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Volume I - Final Report

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14. ABSTRACT
In April 2005, visual and laboratory tests identified cracks in the spokes of several brake discs on coach cars within Amtrak's Acela trainsets, the high-speed trainsets operating on the Northeast Corridor. Amtrak halted operations of the Acela fleet until an assessment of the cracked spokes could be made. With the support of the Federal Railroad Administration, Amtrak launched an extensive test program that relied on a cooperative effort between several organizations, including the Northeast Corridor Maintenance Services Company, Bombardier, Alstom Transportation, the manufacturers of the brake system, and ENSCO, Inc. The test program involved a three-phase over-the-road test effort, finite element analyses, and a series of laboratory tests. The first and second phases focused on characterizing the mechanical and thermal load environment associated with WABTEC/SAB-WABCO supplied brake discs employed on the Acela equipment. In the third phase, the Knorr Brake Corporation provided a replacement disc, and an axle equipped with brake discs of this alternative design was also evaluated. This report documents the background of this issue, as well as the development and implementation of the study. The results of the test program, also detailed in this report, allowed for the identification of the Knorr brake disc as an acceptable alternative to the WABTEC/SAB-WABCO supplied disc, enabling Amtrak to return the Acela fleet to service.

15. SUBJECT TERMS
Brake disc, cracked spoke, Acela brake disc, center and outer brake discs, WABTEC/SAB-WABCO supplied brake disc, Knorr brake disc, out-of-plane bending, in-plane bending, analysis and testing of brake discs

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		1 kilometer (km)	= 0.6 mile (mi)
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1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)	1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
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			= 1.1 short tons
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1 tablespoon (tbsp)	= 15 milliliters (ml)	1 liter (l)	= 2.1 pints (pt)
1 fluid ounce (fl oz)	= 30 milliliters (ml)	1 liter (l)	= 1.06 quarts (qt)
1 cup (c)	= 0.24 liter (l)	1 liter (l)	= 0.26 gallon (gal)
1 pint (pt)	= 0.47 liter (l)		
1 quart (qt)	= 0.96 liter (l)		
1 gallon (gal)	= 3.8 liters (l)		
1 cubic foot (cu ft, ft^3)	= 0.03 cubic meter (m^3)	1 cubic meter (m^3)	= 36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	= 0.76 cubic meter (m^3)	1 cubic meter (m^3)	= 1.3 cubic yards (cu yd, yd^3)
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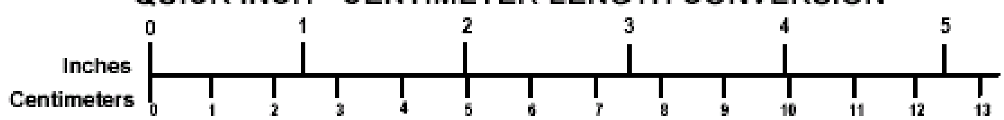

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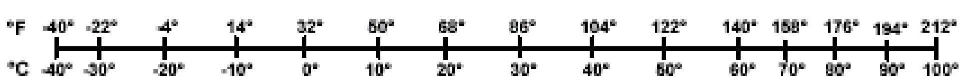

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EXECUTIVE SUMMARY

In April 2005, visual and laboratory tests identified cracks in the spokes of several brake discs on various coach cars within Acela trainsets, the high-speed trainsets operated by the National Passenger Railroad Administration (Amtrak) on the Northeast Corridor (NEC). The cracks were initially discovered during an inspection of Acela Trainset 17 following its use in the annual recertification test. Crack propagation through each of the six spokes joining the friction ring to the hub of a brake disc would lead to a situation in which no rigid connection existed between the braking surface of the disc and the hub, and therefore the axle itself. Not only would this result in an elimination of contribution to braking effort from a disc, it could also result in significant damage caused to the truck, therefore presenting a potential derailment scenario should a portion of the disc separate from the axle. This situation would be exacerbated by the high speeds associated with the operation of the Acela fleet. Although inspections revealed individual spokes in which cracks had propagated completely through the material and exhibited signs of corrosion, indicating the existence of the cracks for a significant period of time, *no* disc within the fleet had the braking surface separate from the hub.

Amtrak decided to halt operations of the Acela fleet until an accurate assessment of the cracked spokes could be made. With the support of the Federal Railroad Administration (FRA), Amtrak, working in conjunction with Northeast Corridor Maintenance Services Company (NECMSC), Bombardier, Alstom Transportation, and the manufacturers of the brake system, Knorr Brake Corporation (Knorr), Faiveley Transport (Faiveley) and Wabtec Corporation (Wabtec), launched an extensive test program. ENSCO, Inc. was given the responsibility of instrumentation, testing, and analysis.

The test program was comprised of a three-phase over-the-road test effort, finite element analyses and a series of laboratory tests. The initial phase of the over-the-road test effort focused on characterizing the mechanical and thermal load environment associated with the WABTEC/SAB-WABCO supplied disc employed on the Acela equipment to date. The second phase of the effort employed additional strain measurements to focus attention on the interaction of the center disc with the axle and on frequencies observed on the WABTEC/SAB-WABCO supplied disc during Phase 1. In the final phase of the effort, Knorr provided a replacement disc, and an axle equipped with brake discs of this alternate design was included in the test program. Direct comparisons were made between the Knorr disc and the WABTEC/SAB-WABCO supplied disc during over-the-road service.

The following key observations and conclusions were drawn from testing and analysis:

1. A detailed metallurgical analysis of a section of a cracked brake disc conducted at the onset of the investigation revealed that cracks developed due to a progression of bending fatigue that originated along a decarburized surface layer. The report states: "Although the decarburized surface provided a site for fatigue initiation, the root cause of the cracking is the level of bending stresses at the crack sites."

   The inspection revealed that, with the exception of the thin decarburized surface layer, the brake disc casting met mechanical and chemical specifications.

2. Sustained out-of-plane bending oscillations were observed on the WABTEC/SAB-WABCO supplied disc during some brake applications. The sustained out-of-plane bending did not occur during all brake applications for the WABTEC/SAB-WABCO supplied disc, and, once it was observed, it was not always repeatable during a given test run. The magnitude of the oscillating strain was observed to grow proportionally with higher brake pressure. During braking events,

these oscillating strains were added to the mean (tension inducing) strains associated with the heating of the disc friction surface. The magnitude of the sustained oscillations on the center disc was approximately three times that observed on the outboard disc. Braking-induced oscillations were sustained through the duration of brake application. This activity was only observed on the WABTEC/SAB-WABCO supplied disc when the test axle was in the leading position of the truck.

This activity was not observed at any time for the Knorr disc. These responses are relevant to the fatigue life evaluation. The absence of this activity in the Knorr disc is expected to provide a beneficial effect on the fatigue life and a reduction in the likelihood of crack formation.

3. Accelerations at the journal box were observed at several track locations with most peaks in the range of 50 to 100 g vertical and 30 to 50 g lateral. Up to 21 peaks were measured in the vertical direction in excess of 100 g per one-way trip between Washington and Boston, with the maximum vertical acceleration reaching 189 g. These were generally observed at switches, bridge approaches, and other special track work. Because these measurements were made in May and June, further stiffening of the ballast as a consequence of cold weather may result in higher loads.

   For center and outer WABTEC/SAB-WABCO supplied discs, when an asymmetric vertical shock occurred independent of braking, it frequently induced large out-of-plane bending oscillations of the spokes. These oscillations were observed to be of similar amplitudes on the center and outer discs. These oscillations were observed at a frequency close to the natural out-of-plane bending frequency of the brake disc determined during laboratory testing. Because shocks of this nature are independent of braking, these oscillations did occur about a wide range of mean strain levels.

   A similar response to vertical shocks was observed for the Knorr disc, but the amplitudes of these strains were typically 40 percent of the strains observed on the WABTEC/SAB-WABCO supplied disc, and these strains damped quicker. These responses are relevant to the fatigue life evaluation of the two disc designs. The reduced level of strains observed in the Knorr disc is expected to provide a beneficial effect on the fatigue life and a reduction in the likelihood of crack formation.

   Lateral shocks did not appear to induce similar oscillations in either of the disc designs tested.

4. Temperatures of the brake disc friction ring and strains associated with this thermal heating under test braking conditions were within normal ranges and on the order of what was expected by the brake suppliers.

5. The installed WABTEC/SAB-WABCO supplied disc retains a compressive preload in the spokes, which laboratory tests confirmed.

6. Finite element analysis indicated the highest strains associated with out-of-plane bending at the location of the observed cracking. Discontinuities found on the surface of some spokes arising from a mold parting line also appeared in this location.

Based on the testing performed and subsequent analysis, the conclusion of the test program is that the mechanical and thermal responses of the spokes of the Knorr-designed brake disc measured during testing with the Acela Express vehicles were within predicted and acceptable values. Although experiencing slightly lower thermal strains, the WABTEC/SAB-WABCO supplied brake disc experienced significantly higher mechanical strains at times. The lower mechanical strains observed in the Knorr designed brake disc, in comparison with those observed in the WABTEC/SAB-WABCO supplied brake disc and associated with the absence of sustained oscillations during braking and the response to vertical shocks, are expected to provide a beneficial effect on the fatigue life associated with the Knorr brake disc design, as well as a reduction in the likelihood of crack formation.

The findings discussed in this report permitted Amtrak to arrive at an acceptable alternative that allowed the Acela equipment to return to service.

1.0 INTRODUCTION

1.1 Background

The Acela high-speed trainsets have been an important part of America's passenger rail service since March 1996 when the Amtrak announced the acquisition of the equipment from Bombardier Transportation and Alstom Transportation (the Consortium). A fleet of 20 trainsets, each consisting of 6 passenger-carrying coach cars and 1 power car on each end, currently moves passengers through the NEC between Washington, DC, and Boston, MA, at speeds up to 150 mph (240 kph). The trainsets employ tilting systems that lean the coach cars into curves at high speeds to provide a comfortable ride for passengers.

Following nearly 1 year of testing on the NEC, FRA granted approval for conditional revenue service operations of the Acela trainsets on September 18, 2000, in accordance with the Federal Track Safety Standards (49 CFR Part 213). On December 11, 2000, Amtrak introduced the high-speed trainsets into service under the name Acela Express.

In compliance with §213.333 of the Track Safety Standards, tests are conducted annually with a typical Acela trainset over the length of the NEC at revenue speeds to confirm the safe operation of the equipment. Following a series of technical discussions between Amtrak and FRA, it was decided that the annual recertification test conducted in 2005 would be run with a speed profile desired by Amtrak for future revenue service; this speed profile employed slightly higher speeds in selected curves over the route referred to as cant deficiency testing. The 2005 annual recertification test runs were made between Washington and Boston with Acela Trainset 17 over a period from April 11 to 14, 2005.

On the evening of April 14, 2005, upon successful completion of the last scheduled high cant deficiency and qualification run round trip between Washington and Boston, Amtrak's Acela Express Trainset 17 was undergoing a post-test general inspection at the Ivy City Maintenance Facility by FRA Inspector Steve Clay and FRA Motive Power and Equipment (MP&E) Safety Specialist Richard Thomas, both from FRA's Region 2, when they identified a crack in the spoke of a brake rotor disc utilized on the coach cars. Subsequent to finding the first cracked disc spoke, other cracked spokes were identified on Trainset 17. After a discussion between personnel from FRA's Headquarters MP&E Division, Region 2, and Amtrak, the remaining trainsets were inspected, and pervasive cracking was identified on brake disc spokes. Details associated with the initial discovery of the cracks have been well documented.[1] Cracks found on the spokes have been classified for the purpose of inspection.[2]

Figure 1.1 provides a drawing of the WABTEC/SAB-WABCO supplied disc, including an indication of its location on an Acela coach car; Figure 1.2 shows photographs of this disc. During braking of the Acela trainset, three sets of calipers each force a set of brake pads to make contact with the large friction ring on both sides of the three brake discs installed on each axle.

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[1]Rich Bowie, Definition of Acceptable Cracks for Acela Monoblock Discs, rev. 6, Knorr Brake Corporation, May 12, 2005, p. 4.

[2]Norbert Behety, TS10 Brake Discs Inspection Procedure, rev. 1, Northeast Corridor Maintenance Services Company, May 9, 2005, p. 8.

