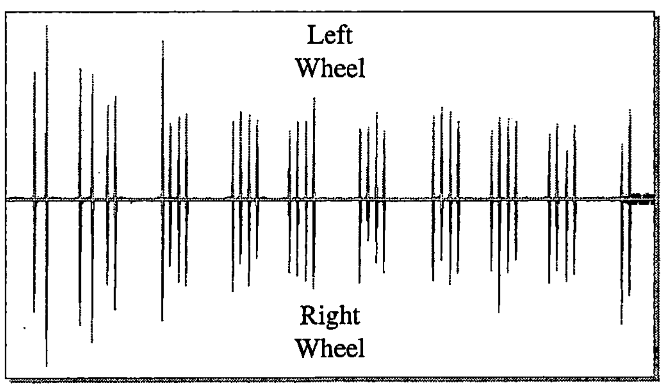


Exhibit 5-6. FRA Test Train and Encore Electronics, Inc. Wheel Size Monitor

The Encore wheel monitor provides a signal, which is close to a "half-sine-wave" for every wheel that passes (see Exhibit 5-7 for a detailed view of responses from a single wheel and test train). The peak response (changing slope & height) of the monitor's signature is related to a passing wheel's diameter. The monitor's output is a measure of wheel curvature because the detector is sensitive to the proximity of a wheel's outer flange. The monitor is typically fixed to the gage side of the rail. The output waveform of the monitor is also speed dependent because the waveform is proportionally compressed along the time-based axis as passing wheels run faster. This means that most applications require these monitors to set up in pairs.



Encore Wheel Sensor Response from a Single Axle
Distance between arrows is related to the wheel diameter and train speed.
Peak response is related to wheel flange overhang and wheel Angle-of-Attack.



Encore Wheel Sensor Response to a Passing FRA Test Train
Precise train speed is obtained by using wheel responses from two laterally off-set sensors

Exhibit 5-7. Encore Wheel Sensor Response

A pair of wheel monitors along with chip-base processors can provide information on the amount of flange overhang, the rate of change of wheel overhang, and estimates of an axle's operating angle-of-attack. The measures are known to relate to the quality of operation of passing trucks. Many of the measures provided by this newly designed wheel monitor are still in their infancy and on the cutting edge of dynamic railcar monitoring technology.

5.3 NSEW MICROPHONE DATA COLLECTION

North-South-East-West (NSEW) is located in Clifton Park, NY 12065 and provided initial consulting services in 1995. Owner Richard Smith provides a variety of engineering services in machinery diagnostics and data evaluation. He has 31 years experience in engineering research covering many government and commercial topics. He is one of the original patent holders of the first wayside acoustic detector put into railroad service. During the past five years, NSEW has provided technical assistance to the AAR and more recently to TTCI.

5.3.1 History of Acoustic Wayside Monitoring

The identification of railcar bearing defects with acoustic technology goes back to 1986 when Mr. Smith presented a paper titled "Acoustic Signatures of Various Roller Bearing Defects" at AAR sponsored conference *Railroad Bearing Failure Detection and Diagnosis* held at the University of Illinois. The first wayside acoustic detection of in-service railroad roller bearing defects was reported in an ASME paper he co-authored.[1]

5.3.2 NSEW Acoustic Wayside Monitoring Participant Results

NSEW used four separate microphones during the FRA Wayside Acoustic Test Evaluation program to record passing bearing signatures from the test trains. Two microphones were of the "parabolic" design and are shown in Exhibit 5-8, as they were mounted in the FRA test recording program. A parabolic microphone is an ideal long

[1] Wayside Acoustic Detection of Railroad Roller Bearing Defects," R.L. Florom, A.R. Hiatt, J.E. Bambara, and R.L. Smith, *Proceeding of the ASME Winter Annual Meeting*, Boston, MA, Dec. 13-18, 1987.

standoff non-contacting sensor and is effective as a remote acoustic monitor of rolling element bearings. Acoustic signals emitted by defective bearings can be picked up from remote locations with a parabolic microphone. Even in the presence of high background noise parabolic reflectors can amplify sounds coming from specific line-of-sight locations.