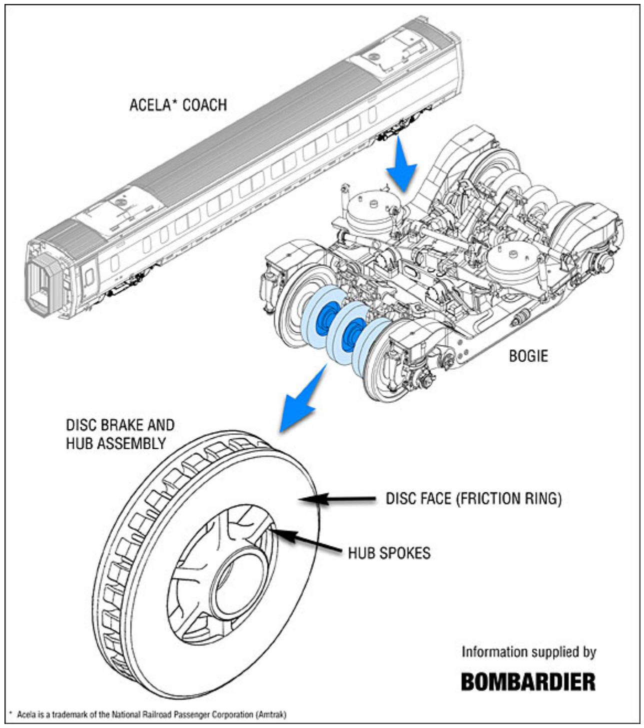


Figure 1.1. Typical Acela Coach, Bogie and Brake Disc

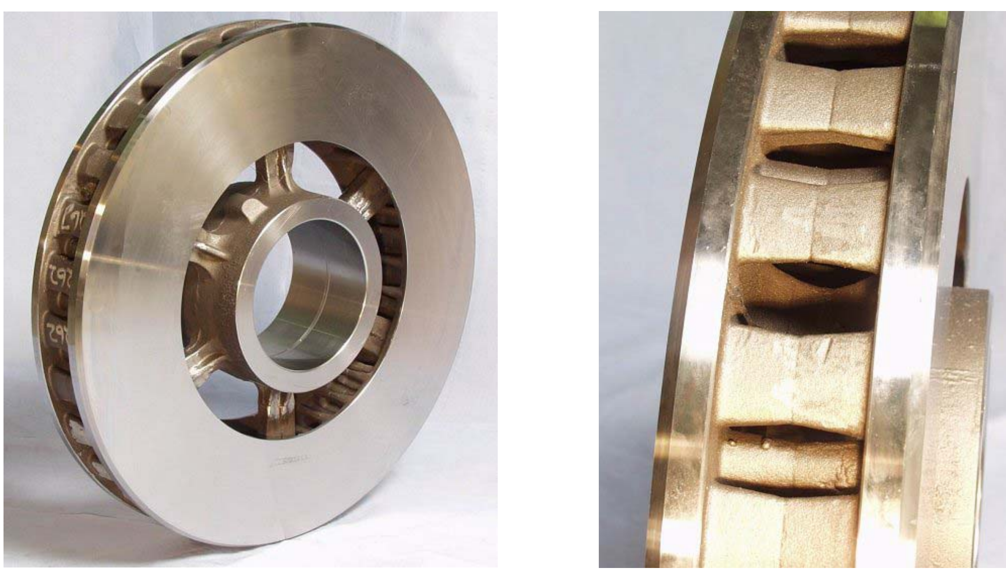


Figure 1.2. WABTEC/SAB-WABCO Supplied Brake Disc

Figure 1.3. Example of a Crack in Spoke of WABTEC/SAB-WABCO Supplied Brake Disc Used on Acela Coach Car

The brake discs are considered a monoblock design, one in which the disc is made from a one-piece casting as opposed to designs that have the friction ring bolted to the hub. Figure 1.3 illustrates an example of a crack identified during the inspections. Many cracks observed on the brake discs were in a location corresponding to discontinuities found on the surface of some spokes arising from a mold parting line. As can be seen by considering the crack shown in Figure 1.3, crack propagation through each of the spokes joining the friction ring to the hub of the disc would lead to a situation in which no rigid connection exists between the braking surface of the disc and the hub, and therefore the axle itself. Not only would this result in an elimination of contribution to braking effort from this disc, it could also result in significant damage caused to the truck, therefore presenting a potential derailment scenario, should a portion of the disc separate from the axle. This situation would be exacerbated by the high speeds associated with the operation of the Acela fleet. Although inspections revealed individual spokes in which cracks had propagated completely through the material, exhibiting signs of corrosion, which indicated that cracks have propagated for a significant period of time, *no* disc within the fleet had the braking surface separate from the hub.

Upon discovery of the cracks, Amtrak voluntarily removed all 20 Acela trainsets from service until the cracking issue could be further understood and resolved; Acela trainset operations ceased on the morning of April 15, 2005. Amtrak, working in conjunction with the NECMSC, the Consortium and the manufacturers of the brake system, Knorr, Sab-Wabco (later acquired by Faiveley) and Wabtec, determined that additional information related to the cause of the cracks was necessary to determine the best course of action and, if necessary, undertake a re-design of the brake disc.

Wabtec contracted Metallurgical Technologies, Inc., P.A. (MTI) to conduct a detailed analysis of one of the cracked discs.[3] A section of a cracked brake disc (S/N 339958) was provided to MTI, and a thorough investigation of the nature of the cracks was conducted. The investigation employed several techniques, including magnetic particle examinations, cross-sectional metallographic analysis, energy dispersive x-ray spectrographic analysis, material hardness/tensile-strength testing, and chemical analysis. The

[3] T.C. Tschanz, P.E., and S. Pendergrass, P.E., Analysis of Cast WC700 Brake Disc, Metallurgical Technologies Inc., P.A. Report No. 2005381, May 25, 2005, p. 7.

investigation revealed that cracks developed due to a progression of bending fatigue that originated along a decarburized surface layer. The report states: “Although the decarburized surface layer provided a site for fatigue initiation, the root cause of the cracking is the level of bending stresses at the crack sites.”

The inspection revealed that, with the exception of the thin decarburized surface layer, the brake disc casting met mechanical and chemical specifications.

As a result of discussions between Amtrak and FRA, it was agreed that an over-the-road test was warranted. ENSCO, Inc. was given the responsibility to instrument Acela Trainset 10 and conduct over-the-road testing to fully quantify the service environment. Appendix A provides the sequence of test plans developed during the program. Amtrak and FRA also tasked ENSCO to analyze test data.

After an intensive 3-month safety review and test program orchestrated by FRA, Amtrak, and the equipment suppliers, a rotor of alternative design was identified and accepted that permitted the trainsets to be returned safely to service. The first trainset was returned to service on the NEC on July 11, 2005, and all trainsets were subsequently retrofitted and returned to service by the end of September 2005.

This report documents the over-the-road test program, subsequent analysis of the data, and selection of an alternative rotor design.

1.2 Test Objectives and Approach

The original goals of this test and evaluation were to gather data from which to determine the causes and contributing factors associated with the observed cracking of the WABTEC/SAB-WABCO supplied disc design and to characterize the load environment associated and the mechanical response of the discs during conditions resulting from 7-inch and 9-inch cant deficiency speed profiles on the NEC. As test data was gathered, the program evolved primarily into a three-phased effort.

Phase 1 was focused on characterizing the mechanical and thermal load environment associated with the WABTEC/SAB-WABCO supplied disc employed on the Acela equipment to date, identifying the strains in the WABTEC/SAB-WABCO supplied disc spokes themselves, and measuring the accelerations generated from the vehicle-track interaction associated with train operation. One objective was to determine if a relationship existed between accelerations and measured strains, and what strains and sources of strain might contribute to spoke failure. A second objective was to characterize the environment in terms of the accelerations so that a replacement disc could be developed and applied that could be successful in that environment. Phase 1 involved the complete instrumentation of the center and an outer disc of a single axle, their calipers, and the accelerations observed on the axle and its bearings. As a result of testing, it was observed that some fairly significant strains appeared to be associated with an out-of-plane bending of the disc. This bending activity appeared to be associated with both braking and impact events and was observed to occur at a frequency of approximately 227 Hz.

In Phase 2, to better characterize the strains associated with out-of-plane bending, additional strain measurements were made on the axle and on opposing spokes of the center disc; the highest strains observed during Phase 1 occurred on the center disc. Attention focused on the interaction of the center disc with the axle and on the investigation of the resonant frequency associated with the WABTEC/SAB-WABCO supplied disc and those frequencies observed during Phase 1. Sampling rates higher than those in Phase 1 were employed to ensure that all of the relevant information was captured. In addition, some laboratory tests were performed to investigate the natural frequencies of the WABTEC/SAB-WABCO supplied disc.

In Phase 3, Knorr identified and provided a replacement disc, and an axle equipped with brake discs of this alternate design was included in the test program. Figure 1.4 provides an illustration of the Knorr disc; Figure 1.5 shows a photograph of the spokes of the Knorr disc. The goal of this portion of the evaluation was to determine if the Knorr disc design demonstrated substantial improvements over the original disc design and was likely to be successful in service. The axle with the set of alternative discs was placed on an adjacent car within the test train, and the instrumentation suite was expanded to accommodate measurements on the axle equipped with the Knorr disc and on the axle equipped with the WABTEC/SAB-WABCO supplied disc. A final test series was run, during which direct comparisons were made between the Knorr disc and the WABTEC/SAB-WABCO supplied disc in over-the-road tests. Data was collected in a manner that would allow decisions to be made about the potential for success of the Knorr design in revenue service.

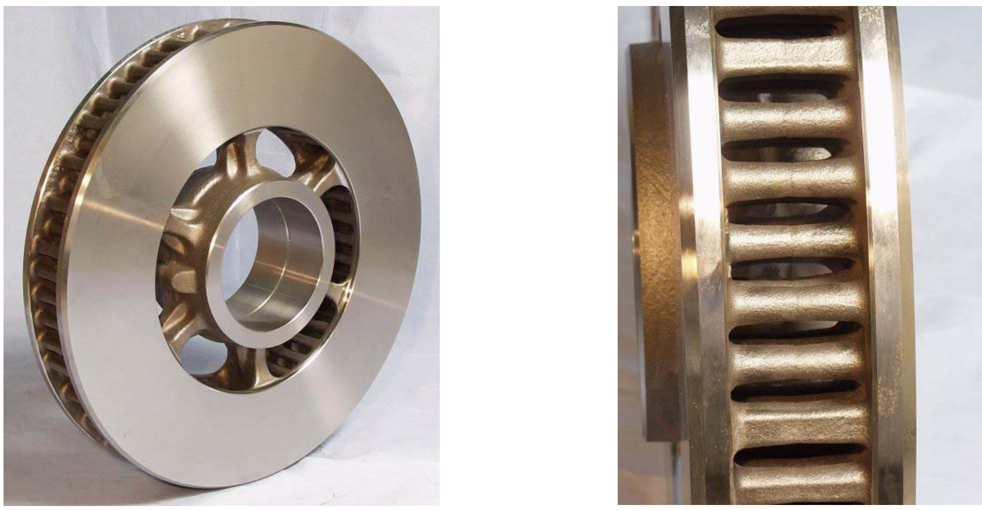


Figure 1.4. Knorr Brake Disc

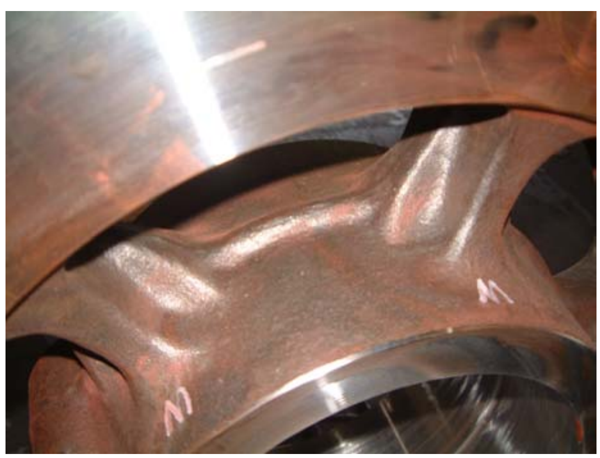


Figure 1.5. Spokes of Brake Disc Provided by Knorr

Analyses were done in a short turn-around time, some in real-time in the field and others very quickly after the test as guidance toward future testing and analysis. In addition to the analysis of the test data, finite element analyses were performed for the original WABTEC/SAB-WABCO supplied disc to enable a better understanding of the test data.

1.3 Test Participants

The test program described in this document was a large effort that required the efforts of many individuals from several organizations. The following provides the names of those most directly involved in the effort. The lead participant from each organization is italicized.

Amtrak

Carl Andreason
Clare Auvil
Earl Braxton
Bob Costello
Kathy Costello
Ed Finn
Greg Gagarin, P.E.
John Hines
Bob Kennedy
Ed Lombardi (TD)
Al Mahler
Pat Malin
Mark Murphy
Mike Minnich
Donald Savidge
Dave Schramm
Paul Steets
Mike Tomas
Michael Trosino

Bombardier

Sylvain Boily
Suzanne El Zawi
Frank Duschinsky
Virgilio Hilario
Denis Oakes
Mario Raymond

ENSCO

Jacinda Clemenzi
Bill Jordan
Kevin Kesler
Tim Martin
David McNew
Boris Nejikovsky
Dr. Ray Owings
Eric Sherrock
Amit Singh
Narayana Sundaram
Brian Whitten

Faiveley

Mike Cook
Björn Neller

FRA

Dr. Thomas Blankenship (Safety)
Daniel Buckley (Safety)
Stephen Carullo (Safety)
Steve Clay (Safety)
Richard Cogswell (R&D
Dr. Magdy El-Sibaie(R&D)
Larry Ewing (Safety)
Gary Fairbanks (Safety)
Mahmood Fateh (R&D)
Leslie Fiorenzo (Safety)
Paul Furman (Safety)
Thomas Herrmann (Chf. Counsel)
Peter Lapre (Safety)
Daniel Lewis (Safety)
John Mardente (Safety)
Shahram Mehrvarzi (R&D)
Ronald Newman (Safety)
Edward Pritchard (Safety)
Dr. Satya Singh (Safety)
Richard Thomas (Safety)
Charles Whalen (Safety)

Knorr

Dr. Frank Guenther (GE)
Frank Hellmer (GE)
Dr. Xaver Wirth (GE)
Rich Bowie (US)
Wade McLain (US)
Markus Seidl (US)
Terry Welsh (US)
Dave Welly (US)
Randall Wingate (US)

NECMSC

Norbert Behety
Sarabpreet Bumra
Jeff Cook
Sylvain Pages

Volpe

Jeff Gordon
Brian Marquis

Wabtec

Bill Slater

Notes:
TD–Test Director
GE–Knorr-Bremse Germany
US–Knorr-Bremse America

1.4 Report Organization

Chapter 2 discusses the test methodology, along with a review of the physical measurements recorded during testing. Measurements included the following:

- Strains on brake discs, axles, and links supporting a caliper assembly
- Temperature of the brake discs
- Accelerations measured on the test axles, caliper assemblies, and caliper mounting components
- Pressures throughout the brake system
- Consist location and speed
- Video images of the WABTEC/SAB-WABCO supplied disc
- Sound measurements collected above the test axles

Chapter 3 presents the results of the analysis of the collected test data; much of the information presented in Chapter 3 is supported by detailed analyses provided in the appendices. Chapter 4 presents the major observations of the test program. Chapter 5 presents conclusions based on the observations discussed in Chapter 4.

Supplemental material is provided in the appendices. A list of the appendices follows:

Appendix A. Record of Test Plans–The documentation of the test plans used in the test program. Electronic copy of test plans provided on CD-ROM.

Appendix B. Instrumentation Suite–Information on the sensors used in the test program, including calibration sheets and documentation on instrumentation verification.

Appendix C. Data Descriptions–Documentation providing formats of the data files generated in the test effort.

Appendix D. Test Documents and Logs–Documentation of data files collected during each day of testing. Includes daily reports provided by Knorr.

Appendix E. Finite Element Analysis Results–Supplemental information pertaining to modeling efforts.

Appendix F. Accelerations–Supplemental information on analysis of accelerations collected during test program.

Appendix G. Spoke Strains–Supplemental information on analysis of spoke strains collected during test program.

Appendix H. Axle Strains–Supplemental information on analysis of axle strains collected during test program.

Appendix I. Temperature–Additional analysis material compiled for temperature measurements collected during test program.

Appendix J. Laboratory Testing–Material compiled from spreader bar testing on WABTEC/SAB-WABCO test axle at end of Phase 1, of pre-load stress determination efforts conducted by Amtrak, and of modal vibration tests conducted during test program.

Appendix K. Brake Support Links–Detailed treatments of information collected from instrumented links used in Phase 3 testing.

Appendix L. Daily Handouts–Electronic copy of strip charts provided on CD-ROM.

Appendix M. Background of the WABTEC/SAB-WABCO Supplied Brake Disc–Supplemental information provided by Faiveley on the design of its brake disc, including discussions of the source of pre-load stresses and the disc's design.

2.0 TEST METHOD

The test program used three methods of investigating the behavior of the WABTEC/SAB-WABCO supplied and Knorr discs. The first and most important was testing of a full trainset under simulated revenue service conditions on the NEC. The second was a series of component level tests to investigate and explain the behavior observed during the NEC testing. Finally, finite element analyses (FEA) were conducted with models of brake discs to gain insight into the response of the discs to different load conditions.

This chapter will focus on the over-the-road and component level tests.

2.1 Over-the-Road Testing

Acela Trainset 10 was used during all tests. Figure 2.1 depicts the test consist and the vehicle number of all coaches and power cars. The test axle employing the WABTEC/SAB-WABCO supplied discs, designated as Axle 1, was installed on the A-end truck of Coach 3413 in the axle 1 position. The test axle with the Knorr discs, designated as Axle 2, was located on the B-end truck of Coach 3534 in the axle 4 position. The following illustrates the position of both test axles.

All data collection instrumentation was housed in Coach Car 3413 throughout the test effort.

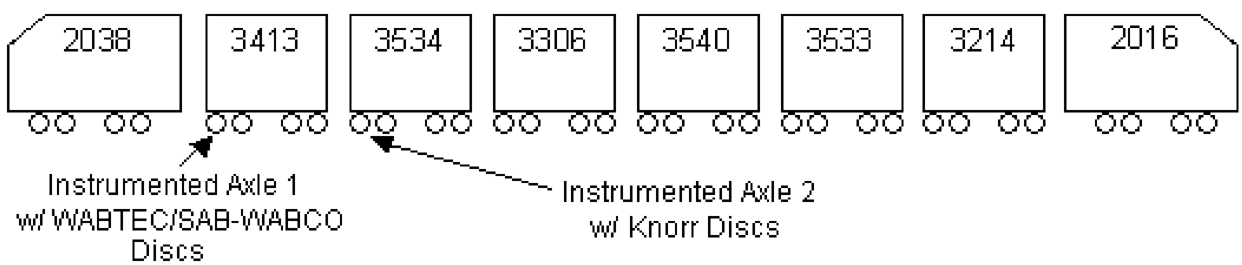


Figure 2.1. Test Consist–Acela Trainset 10

2.2 Over-the-Road Testing Sequence

A total of eight test runs were made during the over-the-road portion of the test program. Table 2.1 summarizes the test runs made.

Table 2.1. Summary of Test Runs Conducted on NEC During Acela Brake Disc Test Effort

Date	Test Day	Cant Deficiency Profile (Inches)	Instrumented Disc	Axle Position (w/Respect to Test Vehicle)	Description
5/14/2005[1]	-	7	W/S-W (center & outer)	Trail	Washington to Wilmington
				Lead	Wilmington to Washington
5/16/2005	1	7	W/S-W (center & outer)	Trail	Washington to Boston
5/17/2005	2	7	W/S-W (center & outer)	Lead	Boston to Washington
5/26/2005	3	7	W/S-W (center)	Lead	Washington to Boston
5/27/2005	4	7	W/S-W (center)	Trail	Boston to Washington
6/16/2005	5	7	W/S-W & Knorr (center) (center)	Lead	Washington to New York
				Trail	New York to Washington
6/17/2005	6	9	W/S-W & Knorr (center) (center)	Lead	Washington to Boston
6/18/2005	7	9	W/S-W & Knorr (center) (center)	Lead	Boston to Washington

[1] Shakedown Run

2.3 Test Instrumentation

The following sections provide details on measurements recorded at various times throughout the test program. Appendix B provides documentation for the sensors discussed in these sections. Instrumentation was installed at NECMSC's Ivy City Maintenance Facility.

2.3.1 Strains

Strains were measured on various components using single-axis, weldable strain gages designed and manufactured for high-temperature applications. The weldable gages, designated as HBWN-35-125-6-1TR, employed Vishay Measurements' WK-series self-temperature-compensated foil strain gages and were provided by Hitec Products, Inc. Appendix B provides specifications of the foil strain gages.

Strain measurements were made at the following locations:

- *Phase 1*

  Axle 1 from Car 3413, outfitted with WABTEC/SAB-WABCO supplied brake discs, was employed during testing. The center disc (serial number 070511) and the disc located closest to the ground brush, designated as the G disc (serial number 728610), were used during Phase 1. These brake discs, as well as all brake pads on the train, were in a new condition at the start of the test program. NECMSC provided train condition and serial number information.

  The strains on each side of a single spoke on the center brake disc and on the outer, or G, brake disc were recorded. During Phase 1, spokes 1 and 6 of each of the discs of interest were instrumented; spoke 6 was designated as the spoke of interest during the test, while spoke 1 was instrumented to serve as a backup in the event of damage to the gages placed on spoke 6. There was no need to collect data with the backup strain gages during Phase 1 of the study. All gages were located 1.2" below the lower edge of the friction ring, corresponding to the location of several observed cracks.

  Figure 2.2 illustrates the designation of the spokes on the WABTEC/SAB-WABCO supplied brake disc. Figure 2.3 provides an illustration of the location of all strain gages employed during Phase 1 of the study. Figure 2.4 shows the installation of a weldable strain gage on one of the spokes of a WABTEC/SAB-WABCO supplied disc.

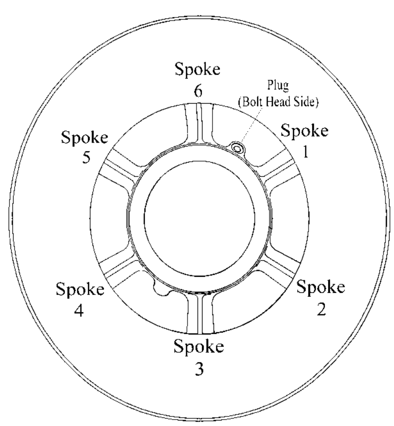


Figure 2.2. Spoke Designations for the WABTEC/SAB-WABCO Supplied Brake Disc

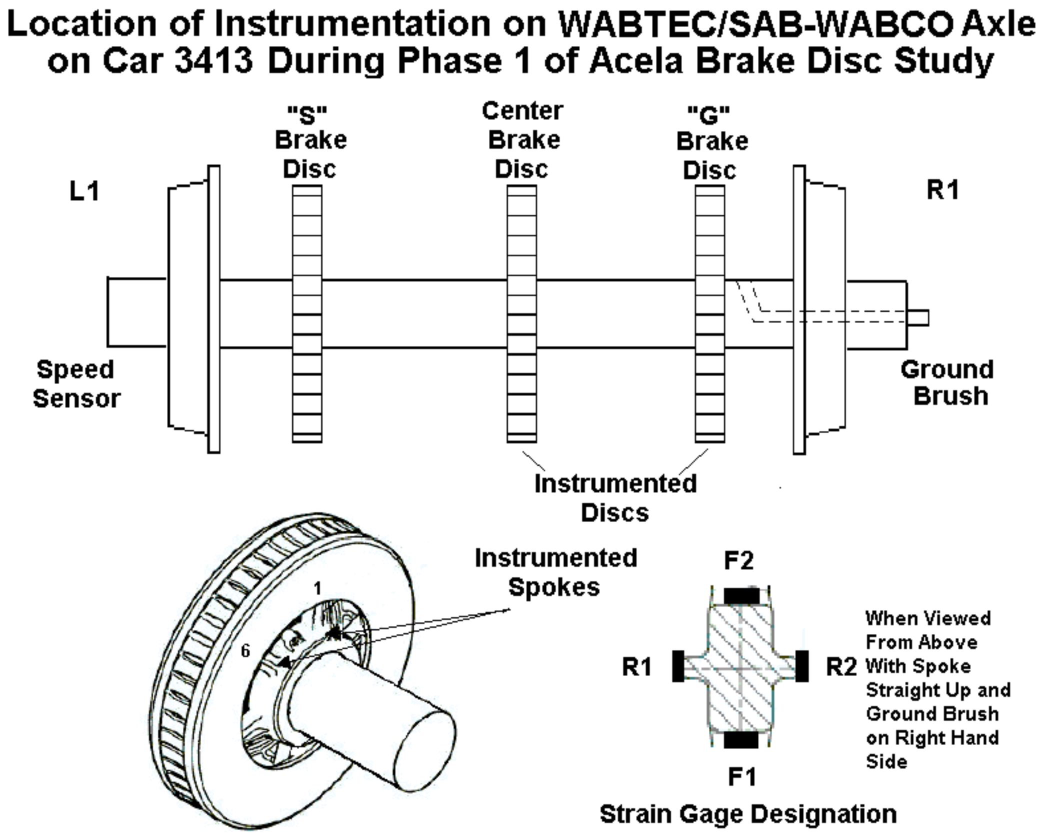


Figure 2.3. Location of Strain Gages on WABTEC/SAB-WABCO Supplied Discs During Phase 1 of Study

a) Spoke Grinding Process; Spoke to Left of Nut Unmodified

b) Gage Being Applied to Web on Spoke to Left of Nut

Figure 2.4. Strain Gage Being Applied to a Spoke of the WABTEC/SAB-WABCO Supplied Brake Disc (Courtesy M. Perkins, Amtrak)

- *Phase 2*

Following the completion of Phase 1, interest existed for focusing on the out-of-plane bending observed during the initial stage of the test. In order to accomplish this, the sides of spokes 3 and 4 of the WABTEC/SAB-WABCO supplied disc located at the center of the test axle were instrumented with strain gages in a manner similar to that employed in preparation for Phase 1. This was done to capture the bending of the spoke directly opposite spoke 6 and to determine the phase relationship between the strains recorded on the two spokes. As was done in the first part of the study, spoke 6 and spoke 3 were designated as the spokes of interest during the test. Spoke 1 and spoke 4 served as a set of backup spokes, but it was not necessary to use these gages during this phase of the study.

In addition to the new strain gages on spokes of the center disc, four strain gages were mounted to the axle, two gages 180º apart as close to the center disc as possible and two gages 180º apart at a location approximately ¼ of the distance between the two wheels. According to Knorr, the purpose of these gages was to observe the behavior of the axle, including the frequency associated with the second mode of axle bending. The strain gages were installed in a manner such that their location corresponded to spokes 6 and 3 of the center disc; due to the geometry of the axle, the geometric centers of the gages were located 9 inches from each other and centered within the space between the two discs. Figure 2.5 shows a picture of an axle-mounted strain gage. Figure 2.6 provides an illustration of the location of all strain gages employed during Phase 2 of the study.

Figure 2.5. Strain Gage on Surface (Longitudinal Direction) of Axle with WABTEC/SAB-WABCO Supplied Discs

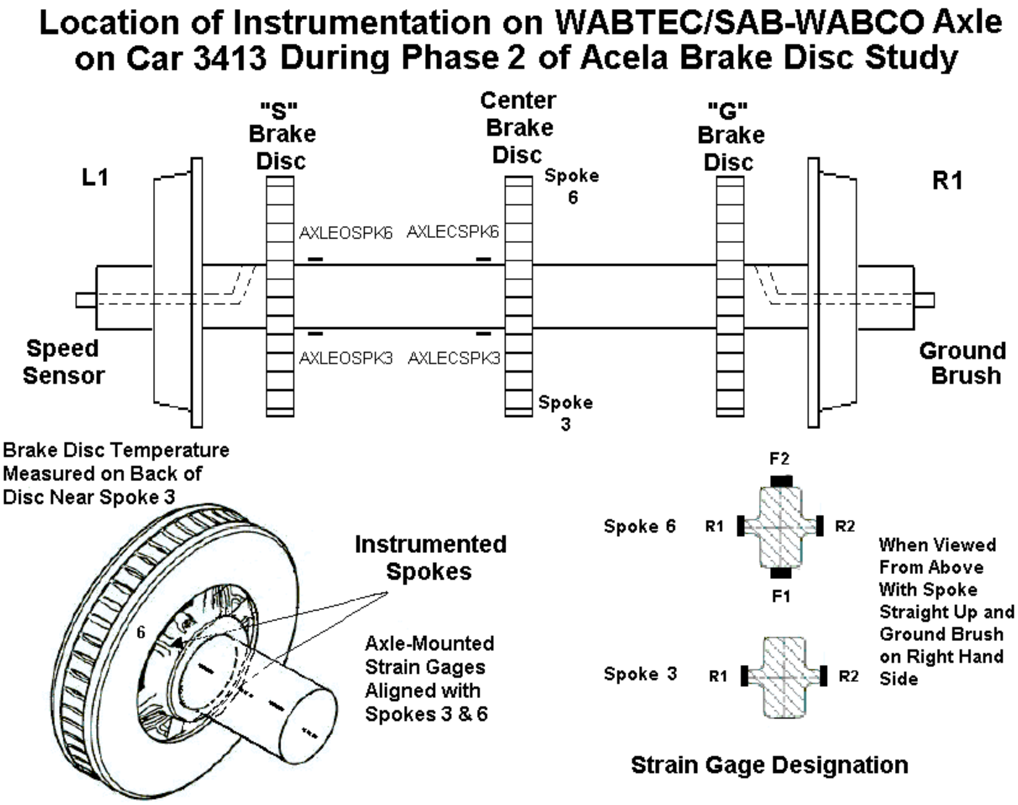


Figure 2.6. Location of Strain Gages on WABTEC/SAB-WABCO Test Axle During Phase 2 of Study

In order to accommodate the additional channels of interest, signals from strain gages mounted to the outer brake disc were not recorded for the remainder of the study.