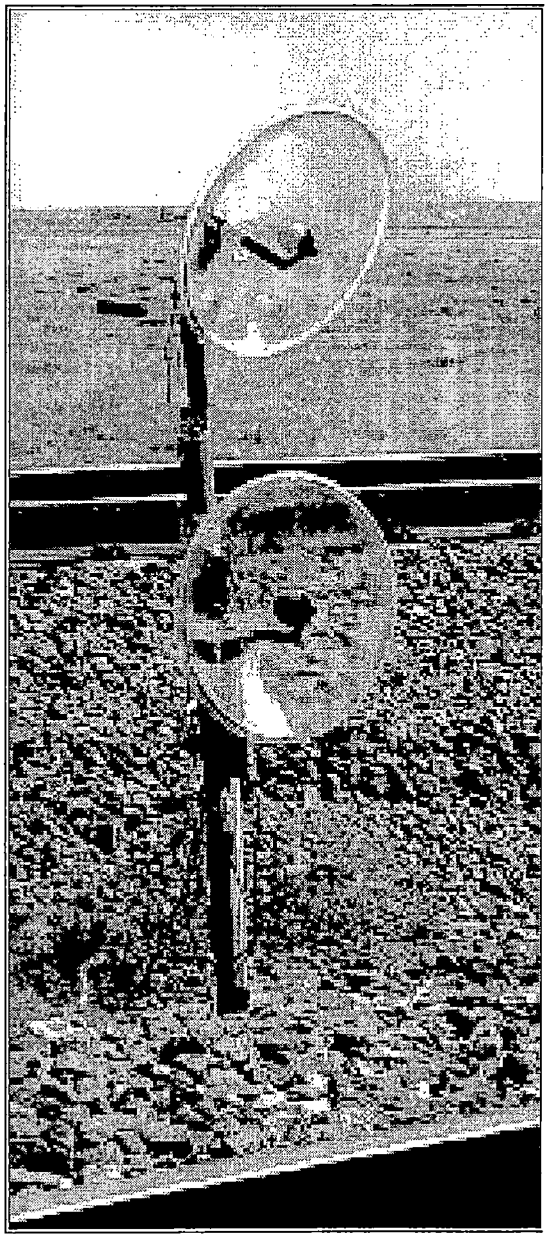


Exhibit 5-8. NSEW Parabolic Microphones

Exhibit 5-9 illustrates one of the NSEW recordings of a passing test train. The figure was derived from post processing one of the deployed microphones. Several specific bearings with known degraded components in the test consist can be identified from this simple graphic (i.e., 6 of the 14 total defects present, if wheel flats are ignored). Flags have been attached to the top of the defective passing bearings with the highest peaks in the figure. The arrows at the base of the display confirm that bearings were in the consist at the locations indicated by the flagged bearings. This simple diagnostic display is instructive because it uses only the peak rankings of the passing bearing's processed acoustic output to accurately locate several defective bearings.

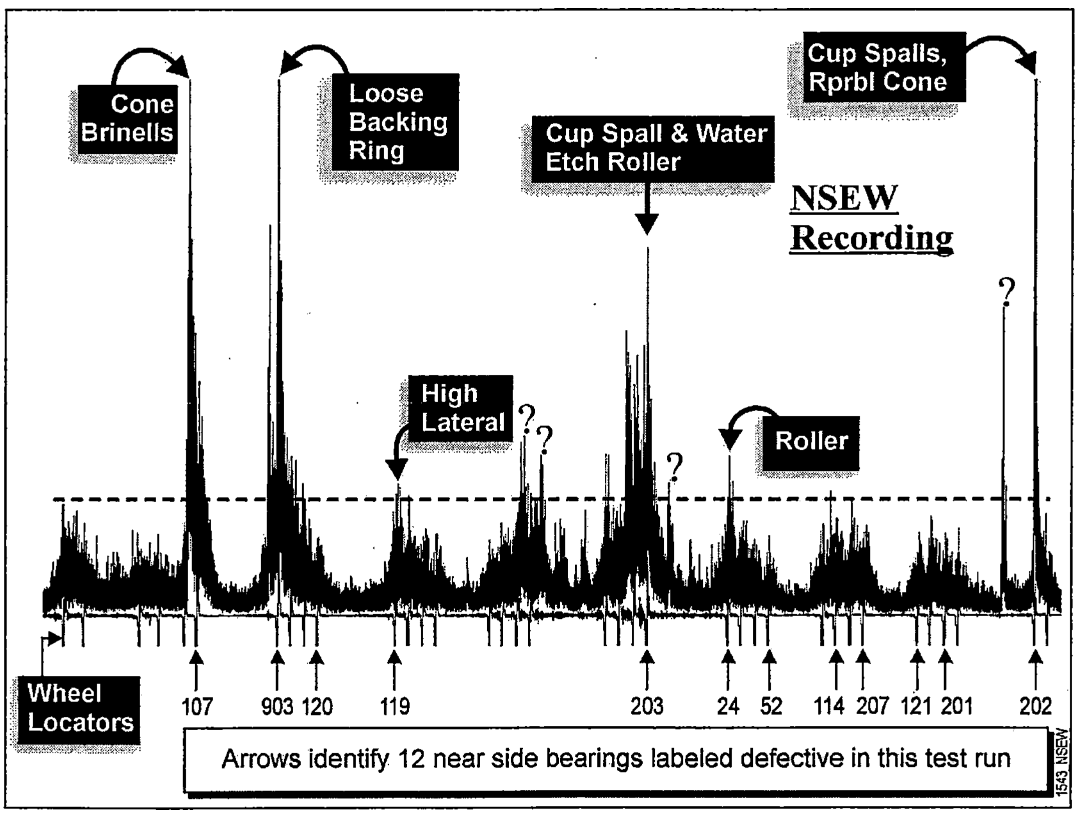


Exhibit 5-9. NSEW Recording of Passing Train

However, note that some defect types will not be found with this type of analysis because they may generate small amounts of acoustic output even though they contain defects. This can be seen from the graphic where arrows are pointing to bearings – yet they have small amplitude acoustic peaks above them.

With this simple diagnostic approach more (or less) bearings could be "culled-out" by changing the "detection" level (dashed line in the graphic), which is arbitrary, and in practice is set by experience. A pre-set detection level provides a higher (or lower) degree of detection accuracy depending upon the number of defects that pass their tendency to provide the high level outputs required of this scheme, and the details of the post-process chosen to generate the acoustic curves displayed. If a higher cut-off level is used to cull-out defective bearings, it tends to provide greater accuracy in defect identification — but fewer bearings are culled for inspection. Likewise, if the detection level is lowered with this scheme, many called-out bearings would contain no defects at all because even the best bearings generate some sound.

6.0 DISCUSSION

6.1 TTCI ACOUSTIC DETECTOR

6.1.1 Summary

Two methods of detector evaluation were made. The first involved TTCI researchers analyzing the processed data by hand, and selecting bearings that fit the defective bearing profile based on their expert knowledge. These results, for the blind test, were presented in Exhibit 5-3, and show that in spite of the extraneous noise in the data, just over 60 percent of the condemnable bearing defects were selected. However, since this process was done for the most part using expert knowledge, it conveys limited information on the evaluation of the TTCI detector. The evaluation technique(s) built into the detector will ultimately determine its effective use. If it had been possible, the expert system model would have been created prior to this evaluation test, but no database using this detector equipment was available. The similar detector installed in New Jersey had not produced the bearing inspection reports to date that would have allowed this to be done, due to business levels not allowing adequate time for bearing removals and inspections. Therefore, a model was undertaken using the data from this test, and it was used to evaluate the detector for this test. In order that the data was not overused (i.e. memorized in pattern recognition terms), a limited model was developed using a small set of bearing feature data.