- *Phase 3*

Following the completion of Phase 2, a replacement disc was identified and provided by Knorr, and an axle equipped with brake discs of this alternate design was included in the series of tests. Brake pads used with the Knorr discs were replaced with new pads at the time of installation. The center-mounted brake disc (serial number 097740 019) was the focus of the test effort. Knorr provided serial number information for this document.

Strain gages were installed on the center-mounted disc at particular locations on spokes designated by Knorr; Figure 2.7 illustrates these locations. The strain gages were located to coincide with the sites of highest strain in the spoke under typical operating conditions determined by FEA treatments conducted by Knorr.

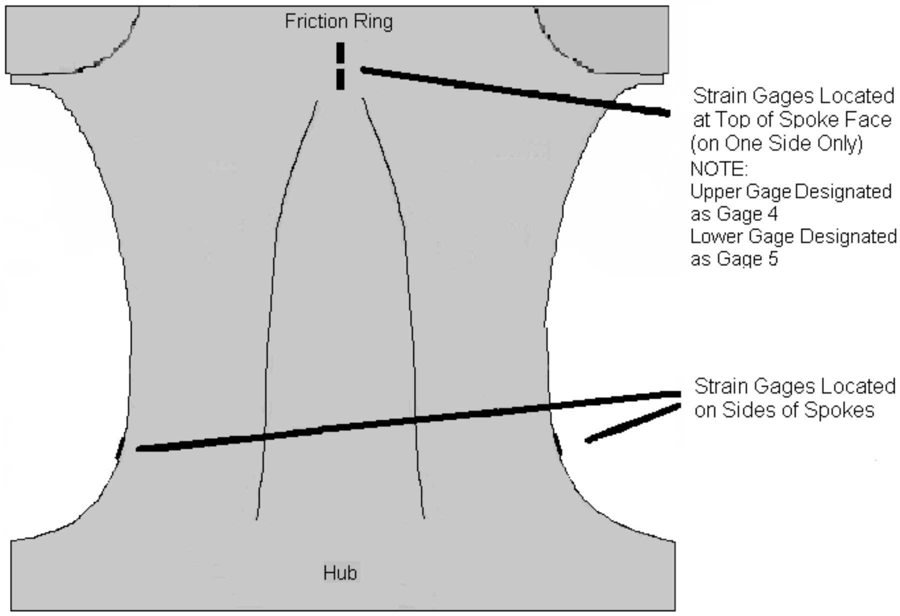


Figure 2.7. Illustration of Strain Gage Locations on Knorr Disc Used During Phase 3 of Acela Brake Disc Study

Gages located near the bottom of the spokes were located 17 millimeters above the surface of the hub; gages located at the top of the spoke were located as close to the transition into the friction rings as possible. As was done in the earlier parts of the study, spokes 6 and 3 on the Knorr instrumented discs were designated as the spokes of interest during the test. Spokes 1 and 4 served as a set of backup spokes, but no reason existed to use the gages on spokes 1 and 4 during Phase 3 of the test. Figure 2.8 illustrates the installation of a weldable strain gage on the side of spoke 3 of the Knorr disc.

a) Spoke 3 Following Grinding on Side

b) Gage Applied to Side of Spoke 3

Figure 2.8. Strain Gage Being Applied to Spoke 3 of the Knorr Brake Disc (Courtesy J. Gordon, VOLPE)

In addition to gages on the spokes of the Knorr disc, gages were installed on the test axle containing the Knorr discs. The location of the gages along the axle corresponded to the location of those installed on the WABTEC/SAB-WABCO test axle; on the Knorr test axle, four strain gages were installed around the axle near the center-mounted disc separated by 90º.

Figures 2.9a and 2.9b provide an illustration of the location of all strain gages employed on the WABTEC/SAB-WABCO and Knorr test axles during Phase 3 of the study.

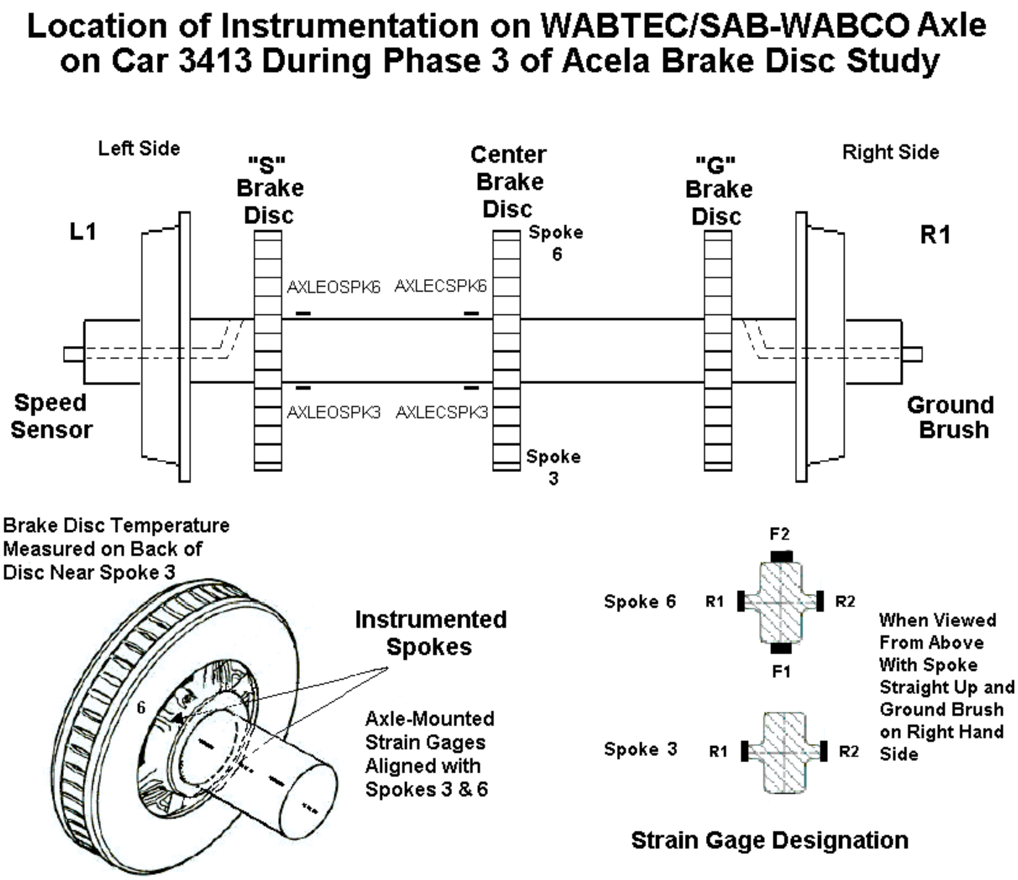


Figure 2.9a. Location of Strain Gages on WABTEC/SAB-WABCO Test Axle During Phase 3 of Acela Brake Disc Study

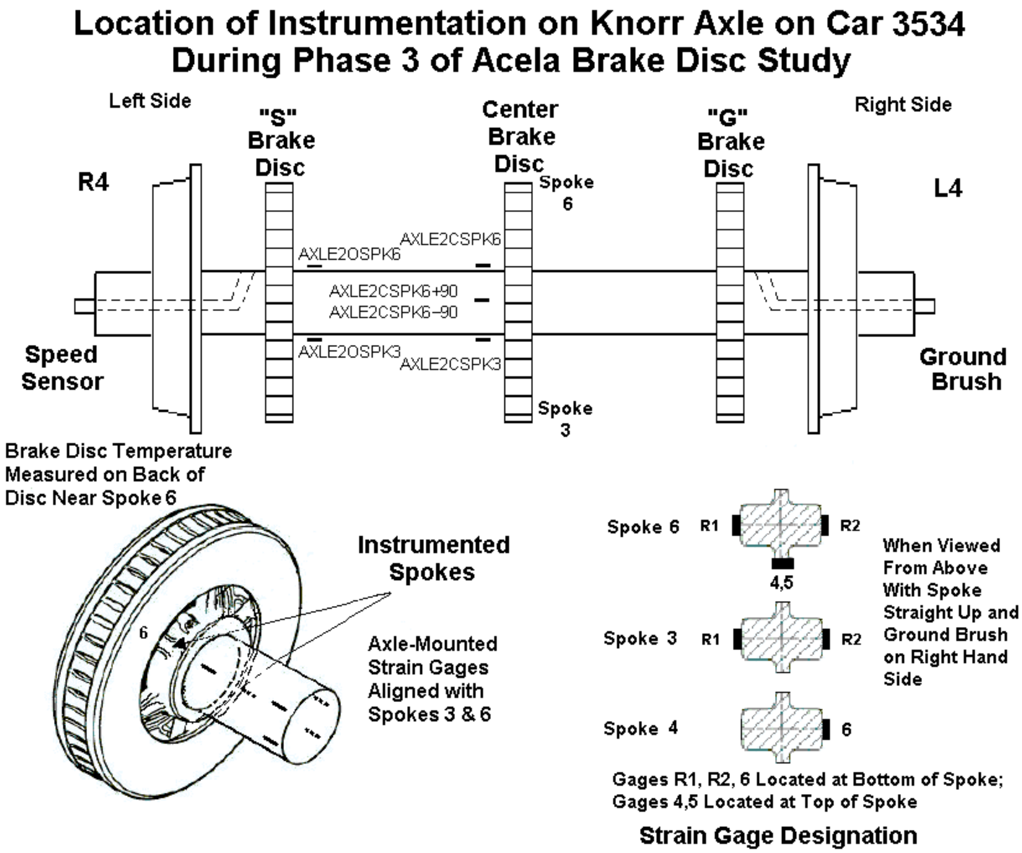


Figure 2.9b. Location of Strain Gages on Knorr Test Axle During Phase 3 of Acela Brake Disc Study

In addition to strain gages mounted to the instrumented discs and the test axles, strain gages were installed on two caliper hanger links (levers) at the request of Bombardier. Figure 2.10 shows the caliper hanger links installed on a truck removed from a coach car. One gage was installed on each of the hangers employed by the center caliper assembly associated with the WABTEC/SAB-WABCO test axle. The gages were installed on the side of the hanger facing the adjacent power car, and the center of each gage was located as close to the geometric center of the link as possible.

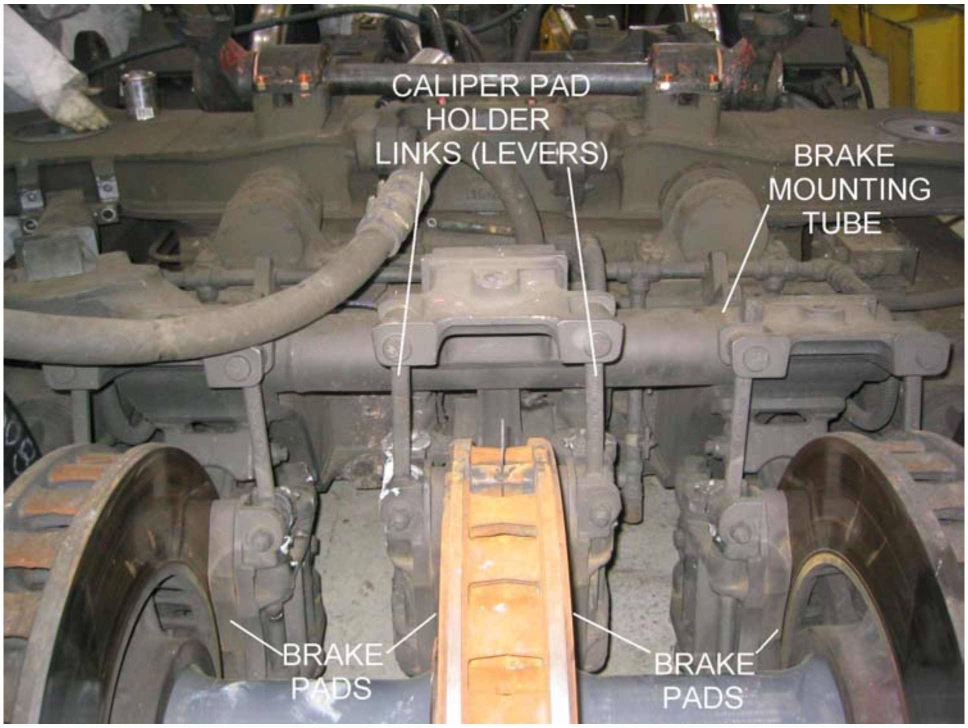


Figure 2.10. Brake Caliper Support Links and Mounting Tube
(Shown on Removed Truck for Clarity)

2.3.2 Accelerations

Many acceleration measurements were made throughout the designated vehicles during the test program. A variety of accelerometers from a number of sources were employed during the program. This section will review these measurements. Appendix B provides accelerometer calibration sheets.

- *Phase 1*

  The lateral and vertical accelerations experienced by both ends of the WABTEC/SAB-WABCO test axle on the non-rotating bearing housing were originally measured using Silicon Designs Model No. 2430-200 +/- 200 g tri-axial accelerometers (see Figure 2.11).

Figure 2.11. Tri-Axial Accelerometer Originally Used to Measure Lateral and Vertical Accelerations on Ends of Test Axle

During the shakedown run on May 14, the sensor located on the left end of the axle experienced trouble. During a stop in Baltimore, MD, the left end of the axle was re-instrumented with two +/- 250 g single-axis piezoelectric accelerometers manufactured by Kistler and provided by Knorr.

Amtrak personnel installed ICP® accelerometers, manufactured by PCB Piezotronics, Inc., on the ends of the WABTEC/SAB-WABCO test axle before the commencement of the test run on May 16 for their own monitoring purposes. Amtrak's instrumentation involved two single-axis accelerometers installed on each end of the test axle, one mounted in the lateral direction and one mounted in the vertical direction.

During the trip from Washington to New York on May 16, the replacement accelerometers provided by Knorr showed signs of unacceptable noise levels. Upon arrival in Newark, NJ, ENSCO's data acquisition hardware was modified to allow for the recording of the Amtrak accelerometers located on the left end of the test axle; the ENSCO-provided accelerometer installed on the right end of the test axle continued to be recorded. This configuration of sensors was used throughout the remainder of Phase 1 of the effort.

The lateral accelerations of the WABTEC/SAB-WABCO test axle in the vicinity of the center brake disc were recorded using a Silicon Designs Model No. 2410-200 +/- 200 g single-axis accelerometer (see Figure 2.12). The sensor was affixed to a mounting block that was held to the axle with a kevlar strap.

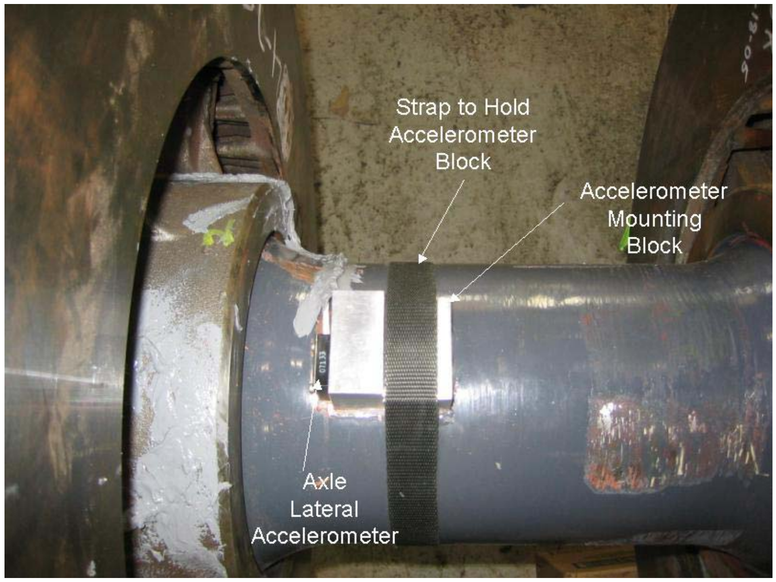
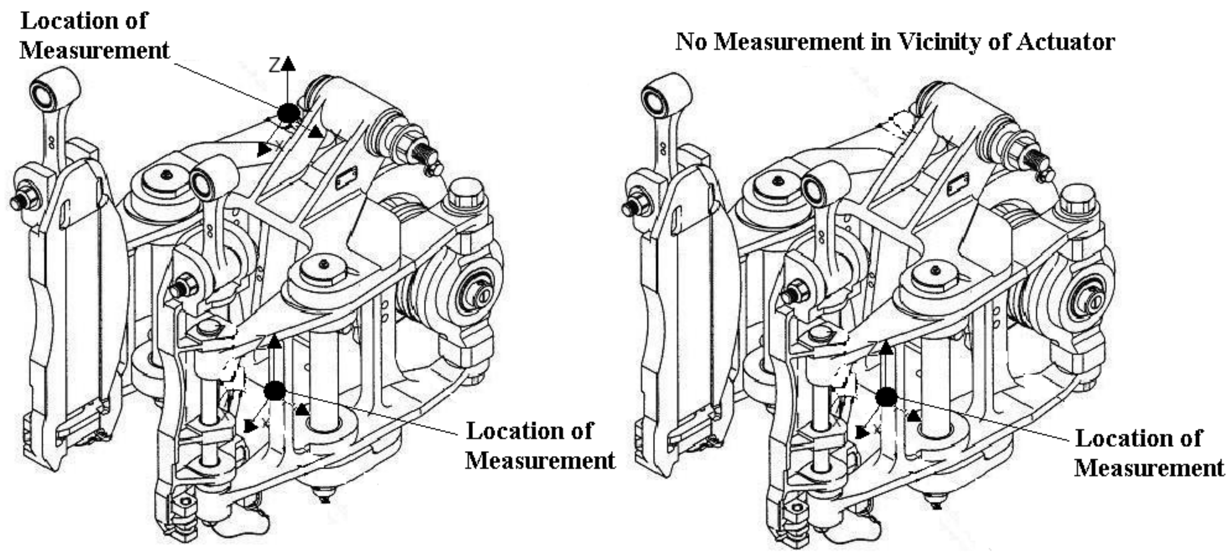


Figure 2.12. Lateral Accelerometer Mounted Near Center Disc on WABTEC/SAB-WABCO Test Axle During Phase 1 of Acela Brake Disc Study

At times throughout the study, the Silicon Designs accelerometer mounted to the axle displayed signs of saturation while traveling through selected curves. In an effort to improve the reliability of the axle lateral acceleration measurement, other types of sensors were evaluated throughout the remainder of the test effort.

The lateral, vertical, and longitudinal accelerations experienced by the brake caliper assemblies associated with the center and outer instrumented discs were measured using Silicon Designs Model No. 2440-100 +/- 100 g tri-axial accelerometers. On the center caliper assembly, accelerations were monitored near one of the brake pads and on the upper portion of the assembly near the actuator. On the outer caliper assembly, only accelerations near one of the brake pads were measured. Figure 2.13 illustrates the locations of these measurements. Figures 2.14 and 2.15 show mounting brackets and sensors affixed to the calipers.



Center Disc Caliper Assembly

Outer Disc Caliper Assembly

Figure 2.13. Acceleration Measurement Locations on the Caliper Assemblies

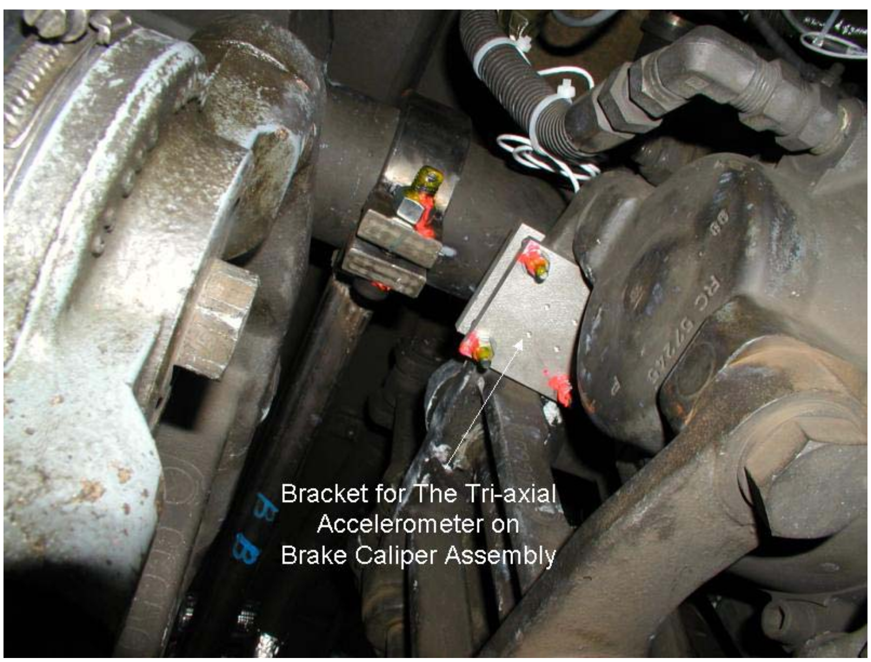


Figure 2.14. Tri-Axial Accelerometer Mounted on Center Brake Caliper Assembly Near Actuator for WABTEC/SAB-WABCO Test Axle, Phase 1 of Acela Brake Disc Study

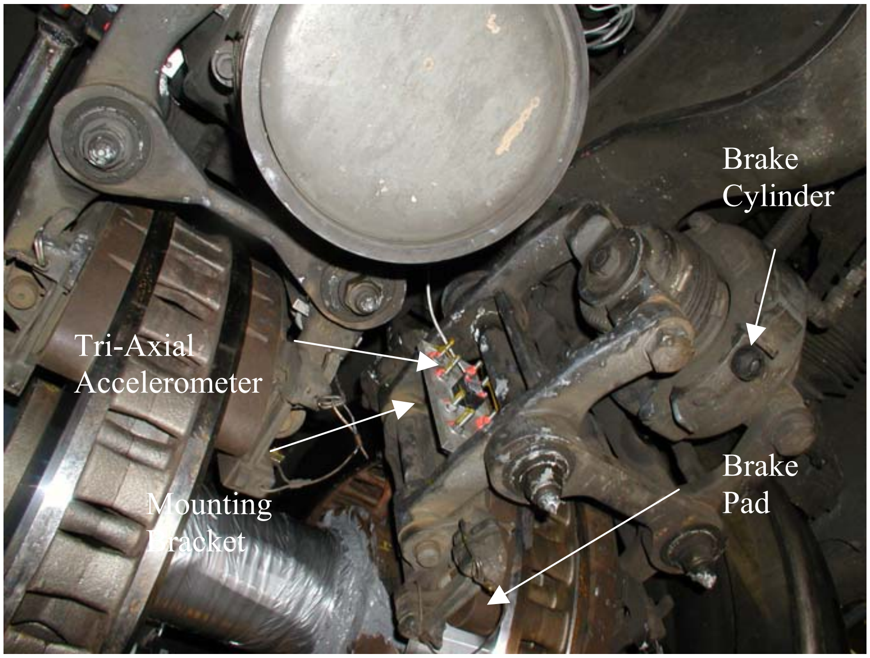


Figure 2.15. Tri-Axial Accelerometer Mounted on Brake Caliper Assemblies Near Brake Pads for WABTEC/SAB-WABCO Test Axle, Phase 1 of Acela Brake Disc Study

- *Phase 2*

  During the second phase of the study, several modifications were made to the arrangements of the accelerometers employed on or near the WABTEC/SAB-WABCO test axle. These changes included the following:

  - It was agreed upon by all test participants that the sampling rate of ENSCO's data collection system would be increased to 3,000 Hz and a second data collection system provided by Amtrak would be used to record selected channels at 10,000 Hz. Due to the higher sampling rates, it was felt that vertical accelerations in excess of 100 g would be observed on the ends of the test axle. To accommodate the possibility of accelerations in excess of the range associated with ENSCO's tri-axial accelerometer, the Amtrak-provided accelerometers mounted to the right end of the test axle were recorded throughout Phase 2 of the study.
  - ENSCO installed two additional types of accelerometers to the mounting block pictured in Figure 2.12 in an attempt to improve the reliability of the axle lateral acceleration measurement. The details associated with these additional sensors are as follows:
    - In an attempt to avoid mechanical frequencies associated with curving, an accelerometer with a high frequency response was obtained. ENSCO obtained a +/- 500 g low impedance voltage mode style accelerometer (Model No. 3030B4) from Dytran Instruments, Inc. Measurements from this sensor were referred to as AXLELAT2.
    - ENSCO also employed a piezoresistive, or strain-based, accelerometer to improve the reliability of lateral acceleration measurements on the axle. The sensor was a +/- 500 g accelerometer (Model No. 7264B-500) from Endevco. Measurements from this sensor were referred to as AXLELAT3.

- Due to the shift in focus to the WABTEC/SAB-WABCO supplied disc mounted in the center position of the test axle, acceleration measurements near the pad of the caliper mounted above the outer disc were no longer collected during Phase 2.

- *Phase 3*

  During the third phase of the study, additional accelerometers were employed to allow for measurements at new locations, as well as over the additional Knorr test axle. These changes are summarized as follows:

  - Amtrak provided five additional ICP accelerometers, manufactured by PCB Piezotronics, Inc., for this portion of the effort. Two single-axis accelerometers were installed on each end of the Knorr test axle, one mounted in the lateral direction and one mounted in the vertical direction. In addition, one single-axis accelerometer was installed on the left end of the WABTEC/SAB-WABCO test axle in the longitudinal direction.
  - A Silicon Designs Model No. 2440-025 +/- 25 g tri-axial accelerometer was mounted on the brake mounting tube over each of the two test axles approximately 5 inches from the center of the tube (i.e., near the center caliper assembly). Figure 2.16 shows the location of the sensor over one of the test axles.

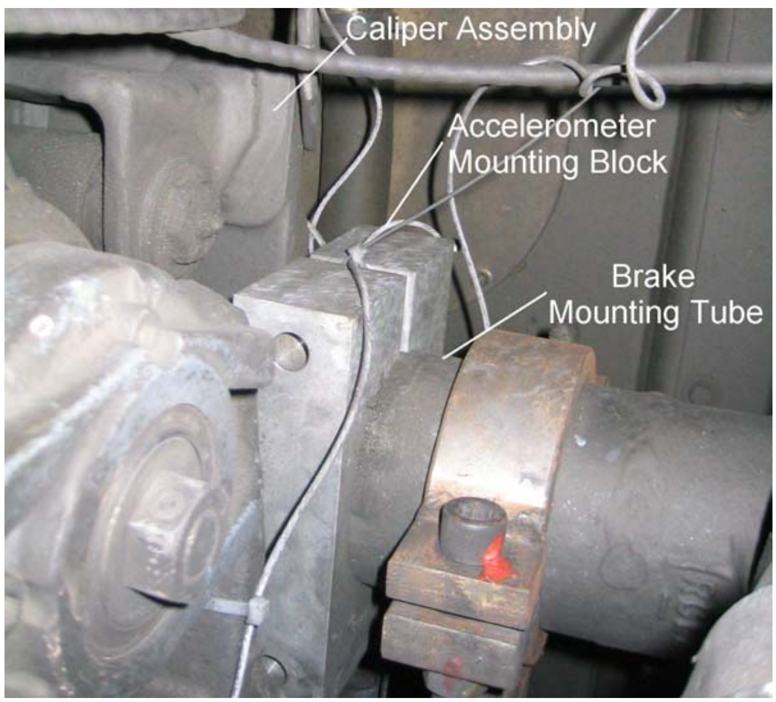


Figure 2.16. Tri-Axial Accelerometer Mounted on Brake Mounting Tube Over WABTEC/SAB-WABCO/Knorr Test Axles, Phase 3 of Acela Brake Disc Study

  - A Silicon Designs Model No. 2440-025 +/- 25 g tri-axial accelerometer was mounted on the truck side frame, over each of the test axles to capture the movement of the truck frame. For the WABTEC/SAB-WABCO axle, the sensor was mounted over the L1 wheel; for the Knorr test axle, the accelerometer was mounted over the R4 wheel. The sensors were located directly over the primary suspension of each of the axles, approximately 8 inches from the end of the frame and approximately 4 inches from the side of the frame. Figure 2.17 shows the accelerometer mounted over the Knorr test axle.