The hand analysis of the blind data did show that sufficient data can be collected with the multiple microphone array to evaluate different bearing defect types. It also showed that there are features that make the condemnable defective bearings stand out from those of lesser defect size or acceptable bearings. This is important because, with training and more data, a pattern recognition method can be used to also find those bearings that stand out, and find critical defects that should be removed from service. The only exception to the blind test results was that the spun cone defects were not selected. Those will be evaluated again in the discussion of the expert system analytical model results.

An expert system analytical model was also used for defective bearing evaluation of the TTCI acoustic detector. Ultimately, the near real-time analysis of bearings by the detector is the method that would be used in service to determine bearing performance. Based on the calculated acoustic bearing condition (ABC) value, a particular bearing would or would not be selected for removal and inspection. The results have suggested that the expert system should be further optimized after the database has been expanded to include a larger quantity and variety of defective bearings under broader operating conditions. It is important, however, to review in some detail just how effective this initial expert system did in selection of defective bearings by defect type. Sorting critical bearing defects by type was an important objective of this joint program.

For this test, the consists were selected to provide a broad scope of bearing conditions and typical service factors that would influence bearing defect recognition. These factors included flat wheels, locomotive noise, and defective bearings on the far side of the car from the detector. In addition, other bearing defects were introduced into this program that had not been used before. These included loose backing rings, oversize cone bore (possibly early spun cone representations), and some non-condemnable (by AAR standards) raceway spalls. These defects were included to try and determine the sensitivity of the detection systems to smaller defect sizes.

When all factors are considered (as mentioned above), the operation of the proprietary TTCI acoustic detector was still good. Of the condemnable defects that the detector was expected to find, during this program, the analytical model correctly identified each defect type at least once. This was not accomplished with the blind test results. On average, there was about a 40 percent success rate based on a mid-range threshold setting based on total bearing passes. With a mid-range threshold, the false results were limited to about 5 percent. What is encouraging about these results is that this system is largely untrained, and can be expected to perform its pattern recognition better when given better data (less noise complications) and more importantly more data (wider range of defect sizes and variations). The caveat to these result is that this model was built on a small database, and its performance in revenue service is unknown at this time.

The most difficult defect type to recognize would appear to be a roller defect on the inboard side of the bearing, followed by inboard cone defects.

A spun cone defect is inherently different from the other defects, which are generally raceway anomalies. A spun cone has lost its fit to the axle journal, and may be moving in a planetary motion about the journal, with its rollers both sliding and rolling on the raceways. An acoustic pattern to this defect was seen in data taken earlier in this program, but it appears that this pattern may vary and not always manifest itself in the same manner. More spun cone examples would be needed to optimize an analytical procedure for selecting this defect on a consistent basis in service. The spun cone defects used in the test were detected about 40 percent of the time at a mid-range threshold level. These were not selected in the blind test analysis by the TTCI researchers.

Generally, the water etch cup defect, in spite of its lack of acoustic volume, was detected fairly consistently. This is encouraging because water etch is a particular problem for low-mileage cars whose bearings tend to see many years of service between reconditioning cycles, and the etching does lead to further bearing degradation and service problems.

The loose backing ring was a new defect introduced into this program. Many within the industry have asked whether this defect can be detected acoustically. The example wheel sets used in the test came from a railroad wheel shop, directly from the inspection track, having been shopped for loose backing rings. Other bearing conditions existing prior to the test was unknown. The post test inspection revealed that the bearings on the loose backing ring wheel sets had some heat discoloration

(W32LBR) and in one case a barline cone spall (W31LBR). These results are encouraging and illustrate that loose backing rings, indicative of other potential problems, may be detected.

In general, cup defects (single or multiple spalls or brinells) were detected as long as the defect was in the load zone under the adapter. It is expected that this defect will be the easier to find in service, as long as the defective area is loaded.

6.1.2 Detector Performance Specifics

Quantifying bearing performance was not a particularly easy task because the condition of all bearings in the test consists were not a known quantity. Although specific bearings with defects were mounted for this test, the remaining bearings in the test cars were of unknown condition. During the course of testing, it became apparent that several of these unknown bearings possibly contained defects as well. It was some time before several of these bearings were dismounted and inspected, and not all the unknown bearings have or will be inspected.

Exhibit 5-3 gives the specific results of the analysis made on each bearing in the various test train consists. These results will be repeated here in a broader manner. For this quantification of defects, the reverse direction consists have been ignored as well as the detection of defects on the far side from the detector array (see Section 6.3 for explanation of low signals from far side defects). The results presented here are from consists 6, 7, and 9. The results from consists 8 and 10 are included only for those good bearings purposefully mounted opposite a defect on the same axle. The good bearings (no defects) were on the near side (proximate to the detector array) in most cases for consists 8 and 10.

The results are quantified based on (1) all known defects (those bearings mounted for this test and those unknown but now inspected bearings that contained defects), and (2) those bearing defects that were expected to be recognized. The expectation of defect recognition is an important point because the list of defects for this entire FRA/AAR Program (refer to Section 1.0) is based on AAR condemnable sizes, and this particular test contained several bearing defects outside the scope of this program. The recognition of smaller defects or defect types outside the scope of the program should be judged separately.

Exhibit 6-1 is an analytical plot from these three days of FRA acoustic bearing testing performed at TTC. The vertical scale is an analytical representation of the ABC values that were calculated from measured microphone signature characteristics collected from nearly 1,000 bearing passes. This plot is a composite output computed from microphone readings collected from all train (and bearing) passes. Each point in the display represents a separate bearing pass.