Figure 2.17. Tri-Axial Accelerometer on Truck Frame Over Primary Suspension of Knorr Test Axle During Phase 3 of Acela Brake Disc Study

- ENSCO installed two Vibra·Metrics Model No. 7002HG2K +/- 500 g accelerometers to monitor the lateral accelerations of the test axles near the center-mounted instrumented discs. On the Knorr test axle, this sensor was mounted in a fashion similar to the one pictured in Figure 2.11. On the WABTEC/SAB-WABCO test axle, the Dytran Instruments accelerometer was replaced with a Vibra·Metrics accelerometer to improve the reliability of the axle lateral acceleration measurement. During Phase 3 of the study, the Vibra·Metrics accelerometer was referred to as AXLELAT2.

2.3.3 Temperatures

Temperature measurements were made at several locations on the test axle using two basic methods – the use of thermocouples and the use of infrared (IR) sensors. This section will discuss the measurement of temperatures in this program.

- *Phase 1*

  During the initial phase of the study, the temperature of the instrumented WABTEC/SAB-WABCO supplied disc in the center position of the test axle was monitored at three locations at various times in the test–on the friction rings in contact with the pads, on one of the spokes of the disc, and on the back of the friction ring. The temperature of the instrumented WABTEC/SAB-WABCO supplied disc in the outer position of the test axle was monitored on the friction rings in contact with the pads. Each of the methods used to make these measurements will be discussed here.

  - Temperature measurements were made on the friction surface using two methods:

- *IR Thermometers*

  ENSCO employed four IR thermometers (Omega Engineering, Inc. Model No. OS553-V1-4) capable of measuring temperatures over a range of 0 °F to 1600 °F (-18 °C to 870 °C). The sensors were arranged such that a sensor was placed on each side of the disc of interest. Figure 2.18 illustrates the arrangement of the sensors.

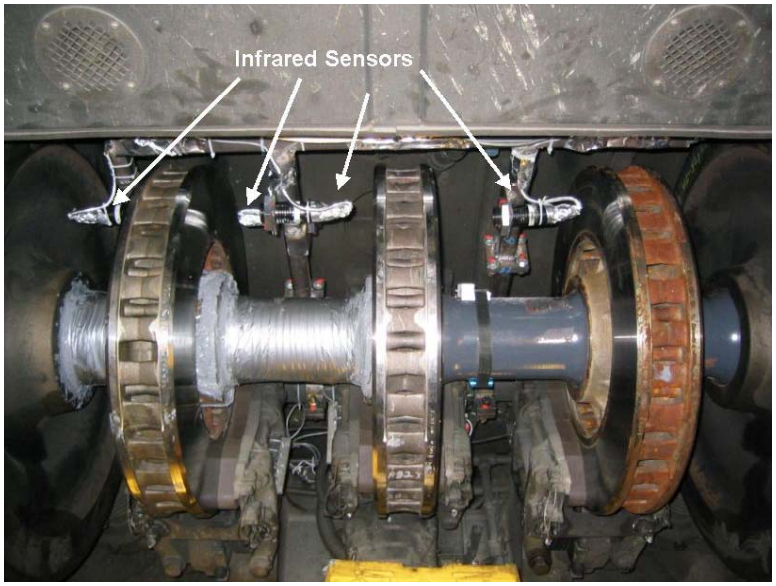


Figure 2.18. Infrared Sensors Mounted to Measure Surface Temperatures of WABTEC/SAB-WABCO Supplied Discs in Center and Outer Positions During Phase 1 of Acela Brake Disc Study

  The signal from the sensor was routed to a readout device mounted on the edge of the truck frame, which in turn supplied a 0-5 VDC signal to the data acquisition hardware for scaling and recording. The readout device also allows the user to specify the emissivity of the device; emissivity settings of 0.78 were established for all the sensors throughout the test program.

  A series of mounting brackets and support frames was fabricated and installed on the truck to mount the sensors and the readout devices.

- *Thermocouples*

  Following a series of brake tests during the shakedown runs of May 14 and test run conducted on May 16, friction surface temperature measurements were made by touching the surface in question with a thermocouple affixed to a mounting pole. The thermocouple employed was the Omega Engineering, Inc. Model No. 5SRTC-KK-K-24-36 K-type thermocouple, capable of collecting temperatures up to 600° F (316° C). The thermocouple was attached to the Omega Engineering, Inc. Model No. 450-AKT readout device for all hand measurements.

- Temperature measurements on the instrumented WABTEC/SAB-WABCO supplied disc mounted at the center of the test axle were initially made on the spokes instrumented with strain gages with the use of an Omega Engineering, Inc. Model No. 5SRTC-KK-K-24-36 K-type thermocouple. As observed in Figure 2.19, the thermocouple was welded in the vicinity of the strain gages installed on the same spoke.

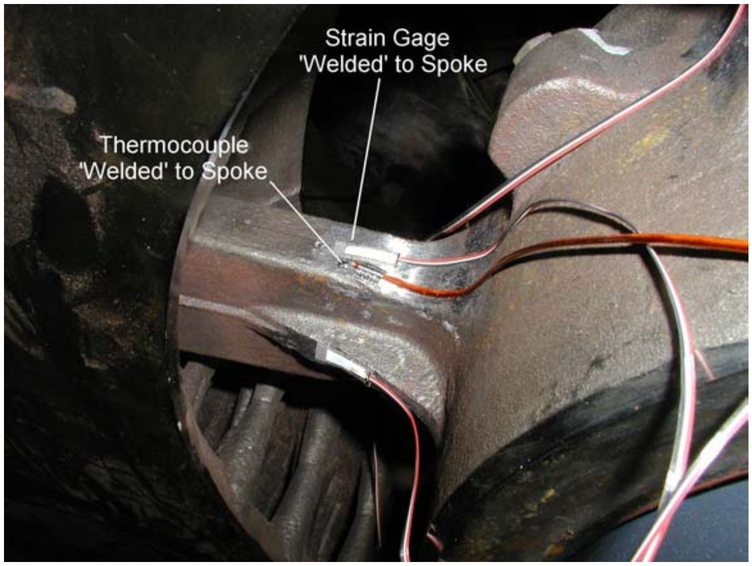


Figure 2.19. Thermocouple Applied to Spoke on Instrumented WABTEC/SAB-WABCO Supplied Disc During Phase 1 of Acela Brake Disc Study

Spoke temperatures from the center-mounted WABTEC/SAB-WABCO supplied disc were recorded during the shakedown runs of May 14 and the test run between Washington and Boston conducted on May 16.

- Temperature measurements on the back of the friction ring on the instrumented WABTEC/SAB-WABCO supplied disc in the center position of the test axle commenced at FRA's request following the test runs conducted on May 16. A new thermocouple was installed on the back of the friction ring (see Figure 2.20) approximately ¾ of an inch below the edge of the friction ring, and this temperature was considered the disc temperature for the remainder of the test program.

Figure 2.20. Thermocouple Applied on Back of Friction Ring of Instrumented WABTEC/SAB-WABCO Supplied Disc During Phase 1 of Acela Brake Disc Study

The thermocouple used for this measurement was the Omega Engineering, Inc. Model No. WTK-6-36 thermocouple, capable of measuring temperatures up to 900° F (480° C).

- *Phase 2*

  During the second phase of the study, the focus of the test was on the WABTEC/SAB-WABCO supplied disc mounted at the center of the test axle. As a result of this change, the IR temperature sensors mounted on either side of the instrumented disc at the outer position of the test axle were neglected for the second phase of the study. Output from the IR sensors mounted near the center disc was recorded throughout the second phase of the test.

  The center disc temperature during the second phase of the test continued to be based on the thermocouple mounted near the edge of the friction ring pictured in Figure 2.20.

- *Phase 3*

  During the third phase of the study, the focus of the test expanded to include both the WABTEC/SAB-WABCO and the Knorr test axles. None of the IR temperature sensors mounted near the WABTEC/SAB-WABCO test axle were monitored during Phase 3 because information collected during the earlier phases of the test effort indicated that friction surface temperatures were not excessive.

  The temperature of the instrumented Knorr disc was monitored in a similar fashion as that employed on the WABTEC/SAB-WABCO supplied instrumented disc throughout Phase 2 of the study. The type of thermocouple used for this measurement, as well as its location, was the same that was used to measure the temperature on the back of the friction ring on the WABTEC/SAB-WABCO supplied instrumented disc.

2.3.4 Pressures

All brake system pressures monitored throughout the test program were measured and recorded using Omega Engineering, Inc. Model No. PX41C1-200G10T pressure transducers. The transducers are capable of producing an analog signal between 0 and 2.5 volts proportional to a pressure between 0 and 200 psi. All pressure measurements were achieved by attaching the pressure transducer to one of several test points within the brake system. A Knorr test fitting was required for all connections; the T2 position on the test fitting was used at all connections.

The measurements made during each of the phases of the test program are provided below:

- *Phase 1*

  During the initial phase of the study, the following parameters were measured for the WABTEC/SAB-WABCO test axle:

  - Brake Cylinder Pressure–Measured by connecting a transducer to the test point labeled T1 on the manifold in the Dump Valve/Truck Cut-Out compartment at the A-end of Coach Car 3413.
  - Brake Pipe Pressure–Measured by connecting a transducer to the test point labeled BPTP on the main brake manifold of Coach Car 3413, located at the B-end of the vehicle.
  - Parking Brake Pressure–Measured by connecting a transducer to the test point labeled PBTP on the main brake manifold of Coach Car 3413, located at the B-end of the vehicle.

  Figure 2.21 shows the pressure transducer used to monitor the brake cylinder pressure on Coach Car 3413.

Figure 2.21. Pressure Transducer Used to Measure Brake Cylinder Pressure on Coach Car 3413

- *Phase 2*

  The same pressures monitored in Phase 1 of the study were monitored during the second phase of the study.

- *Phase 3*

  During the third phase of the study, only the brake cylinder pressures associated with each of the test axles were recorded. The pressure sensor originally used to measure the parking brake pressure on Car 3413 was moved to the B-end of Car 3534 and connected to the test point labeled BCTP4.

2.3.5 Axle Angular Position and Speed

The slip ring assembly used to transfer strain, accelerometer, and temperature signals from the rotating axle to the non-rotating instrumentation station was equipped with an angle resolver, which produces a single cycle of an analog sine wave signal for each revolution of the axle. Figure 2.22 shows the slip ring/resolver assembly.

Figure 2.22. Slip Ring/Resolver Assembly with Wheel Position Output

The output of the resolver was used to determine the angular position of the instrumented brake discs at all times. In order to determine the relationship between the output of the resolver and the position of the brake discs following the installation of the instrumented axle with the WABTEC/SAB-WABCO supplied disc, the axle was positioned over a drop table and the rails were lowered until the wheels no longer touched the rail. The signal from the slip ring resolver was then recorded as the wheel was rotated by hand, pausing as each spoke was positioned in a straight up position. The axle was rotated towards Power Car 2038, the same manner in which the axle would be rotating if Power Car 2038 were the lead unit in the consist. This established the important phase relationship between the angular position of the strain-gaged spoke 6 of each disc and the sine wave output from the resolver that is shown in Figure 2.23. From this relationship, the angular location of spoke 6 for the center and outer discs could be determined at any time during the NEC testing. Based on observations, spoke 6 of the instrumented outer disc appeared to be approximately 5° from the instrumented center disc in a counter-clockwise direction when viewing the test axle from the R1 wheel.

A similar procedure was used in the determination of the relationship between the output of the resolver and the position of the brake discs on the instrumented axle with the Knorr brake discs. Figure 2.24 shows the results of this exercise.

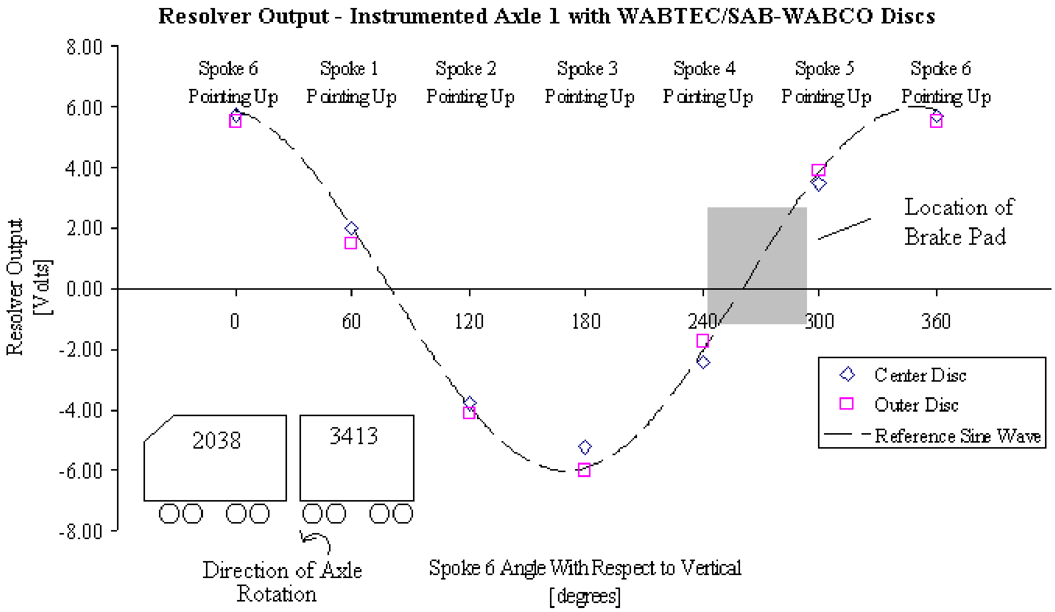


Figure 2.23. Instrumented Spoke Phase Based on Wheel Angular Position, WABTEC/SAB-WABCO Supplied Discs

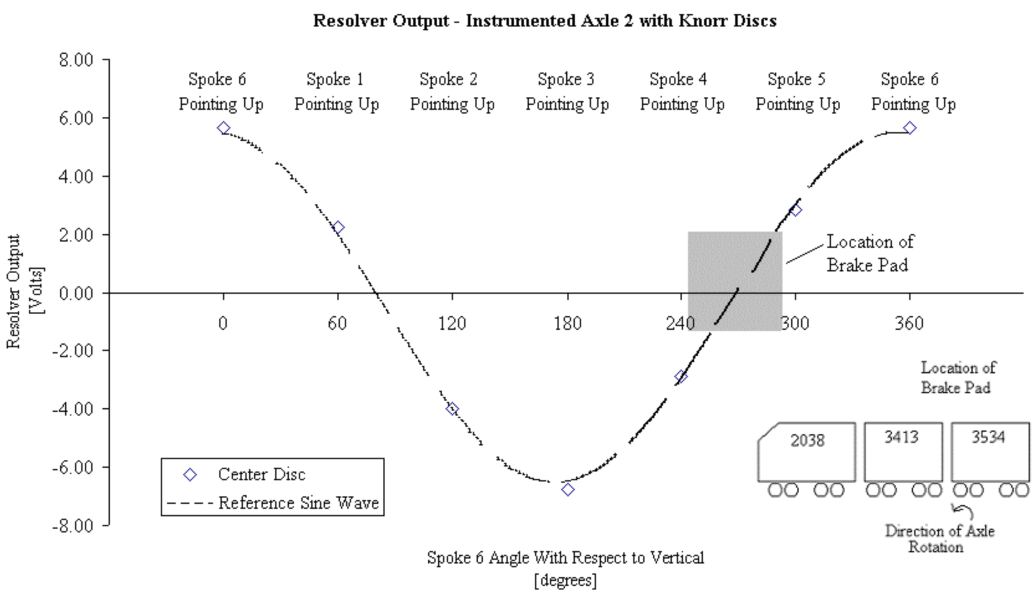


Figure 2.24. Instrumented Spoke Phase Based on Wheel Angular Position, Knorr Disc

The phase shift between a pure sine wave and the output of the resolver when spoke 6 on the center WABTEC/SAB-WABCO supplied disc was straight up was 100°; a small misalignment of the center and outer WABTEC/SAB-WABCO supplied discs occurred between approximately 5-10.° The phase shift between a pure sine wave and the output of the resolver when spoke 6 on the center Knorr disc was straight up was 96.°

As a method of recording speed, the sine wave generated by the resolver located within the slip ring on the right side of the WABTEC/SAB-WABCO test axle was recorded throughout the test effort, and a simple series of calculations was performed to determine the train's speed.

A signal reflective of speed was acquired by determining the time required for the sine wave produced by the slip ring/resolver assembly to produce two zero crossings; this represents the time required for the wheel to make a complete revolution, denoted as T_{rev} in Figure 2.25.

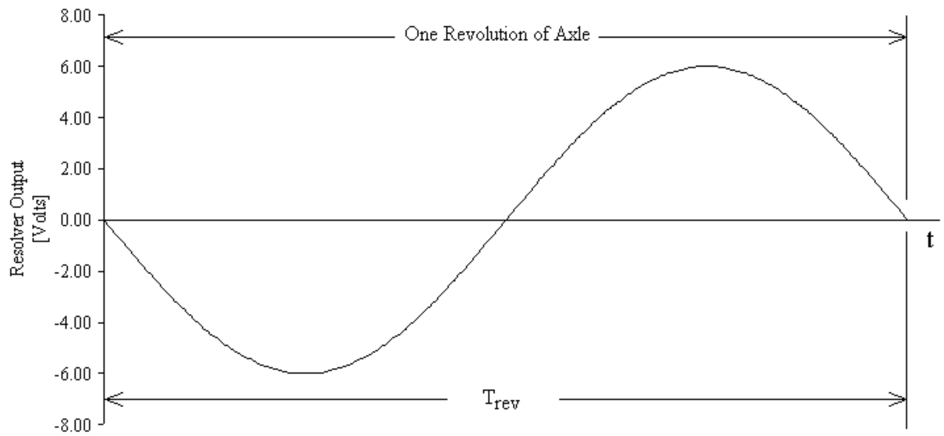


Figure 2.25. Resolver Output During One Revolution of Instrumented Axle

Knowing the time associated with one revolution of the axle and the circumference of the wheel allows for the calculation of speed as follows:

Speed = Circumference of Wheel/T_{rev}

The value of the circumference of the wheel used during this investigation was 9.42 feet, corresponding to the tape measurement made before the study.

2.3.6 Vehicle Location and Speed

Global Positioning System (GPS) information was used to determine location and speed of the test train at all times. This information was digitally recorded along with strain, accelerations, temperatures, and pressures. The antenna of the GPS receiver was mounted to the roof of Car 3413 near the end of the car above the test axle.

2.3.7 Video System

ENSCO installed a video monitoring system underneath Coach 3413 to record the behavior of the test axle with the WABTEC/SAB-WABCO supplied brake discs. The goal of this effort was to capture images of any behavior of the WABTEC/SAB-WABCO supplied discs that would lead to an indication of the cause of the condition of the spokes. Two PULNiX Model TMC-7DSP color charge-coupled device cameras were employed for the effort. Each of the cameras was outfitted with 3.5 mm fixed focal length lens and mounted to a platform that was bolted to a support beam under the floor of Coach 3414 above the test axle. The cameras were positioned so that each camera had one-half of the test axle in its field of view.

The video signal of interest was used as input to GeoStamp, a device used to overlay location, heading, speed, and time information provided by a GPS receiver; the GeoStamp unit is manufactured by Intuitive Circuits, LLC. The Flexpak-SSII GPS receiver, manufactured by NovAtel, Inc., was employed for the video monitoring system. The video signal with integrated GPS location, heading, speed, and time information was displayed on a monitor and recorded with a videocassette recorder throughout the test effort.

Figure 2.26 provides a sample frame from the video recorded over the WABTEC/SAB-WABCO test axle near MP 79 on the Philadelphia Division on May 16. Information provided on the video image and the views of the brake discs are labeled within the figure.

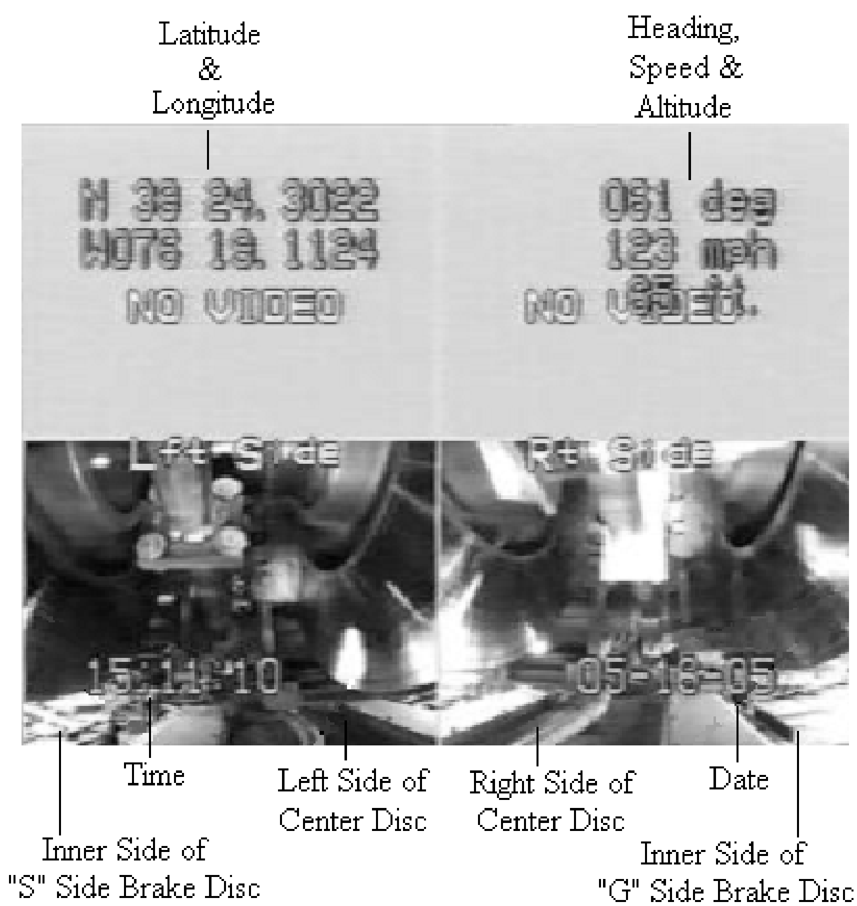


Figure 2.26. Example of Video Collected Over WABTEC/SAB-WABCO Test Axle

Upon review of the video images, it was felt that little value existed in the video images recorded throughout the test effort.

2.3.8 Sound Level Measurements

During the second phase of testing, sound levels under the test vehicle were recorded using the OROS Model OR24 four channel sound and vibration analyzer. Sound level measurements were made to attempt to capture and analyze two types of noise:

- The high frequency noise heard during the movement of the test train through certain curves. A high frequency noise, or a squeal, was heard during times in which signs of saturation were observed on some or all of the accelerometers mounted directly to the axle.
- A moaning noise heard above many of the axles of the test train during braking.

Two microphones were affixed to the camera mounting platform above the WABTEC/SAB-WABCO test axle during Phase 2, and the system was configured to record 15 seconds worth of sound upon each manual triggering of the system.

During Phase 3 testing, two additional microphones were installed above the Knorr test axle, for a total of four microphones. During this round of testing, 25 seconds worth of sound were recorded upon each manual triggering of the system.

2.3.9 Data Acquisition Hardware Settings

The temperature, strain, acceleration, pressure, and other pertinent measurements were filtered for anti-aliasing purposes and sampled at various rates during the course of the test program. The analog data was digitized in a 12 bit format based on a ± 5 volt input and stored in binary integer format in data files as described in Appendix C. Table 2.2 provides a summary of the data sampling rates and anti-alias filter settings employed for the test runs.

Table 2.2. Data Acquisition Sampling Rates and Filter Settings

Date	Segment		Sampling Rate (Hz)	Anti-Alias Filter Setting (Hz)
5/14/2005	Washington–Wilmington–Washington (Shakedown Run)		1200	> 600 Hz
5/16/2005	Washington–Boston		2000	500 Hz
5/17/2005	Boston–Baltimore		2000	500 Hz
	Baltimore (MP96.5)–MP96		4000	1000 Hz
	MP96–Washington		3000	1000 Hz
5/26/2005	Washington–Boston	Primary 32-Channel File	3000	750 Hz
		Secondary 16-Channel File	10000	No Filter
5/27/2005	Boston–Washington	Primary 32-Channel File	3000	750 Hz
		Secondary 16-Channel File	10000	No Filter
6/16/2005	Washington–New York–Washington (Shakedown Run)		3000	750 Hz
6/17/2005	Washington–Boston		3000	750 Hz
6/18/2005	Boston–Washington		3000	750 Hz

2.4 Component Level Testing

A series of component level static tests was conducted to assist in the interpretation of the data and results from over-the-road testing. The procedures used during these tests will be described here. The following chapter will discuss the results from each of these tests.

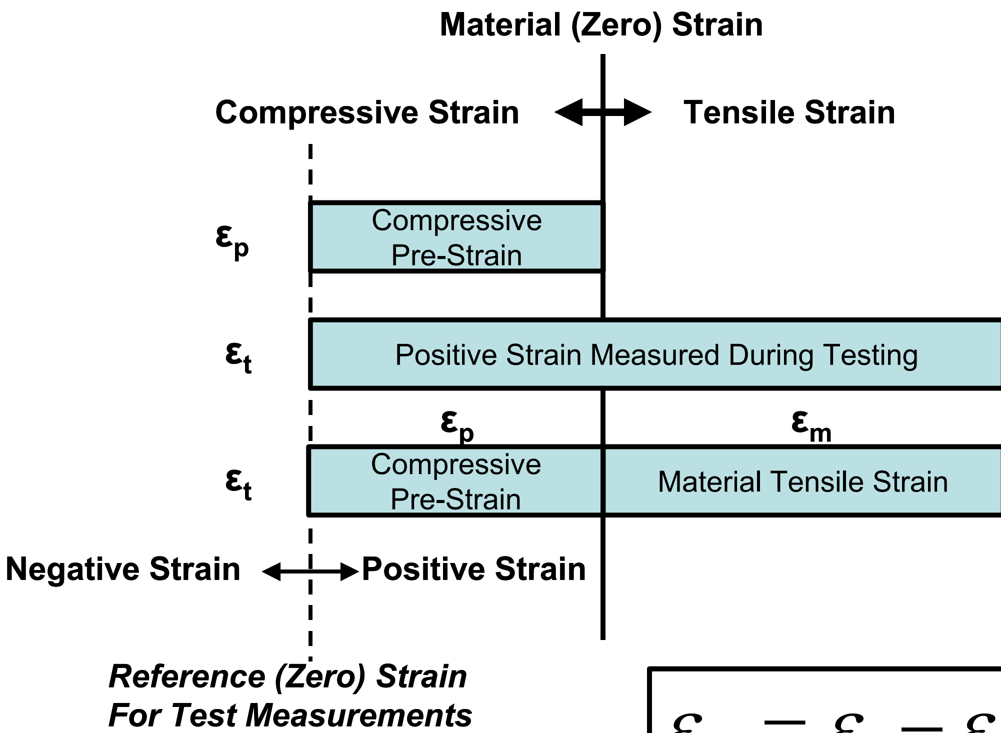
2.4.1 Spreader Bar Testing, WABTEC/SAB-WABCO Supplied Discs

In order to confirm proper operation and assess the response of gages placed on the spokes of the center and outer WABTEC/SAB-WABCO supplied discs following the May 17 test run, a spreader bar test was conducted. This test was an exercise in which a hydraulic ram and load cell were placed between the center brake disc and the outer brake disc, and a series of normal spreading forces were applied to the two discs. Spreading forces were applied at the outer circumference of the discs at circumferential positions aligned with each spoke of the center disc and in line with each spoke of the outer disc. Strain readings were recorded from each disc and are included in Part A of Appendix J.

A test of a similar nature was conducted on the instrumented Knorr disc on Instrumented Axle 2 before Phase 3 testing. This exercise used a hydraulic jack instead of a ram and did not employ a load cell, so no measure of applied load was recorded. This test was conducted only to confirm the operation of the strain gages installed on the Knorr disc. Results of this exercise confirmed proper operation of the strain gages but are not provided in this report.