The horizontal axis provides the axle location of the bearings as they went by the wayside array. Three separate consists, with axle counts ranging from 24 to 36, were run by the detector during the test cycle. The first four axles in the display represent locomotive bearings. All other data points are derived from test car bearings.

The large "squares" are from shop-confirmed inspected defective bearings with at least one or more condemnable mounted component(s). Right slanted "slash-marks" are from bearings with one or more, non-condemnable, yet visually detectable component defect(s). The small "lightly-shaded" dots are from bearings that were not inspected but were assumed to be acceptable by AAR standards.

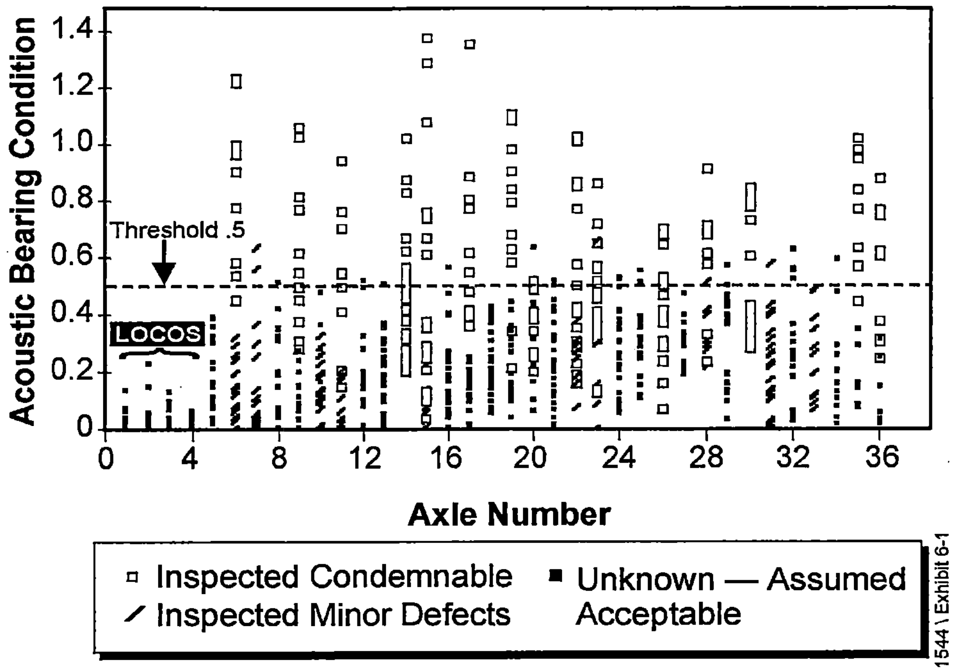


Figure 6-1. ABC Value vs. Axle Number

There are 54 "condemnable" defects that have ABC values greater than 0.80 in the displayed plot. There were no non-condemnable bearings that produced ABC outputs above this arbitrary cut-off level.

Note that there were 132-bearing passes with an ABC ranking value above the 0.50 level. Oh these, 82 percent contained proven condemnable defects. The 0.50 ABC value was used as a mid-rage threshold level for analyzing results. This level produced only 5 percent truly false readings. The difference between the 82 percent defects and the 5 percent false were 13 percent bearings of unknown condition. If a lower threshold ABC value is used, it will capture more of the defective bearing passes, but with a higher false selection rate. Exhibit 6-2 shows the percentage of defect selections and false selections at varying threshold levels. From this information, it was deduced that 0.50 was a good threshold level to use.

The composite plot of ABC values in Exhibit 6-1 indicates that each bearing, regardless of its condition, provides a slightly different level of acoustic output during every train pass. Various levels of acoustic output occur – even if the bearings go by at identical speeds. When successful, the defect identification expert system that computes the ABC values of a passing bearing lift out many passing defective bearings and suppress many of those assumed to be defect free.

Exhibit 6-3 contains a table listing the defect categories with the number of those selected at the various threshold levels. At the 0.50 level, about 40 percent of the defective bearings for all train passes (different speeds and carloads) are selected. The data in this table also illustrates that the location and type of defect greatly affects the ability of the detector to discern (i.e. inboard vs. outboard). This table also shows that the critical spun cone defect was selected over 40 percent of the time using a threshold of 0.50. This is an important point for the future development of this technology.

Further analysis of the data may be needed to determine the cause of the wide variations seen within the data. A large component of this variation is expected to be due to the extraneous noise in the data, speed, and bearing load variations. Noise problems can be abated by selection of a track location that has a fairly constant train speed range. Bearing load variations can be mitigated by ignoring empty car bearings until additional empty car data is available for detector training.

Exhibit 6-2. Table of Bearing Selections vs. ABC Level

	ABC Value Ranges					
	>1.0	>0.75	>0.50	>0.25	>0.00	> -.50
No. of Bearing Passes > ABC Value	16	54	132	391	769	912
Condemnable Bearings > ABC Value	16	54	108	189	219	219
% Condemnable Bearings > ABC Level	100%	100%	81.8%	48.3%	28.5%	24.0%
Non-Condemnable Bearings > ABC Level	0	0	24	202	550	693
% Non-Condemnable Bearings > ABC Value	0%	0%	18.2%	51.7%	71.5%	76.0%

Exhibit 6-3. Table of Bearing Selection by Defect type vs. ABC Level

Condemnable Bearings by Defect Type	Bearing Passes with ABC Values Above Range Specified					
	>1.0	>0.75	>0.50	>0.25	>0.00	> -.50
Cup Inboard Defects	8	24	48	85	96	96
Cup Outboard Defects	8	18	28	55	61	61
Cone Inboard Defects	0	3	12	31	37	37
Cone Outboard Defects	3	12	29	57	68	68
Roller Inboard Defects	0	3	5	30	38	38
Roller Outboard Defects	2	10	18	40	49	49
Spun Cone Defects	0	3	13	23	30	30
Total No. of Bearings	21	73	153	321	379	379

6.2 TTCI ACOUSTIC BEARING DETECTOR – FLAT WHEEL COMPLICATIONS

Wheels with flats were introduced into this test to see the effect they would have on bearing detection. It is readily apparent that there is an effect, and it is significant.

Exhibit 6-4 contains a typical acoustic signature from a complete train pass that has at least three "flat" wheels. The center of each passing flat wheel is indicated with an arrow at the base of the plot. The wheel indicated by the arrow in the middle has a single flat spot on its periphery. The other flat wheels have multiple flats that generate more then one impact per revolution of the wheels. This is evident even from the highly compressed plot.

A close-up view of one of the passing flat wheels is shown in Exhibit 6-5. Five impacts can be seen at equally spaced intervals. Even with the evidence of the impacts, however, there are many other acoustic variations intermixed in the signature. The question is: Can the acoustic information from bearing defects be detected even though the impacts are present? In most cases, the answer is yes. But in other cases, the bearing signature will be degraded. Since a large flat on a wheel can generate once per revolution signals with potentially broad band frequency content, it may ultimately "mask" the defect signatures produced by bearings.

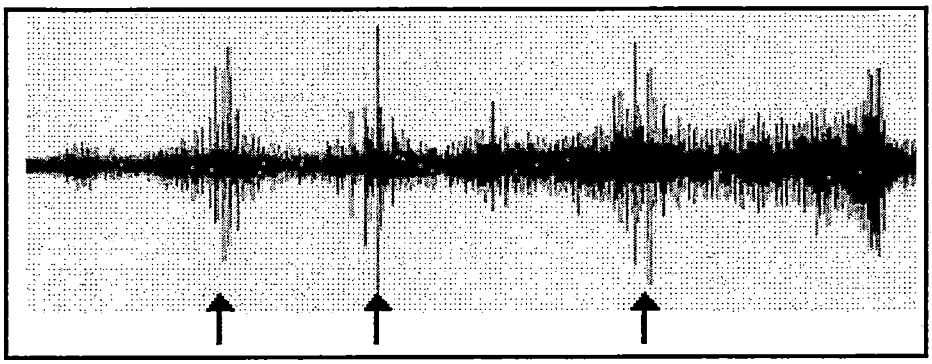


Exhibit 6.4. Train Acoustic Time History with Wheel Flats

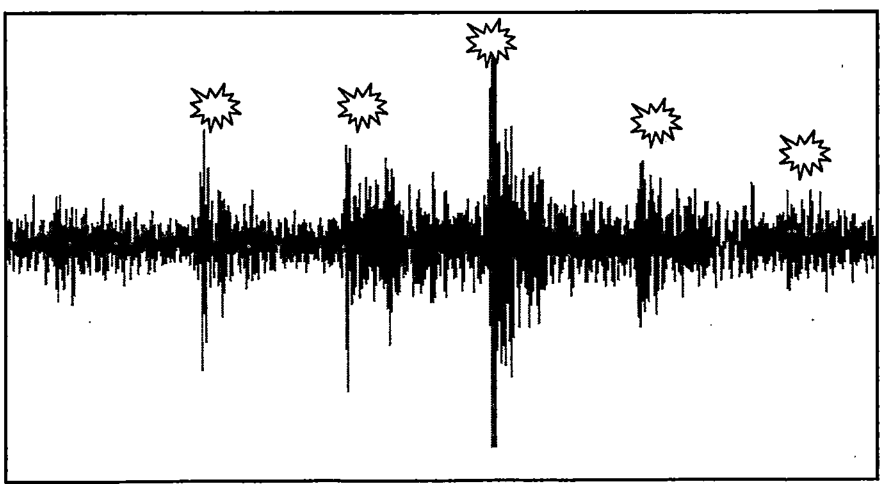


Exhibit 6-5. Close-up View of Acoustic Time History of a Single Flat Wheel's Multiple Impacts

The main reason the bearing signatures can often be discerned (even when wheel impacts are present) lies in the differing character of the frequencies generated by wheel flats versus bearing defects. Much like speech can be heard over hammering in a production plant, some bearing signals can be heard when wheel impacts are nearby or on the same wheel. An impacting wheel generates large amplitude signals, but a bearing generates a steadier repetitive periodic acoustic output. It is on these subtle differences that most of today's diagnostic schemes depend. Steady periodic signals from defective bearings essentially ride the wave of the impacting wheels. Just as specific words can be heard over hammer blows so can bearing defects. The flat wheels used in this test were not likely to have exceeded the removal criteria for a wheel flat detector per AAR standards.

It is well known that a wheel's "flatness" characteristic changes over time. As soon as a flat is created on a wheel, it begins to hammer itself out. During each wheel revolution, the sharp edges of the flat strike the rail hardest and as a result get smoother over a short period of time (although this will tend to depend on initial flat size). This process tends to reduce the number and magnitude of high level impacts that are present at any time in rail service (again based on initial size). This is actually a positive situation from a bearing diagnostic standpoint. The lower the levels of wheel impacts, the easier it is to discern bearing problems that are present.

6.3 BEARING DEFECTS ON OPPOSITE SIDE OF CAR FROM THE DETECTOR

Defective bearings on both ends of the same axle may degrade the accuracy of defective bearing detection. Just as flat wheels may confuse bearing defect detection, so could a second defect signal generated on the far end of a given wheel set. A few details related to the arrival of multiple defective bearing sound sources present on a single axle are considered in the following paragraphs.

Acoustic signals emanating from a defective bearing on the far end of a passing axle can reach a wayside microphone in two ways. The signal can pass through the steel axle and come out the near side. Or it can come around the far side wheel through the air. In either case, the acoustic signal from the far side bearing is greatly reduced compared to that emanating from a near side bearing.

An estimate of the relative intensities from dual signatures arriving through the air can be made. First assume that the monitoring microphones are positioned 4 feet back from the nearest side rail. A freight car axle is approximately 6 feet long. It is also known that acoustic signals from any source decrease in intensity by the square of the distance from the microphone. From these facts, it is estimated that the sounds from a far side bearing will be 6.25 times smaller (or 0.16 times the magnitude) than a signal from the near side bearing [(4x4)/(10x10)]. In practice, the far side sounds will be reduced even further since the far side wheel prevents those sounds from traveling a straight-line path to the nearest microphone. In order to reach the near side microphone, a far side source must go out and around the far side wheel, further increasing the path length.

Sound attenuation estimates of signals traveling through the axle are more difficult to calculate than those traveling through the air. Sound that travels through the axle can be attenuated (absorbed) in many ways. Material acoustic damping and the reduction of acoustic signals transferred through solids is very complex. Attenuation depends on temperature, specific material composition, support structure interfacing, and the composite fits of the various components that make up the solid (i.e., wheel, axle, bearing, spacers, backing rings, etc.). Despite the complexity, it is estimated that the attenuation of vibrations arriving from the far side via the axle structure would be reduced by a factor of 10 to 20 compared to a near side source. The only caveat would be that the signals were so strong that they would induce a resonance in the axle structure or wheel set.

To summarize, it is anticipated that the presence of defects on both ends of the axle should be totally separate since wayside installations would have dual microphone arrays on each side of a passing train. From the above discussion, it would appear that the signals from each side of the train would be separable due to the proximity of the passing bearings to its microphone array. During the course of this test at TTC, defective bearings were placed on the far side of the train on order to estimate the above mentioned effects. There were not, however, two defective bearings on any same axle.

The results of a far side bearing defect signal reaching the array are best illustrated in Exhibit 5-4, for consists 8 and 10. For these consists, the train was reversed and the majority of defective bearings were on the far side. As shown, the far side signals were greatly attenuated compared to the train operating in the reverse direction with identical bearings on the near side of the train (consists 7 and 9, respectively). Although signal strengths are not shown in this exhibit, these are the Expert System model results estimating the likely presence of defects. Defects "heard" on the near side were missed – almost without exception – when located on the far side. For the blind test, selections of far side bearings were very low (<15%), correlating with these model results.

7.0 CONCLUSIONS

A defective bearing produces acoustic features that can be used to characterize its internal operating integrity from wayside microphone arrays. Bearings with minor or no internal component defects also produce acoustic outputs with different characteristics that will allow wayside array systems to evaluate their good condition as well. The following conclusions have been drawn from the evaluation of the TTCI wayside acoustic bearing detector.

1. Manual methods applied to the blind data had some success in selecting condemnable defects (about 60% of total bearings used) using multiple train passes to aid in the analysis. The analytical model results were based on bearing passes (was the bearing selected each time it passed the detector).
2. Using a mid-range detection threshold and the analytical model, the detector was able to select about 40 percent of the defective bearings on an average train pass (based on an average of all data from all train passes). The false indication rate was 5 percent at this threshold level. Some of the test train bearings are still of unknown condition and were excluded in these percentages.
3. Critical defects such as the spun cone were detected at about the average level (40%)
4. Analysis of data by defect type shows that roller defects were the hardest to detect (26%).
5. The analysis of data by defect location shows that inboard components (inboard cone assembly and rollers) will be harder to detect for defects than outboard locations.
6. For a given type of defect, the acoustic output of the bearings as analyzed by the detector shows wide variations. These variations are likely due to extraneous noise, variations within the bearings themselves, and various

train operating and environmental conditions (i.e. speeds, wind, other car borne noise, and wheel/rail interaction).

7. A careful analysis of the raw acoustic time histories showed that extraneous noise was present in the data caused by the sensors and data collection equipment.
8. Based on the type of technology and analysis techniques in use, it is expected that the detector should have considerably better results with extraneous noise abatement, train noise mitigation, and additional training (exposure to broader defective bearing sample).
9. Bearing defects located on the far side of the axle should have little impact on the analysis of the near side bearing.
10. Wheel defects that create impacts with the rail will tend to mask bearing acoustic signatures. The larger the impact of the wheel, the greater the effect on the bearing data.
11. In general, the Phase III test was a success in that a performance evaluation of the only North American advanced prototype acoustic bearing detector was performed.

8.0 RECOMMENDATIONS

Based on the discussion of results and the conclusions drawn, the following recommendations are made:

- The performance of the TTCI detector should be further developed to eliminate the extraneous noise problems that were seen in this data.
- The TTCI acoustic bearing detector needs further training to be more effective in service use. The bearing defect populations were small in light of the variations in the data seen (i.e. for a single bearing over multiple passes).

- The performance of this kind of technology (pattern recognition) is difficult with a restricted test sample size.
- Although difficult to determine, a performance standard for evaluation of bearing detection should be developed.
- The results of this test were encouraging enough to recommend that field testing and training of advanced acoustic bearing detection be undertaken in railroad service.
- Additional analytical techniques may be recommended for improving performance for hard to detect defects (inboard rollers and cones).
- Since bearing load is an important parameter in bearing defect recognition, a means of obtaining this information for the detector should be explored.

ACKNOWLEDGEMENTS

The authors thank John Punwani, Monique Stewart, and Gunars Spons of the Federal Railroad Administration for their input and encouragement during Phase III. In addition, special thanks to the train crews, test controllers, and car men for their efforts in accomplishing the test work in a timely and cost effective fashion. Final thanks to the engineering interns who persevered in their efforts to tear down, inspect, and log the many bearing components used in the test.

APPENDIX A
List of Participants
Program Review Meeting
January 1998 — Colorado Springs, Colo.

1. Transportation Technology Center, Inc.

TTCI installed a wayside acoustic bearing detector system prototype for evaluation in this program. The system consisted of a wayside microphone enclosure housing multiple microphones, wheel sensors, and a computer system for data acquisition and analysis.

2. Encore Electronics, Inc.

Encore Electronics mounted an improved wheel sensor for wheel size determination, as well as wheel speed.

3. North-South-East-West

NSEW installed two parabolic microphones to collect wayside data during this test program.

APPENDIX B

Compact Disk of Photographs of All Defects by Bearing Number

Appendix C
Defect Bearing Location and Description Table

Con-sist	Axle No.	Car No.	Lead-ing	Date	Direction	Normal Near Side	FRA List # Prior Inspection Breakdown	Reverse Near Side
						Defective Bear Detector		
6	5	2	A	26 7 99	Normal			
6	6	2	A	26 7 99	Normal	B107	Cone Brinells	ReMan
6	7	2	A	26 7 99	Normal	W32LBR	Loose Backing Ring	ReMan
6	8	2	A	26 7 99	Normal			
6	9	3	A	26 7 99	Normal			
6	10	3	A	26 7 99	Normal	B120	Oversize Bore	ReMan
6	11	3	A	26 7 99	Normal	B119	High Lateral	ReMan
6	12	3	A	26 7 99	Normal			
6	13	4	A	26 7 99	Normal			
6	14	4	A	26 7 99	Normal	ReMan	Cup Brinell Cone Spall OB	B205
6	15	4	A	26 7 99	Normal	ReMan	Cup Spall	B210
6	16	4	A	26 7 99	Normal			
6	17	5	A	26 7 99	Normal			
6	18	5	A	26 7 99	Normal			
6	19	5	A	26 7 99	Normal			
6	20	5	A	26 7 99	Normal			
6	21	6	A	26 7 99	Normal			FLAT
6	22	6	A	26 7 99	Normal	B203	Cup Spall WE Roller	ReMan
6	23	6	A	26 7 99	Normal	B24	Roller	ReMan
6	24	6	A	26 7 99	Normal			
6	25	7	B	26 7 99	Normal			
6	26	7	B	26 7 99	Normal	SC	Spun Cone	ReMan
6	27	7	B	26 7 99	Normal			
6	28	7	B	26 7 99	Normal	B114	Cone 1 Spall Un-repaired	ReMan
6	29	8	A	26 7 99	Normal			
6	30	8	A	26 7 99	Normal	B207	Roller Spalls 2-lb 1-OB +WE C	ReMan
6	31	8	A	26 7 99	Normal	B116	Oversize Bore	ReMan
6	32	8	A	26 7 99	Normal			
6	33	9	B	26 7 99	Normal	B201	Cup WE Cone tight	ReMan
6	34	9	B	26 7 99	Normal			
6	35	9	B	26 7 99	Normal	B202	Spalls Cup rpb cone OB-1	ReMan
6	36	9	B	26 7 99	Normal			
7	5	2	B	27 7 99	Normal			
7	6	2	B	27 7 99	Normal	B103	WE cup	ReMan
7	7	2	B	27 7 99	Normal	B105	Cone Spalls 2 REPAIRED	ReMAn
7	8	2	B	27 7 99	Normal			
7	9	3	B	27 7 99	Normal	B211	Cup Spall	ReMan
7	10	3	B	27 7 99	Normal			
7	11	3	B	27 7 99	Normal	W51SC	Spun Cone	ReMan
7	12	3	B	27 7 99	Normal			

Defect Bearing Location and Description Table – Con't

Con-sist	Axle No.	Car No.	Lead-ing	Date	Direction	Normal Near Side	FRA List # Prior Inspection Breakdown	Reverse Near Side
7	13	4	A	27 7 99	Normal			
7	14	4	A	27 7 99	Normal	B212	Cup Brinell Cone Spall OB	ReMan
7	15	4	A	27 7 99	Normal	B33	Multiple Cup	ReMan
7	16	4	A	27 7 99	Normal			
7	17	5	A	27 7 99	Normal	B102	Cone Spalls 2 Un-repaired	ReMan
7	18	5	A	27 7 99	Normal			
7	19	5	A	27 7 99	Normal	B101	WE Cup	ReMan
7	20	5	A	27 7 99	Normal			
7	21	6	A	27 7 99	Normal			
7	22	6	A	27 7 99	Normal	B214	Roller and Cup Frag Dents	ReMan
7	23	6	A	27 7 99	Normal	W30LBR	Loose Backing Ring	ReMan
7	24	6	A	27 7 99	Normal			
8	5	2	B	27 7 99	Reversed			
8	6	2	B	27 7 99	Reversed	ReMan		W30LBR
8	7	2	B	27 7 99	Reversed	ReMan		B214
8	8	2	B	27 7 99	Reversed			
8	9	3	B	27 7 99	Reversed			
8	10	3	B	27 7 99	Reversed	ReMan		B101
8	11	3	B	27 7 99	Reversed			
8	12	3	B	27 7 99	Reversed	ReMan		B102
8	13	4	B	27 7 99	Reversed			
8	14	4	B	27 7 88	Reversed	ReMan		B33
8	15	4	B	27 7 99	Reversed	ReMan		B212
8	16	4	B	27 7 99	Reversed			
8	17	5	A	27 7 99	Reversed			
8	18	5	A	27 7 99	Reversed	ReMan		W51SC
8	19	5	A	27 7 99	Reversed			
8	20	5	A	27 7 99	Reversed	ReMan		B211
8	21	6	A	27 7 99	Reversed			
8	22	6	A	27 7 99	Reversed	ReMan		B105
8	23	6	A	27 7 99	Reversed	ReMan		B103
8	24	6	A	27 7 99	Reversed			
9	5	2	A	29 7 99	Normal			
9	6	2	A	29 7 99	Normal	B218	Cone Spall OB?	ReMan
9	7	2	A	29 7 99	Normal	B215	Over Size Bore Ib	ReMan
9	8	2	A	29 7 99	Normal			
9	9	3	A	29 7 99	Normal			
9	10	3	A	29 7 99	Normal	B213	Loose Backing Ring	ReMan
9	11	3	A	29 7 99	Normal	ReMan		B118
9	12	3	A	29 7 99	Normal			
9	13	4	A	29 7 99	Normal			
9	14	4	A	29 7 99	Normal	ReMan		B205

Defect Bearing Location and Description Table – Con't

Con-sist	Axle No.	Car No.	Lead-ing	Date	Direction	Normal Near Side	FRA List # Prior Inspection Breakdown	Reverse Near Side
9	15	4	A	29 7 99	Normal	B217	Roller Spall OB	ReMan
9	16	4	A	29 7 99	Normal			
9	17	5	A	29 7 99	Normal			
9	18	5	A	29 7 99	Normal			
9	19	5	A	29 7 99	Normal			
9	20	5	A	29 7 99	Normal	ReMan		B203
9	21	6	A	29 7 99	Normal			
9	22	6	A	29 7 99	Normal	B216	Roller Spall OB	ReMan
9	23	6	A	29 7 99	Normal	B207	Roller Spalls 2-lb 1-OB +WE C	ReMan
9	24	6	A	29 7 99	Normal			
9	25	7	B	29 7 99	Normal			
9	26	7	B	29 7 99	Normal	W54SC	Spun Cone	ReMan
9	27	7	B	29 7 99	Normal			
9	28	7	B	29 7 99	Normal	W31LBR	Loose Backing Ring	ReMan
9	29	8	A	29 7 99	Normal			
9	30	8	A	29 7 99	Normal	B208	K65 sn#411	ReMan
9	31	8	A	29 7 99	Normal	B116	Oversize Bore	ReMan
9	32	8	A	29 7 99	Normal			
9	33	9	B	29 7 99	Normal	B201	Cup WE Cone tight	ReMan
9	34	9	B	29 7 99	Normal			
9	35	9	B	29 7 99	Normal	B202	Spalls Cup RPB Cone OB-1	ReMan
9	36	9	B	29 7 99	Normal			
10	5	2	A	29 7 99	Reversed			
10	6	2	A	29 7 99	Reversed	ReMan		B202
10	7	2	A	29 7 99	Reversed			
10	8	2	A	29 7 99	Reversed	ReMan		B201
10	9	3	B	29 7 99	Reversed			
10	10	3	B	29 7 99	Reversed	ReMan		B116
10	11	3	B	29 7 99	Reversed	ReMan		B208
10	12	3	B	29 7 99	Reversed			
10	13	4	A	29 7 99	Reversed	ReMan		W31LBR
10	14	4	A	29 7 99	Reversed			
10	15	4	A	29 7 99	Reversed	ReMan		W54SC
10	16	4	A	29 7 99	Reversed			
10	17	5	B	29 7 99	Reversed			
10	18	5	B	29 7 99	Reversed	ReMan		B207
10	19	5	B	29 7 99	Reversed	ReMan		B216
10	20	5	B	29 7 99	Reversed			
10	21	6	B	29 7 99	Reversed	B203	Cup SP WE OBC Roller SP	ReMan
10	22	6	B	29 7 99	Reversed			
10	23	6	B	29 7 99	Reversed			
10	24	6	B	29 7 99	Reversed			
10	25	7	B	29 7 99	Reversed			
10	26	7	B	29 7 99	Reversed	ReMan		B217

Defect Bearing Location and Description Table – Con't

Con-sist	Axle No.	Car No.	Lead-ing	Date	Direction	Normal Near Side	FRA List # Inspection Breakdown	Reverse Near Side
10	27	7	B	29 7 99	Reversed	B205	Cup Brinell Cone Spall OB	ReMan
10	28	7	B	29 7 99	Reversed			
10	29	8	B	29 7 99	Reversed			
10	30	8	B	29 7 99	Reversed	B118	Oversize Bore	ReMan
10	31	8	B	29 7 99	Reversed	ReMan		B123
10	32	8	B	29 7 99	Reversed			
10	33	9	B	29 7 99	Reversed			
10	34	9	B	29 7 99	Reversed	ReMan		B215
10	35	9	B	29 7 99	Reversed	ReMan		B218
10	35	9	B	29 7 99	Reversed			

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July 28, 2000
CON/ERW/00-020

Ms. Monique Stewart
Task Order Technical Monitor

Federal Railroad Administration
Office of Research and Development, RDV-32
1120 Vermont Avenue, N.W., MS-20
Washington, DC 20590

Subj: **Draft Final Report** - Roller Bearing Acoustic Detector/Wayside Train Inspection Research Project

Refr: Contract DTFR53-93-C-00001, **Task Order Number 122**, Modification 01

Dear Ms. Stewart:

Forwarded are three copies of a report titled *Improved Roller Bearing Wayside Detection Research Phase III System Evaluation Test* as required under Part VI of the task order and section 4.6 of the Statement Of Work.

In order to provide sufficient time for FRA's review process, we again request a task order performance extension to September 30, 2001. Please provide me with FRA's collective written remarks/comments upon review conclusion.

Sincerely,
TRANSPORTATION TECHNOLOGY CENTER, INC.

Edward R. Walsh

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IMPROVED ROLLER BEARING
WAYSIDE DETECTION RESEARCH
Phase III System Evaluation Test

G.B. Anderson
J.E. Cline
R.L. Smith

TTCI
Transportation
Technology Center, Inc.


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