2.4.2 Strain Measurements Made During Disc Removal and Installation

During the initial phase of the investigation, it was recognized that a measurement of mean strains in a spoke during service was not sufficient to yield a complete picture of the absolute strain, and consequently stress, in a spoke. Residual compressive stresses within the disc arising from several sources will subtract from those strains resulting from service loads; the sources of these compressive stresses are discussed in the document in Appendix M provided by Faiveley. A complete assessment of the stresses/strains associated with the discs required knowledge of the residual compressive stress or equivalent strain within the spoke. Figure 2.27 illustrates this concept.



$$\varepsilon_m = \varepsilon_t - \varepsilon_p$$

Figure 2.27. Illustration of Concept of Compressive Pre-Strain

During the preparation of Phase 3 tests focusing on both the WABTEC/SAB-WABCO supplied disc and the Knorr disc, Amtrak test personnel conducted a series of investigations to determine residual stresses within the discs. For the Knorr discs to be employed on the test train, a single axle was removed from Coach Car 3524 following the completion of Phase 2 testing with the intent to remove the three WABTEC/SAB-WABCO supplied brake disc rotors and replace them with discs of the Knorr design. The removed axle was shipped to the ORX facility in Tipton, PA, for the WABTEC/SAB-WABCO supplied discs to be pressed off the test axle and for the Knorr discs to be pressed on the test axle. Before the removal of the original WABTEC/SAB-WABCO supplied discs, Amtrak personnel installed strain gages on both sides of each spoke of the WABTEC/SAB-WABCO supplied center disc. The outputs of the strain gages prior to and following the removal of the disc were recorded, resulting in a measure of the strains found on the WABTEC/SAB-WABCO supplied disc caused by the pressing operation.

Using a procedure similar to the one described above, Amtrak personnel installed strain gages on both sides of each of the spokes of the Knorr brake disc designated for the center position before having it pressed on to the test axle. The outputs of the strain gages prior to and following the installation of the Knorr designed disc were recorded, resulting in a measure of the strains associated with the Knorr-designed disc ensuing from the pressing of the disc on to the axle.

Finally, Amtrak personnel cut all the strain-gaged spokes of the WABTEC/SAB-WABCO supplied center disc that was removed from the test axle to relieve any remaining stress in the spokes. The outputs of the strain gages prior to and following the severing of the spokes were recorded, resulting in a measure of the strains found on a WABTEC/SAB-WABCO supplied disc attributable to the manufacturing process.

Chapter 3 will present results from these tests, with details of the testing provided in Appendix J.

2.4.3 Modal Analysis

Simple laboratory vibration tests were performed using the OROS Model OR24 four-channel sound and vibration analyzer and associated software to identify some fundamental natural frequencies of both the WABTEC/SAB-WABCO supplied disc and the Knorr disc mounted on their respective axles. For these tests, each wheelset was free from its respective truck and was resting on the shop floor.

Figure 2.28 provides an illustration of a typical test set-up. A force input was provided to the center disc being studied by striking it with a 45-ounce dead blow hammer. Response to the force input was measured using accelerometers, magnetically mounted to the disc. In the example shown in Figure 2.27, the accelerometers were placed at the top and bottom of the brake disc near the outer edge, 180º across from each other.

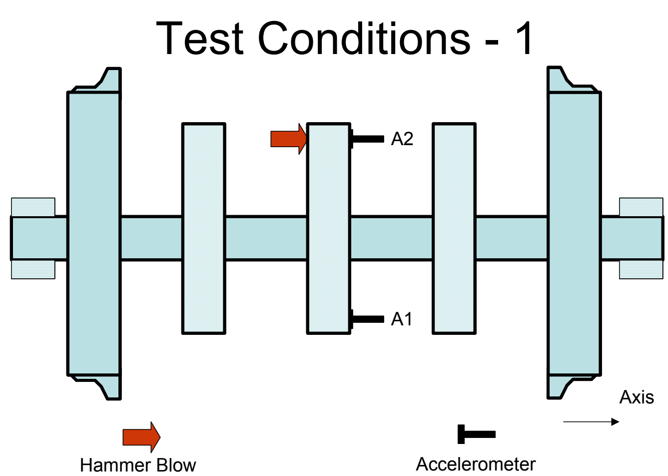


Figure 2.28. Illustration of Typical Setup for Modal Assessment of Brake Discs

The frequency amplitude spectrum was computed for each acceleration signal over a 1-second window immediately following the force input. A comparison of the relationship between the responses of the two accelerometers was also computed. Appendix J, Part C, provides details of all of these tests.

After completion of the Phase 3 over-the-road testing, an additional vibration-based test was conducted on the Knorr disc to investigate frequencies observed in the over-the-road test data. The center Knorr disc on Instrumented Axle 2, still installed under Coach 3534, was used for this test. In this series of tests, the strains on spokes 3 and 6 were recorded and their time histories analyzed. Several successive hammer blows applied at approximately 5-second intervals to the friction ring provided excitation. The hammer blows were applied near spoke 3 with spoke 6 positioned within the brake pads. During the investigation, the brakes were not applied, and no incidental contact occurred between the Knorr disc and the brake pads. The results of the analysis of these strains will be presented in the following chapter and are detailed in Appendix J, Part C.

2.5 Procedures Used During Over-the-Road Testing

Before the commencement of each test, the following procedures were followed to establish/confirm instrumentation settings:

- All strain gage and accelerometer signals were zeroed by collecting a sample of the signals, calculating an average reading, and subtracting this reading from all measurements within the data collection software. Data was recorded during this step.
- A shunt calibration was performed on all strain gage signals to establish proper scale factors and to confirm proper working order of the strain gages (NOTE: Scale factors for all other sensors were set based on information contained on calibration sheets.) Data was recorded during this step.
- A known signal (i.e., sine wave) of a fixed frequency was fed into one channel on each data acquisition board–anti-alias filter board set in order to confirm proper sampling rate settings. Data was recorded during this step.
- A known signal (i.e., sine wave) of variable frequency was fed into one channel on each data acquisition board–anti-alias filter board set in order to confirm proper anti-alias filter settings. Data was recorded during this step.
- The various temperatures being monitored throughout the test train were reviewed, and any temperature that had drifted significantly from any of the others would be checked and adjusted to an acceptable level. In the tests in which IR temperature sensors were employed, the emissivity setting of the individual sensors was confirmed.

Zeroes were checked every morning; strain gage signals typically varied by approximately 10 micro-strain from the end of one test day to the beginning of the next test day. Zero settings of the sensors were not typically adjusted over the course of a test unless noted in the test logs.

2.5.1 Data Processing Methods

ENSCO used two data processing programs for analyzing the data from the Acela brake disc tests, DaDisp and Matlab. DaDisp (www.dadisp.com) allows manipulation of large data sets and was used to create daily stripcharts and most of the graphs in this document. Matlab (www.mathworks.com) is a scripting language for mathematical analysis. Matlab was used to combine all the files for a test day and search through the data for interesting events.

When it was necessary to consider the frequency domain of certain data elements, a power spectral density (PSD) of the data was prepared. PSDs illustrated in this document were prepared by selecting an area of interest from the data set and extracting 16,384 points; it was important for the number of points to be a power of two. The PSD was then calculated on the extracted data, and the mean, or average, was removed. The y-axis of the plots are expressed in decibels (dB):

$$y = 10 \cdot \log_{10}\left(PSD\left(x - \bar{x}\right)\right)$$

where this expression is based on the definition of dB. Data was smoothed on selected plots by employing a five-point moving average.

Stripcharts were produced each day for each data file. They consisted of each of the main sensors and were saved into PowerPoint files, which have been included on CD-ROM with this report in Appendix L. Stripcharts were created using DaDisp through May 26 and in Matlab for the remainder of the days of testing.

2.5.2 Channel Assignments During Over-the-Road Testing

Tables 2.3, 2.4 and 2.5 provide summaries of the channel designations/assignments for tests conducted during Phases 1, 2 and 3, respectively. Appendix C provides formats of the recorded data files.

Table 2.3. Channel Designation During Phase 1 Test Runs, May 16-17, 2005

Channel Short Name	Chan No.	Parameter	Units
CTRSPKF1	1	Strain gage, W/S-W center disc, spoke 6, F1 side	uε
CTRSPKF2	2	Strain gage, W/S-W center disc, spoke 6, F2 side	uε
CTRSPKR1	3	Strain gage, W/S-W center disc, spoke 6, R1 side	uε
CTRSPKR2	4	Strain gage, W/S-W center disc, spoke 6, R2 side	uε
OUTSPKF1	5	Strain gage, W/S-W outer disc, spoke 6, F1 side	uε
OUTSPKF2	6	Strain gage, W/S-W outer disc, spoke 6, F2 side	uε
OUTSPKR1	7	Strain gage, W/S-W outer disc, spoke 6, R1 side	uε
OUTSPKR2	8	Strain gage, W/S-W outer disc, spoke 6, R2 side	uε
CTRSPKTEMP	9	Thermocouple, W/S-W center disc, spoke 6	°F
CTRRTRTEMPL	10	Temperature, IR, W/S-W center disc braking surface	°F
CTRRTRTEMPR	11	Temperature, IR, W/S-W center disc braking surface	°F
OUTRTRTEMPL	12	Temperature, IR, W/S-W outer disc braking surface	°F
OUTRTRTEMPR	13	Temperature, IR, W/S-W outer disc braking surface	°F
RAWSPEED	14	Speed sine wave from resolver	Volts
PROCSPEED	15	Computed Speed from resolver sine wave	Mph
AXLELAT	16	Lateral Acceleration, axle-mounted near W/S-W center disc	g
LBOXLAT	17	Lateral Acceleration, Axle Box left, Axle 1	g
LBOXVERT	18	Vertical Acceleration, Axle Box left, Axle 1	g
RBOXLAT	19	Lateral Acceleration, Axle Box right, Axle 1	g
RBOXVERT	20	Vertical Acceleration, Axle Box right, Axle 1	g
CTRCALPLAT	21	Lateral Acceleration, center caliper, near pad	g
CTRCALPVERT	22	Vertical Acceleration, center caliper, near pad	g
CTRCALPLONG	23	Longitudinal Acceleration, center caliper, near pad	g
CTRCALALAT	24	Lateral Acceleration, center caliper, near actuator	g
CTRCALAVERT	25	Vertical Acceleration, center caliper, near actuator	g
CTRCALALONG	26	Longitudinal Acceleration, center caliper, near actuator	g
OUTCALPLAT	27	Lateral Acceleration, outer caliper, near pad	g
OUTCALPVERT	28	Vertical Acceleration, outer caliper, near pad	g
OUTCALPLONG	29	Longitudinal Acceleration, outer caliper, near pad	g
PIPEPRESS	30	Brake Pipe Pressure	psi
CYLPRESS	31	Brake Cylinder Pressure, center caliper	psi
PARKPRESS	32	Brake Park Pressure, center caliper	psi

Table 2.4. Channel Designation During Phase 2 Test Runs, May 26-27, 2005

Channel Short Name	Chan No.	Parameter	Units
CTRSPK6F1	1	Strain gage, W/S-W center disc, spoke 6, F1 side	uε
CTRSPK6F2	2	Strain gage, W/S-W center disc, spoke 6, F2 side	uε
CTRSPK6R1	3	Strain gage, W/S-W center disc, spoke 6, R1 side	uε
CTRSPK6R2	4	Strain gage, W/S-W center disc, spoke 6, R2 side	uε
CTRSPK3R1	5	Strain gage, W/S-W center disc, spoke 3, R1 side	uε
CTRSPK3R2	6	Strain gage, W/S-W center disc, spoke 3, R2 side	uε
AXLECSPK6	7	Strain gage, axle near center, disc adjacent spoke 6	uε
AXLECSPK3	8	Strain gage, axle near center, disc adjacent spoke 3	uε
AXLEOSPK6	9	Strain gage, axle near ¼ location, adjacent spoke 6	uε
AXLEOSPK3	10	Strain gage, axle near ¼ location, adjacent spoke 3	uε
CTRDSKTEMP	11	Thermocouple, back of friction ring	°F
CTRRTRTEMPL	12	Temperature, braking surface, IR, center rotor	°F
CTRRTRTEMPR	13	Temperature, braking surface, IR, center rotor	°F
SINE	14	Speed sine wave from resolver	volts
PROCSPEED	15	Computed Speed from resolver sine wave	mph
AXLELAT	16	Lateral Acceleration, axle mounted near rotor	g
LBOXLAT	17	Lateral Acceleration, Axle Box left	g
LBOXVERT	18	Vertical Acceleration, Axle Box left	g
RBOXLAT	19	Lateral Acceleration, Axle Box right	g
RBOXVERT	20	Vertical Acceleration, Axle Box right	g
CTRCALPLAT	21	Lateral Acceleration, center caliper, near pad	g
CTRCALPVERT	22	Vertical Acceleration, center caliper, near pad	g
CTRCALPLONG	23	Longitudinal Acceleration, center caliper, near pad	g
CTRCALALAT	24	Lateral Acceleration, center caliper, near actuator	g
CTRCALAVERT	25	Vertical Acceleration, center caliper, near actuator	g
CTRCALALONG	26	Longitudinal Accel, center caliper, near actuator	g
AXLELAT2	27	Lateral Acceleration, axle-mounted (piezo-electric)	g
SYNC	28	File Synchronization signal	volts
AXLELAT3	29	Lateral Acceleration, axle (strain-based)	g
PIPEPRESS	30	Brake Pipe Pressure	psi
CYLPRESS	31	Brake Cylinder Pressure, center caliper	psi
PARKPRESS	32	Brake Park Pressure, center caliper	psi

NOTE: Channels Recorded on with 10,000 Hz data collection system

Table 2.5. Channel Designation During Phase 3 Test Runs, June 17-18, 2005
(NOTE: Axle 1–WABTEC/SAB-WABCO Supplied Brake Discs, Axle 2–Knorr Brake Discs)

Channel Short Name	Chan No.	Parameter	Axle	Units
AXLELAT1-1	1	Lateral Acceleration, axle mounted	1	g
TRFLLAT1	2	Lateral Acceleration, Truck Frame Left	1	g
TRFLVERT1	3	Vertical Acceleration, Truck Frame Left	1	g
TRFLLONG1	4	Longitudinal Acceleration, Truck Frame Left	1	g
BRMTLAT1	5	Lateral Acceleration, Brake Mounting Tube	1	g
BRMTVERT1	6	Vertical Acceleration, Brake Mounting Tube	1	g
SINE1	7	Sine wave from resolver	1	volts
SINE2	8	Sine wave from resolver	2	volts
BRMTLONG1	9	Longitudinal Acceleration, Brake Mounting Tube	1	g
CTRCALPLAT1	10	Lateral Acceleration, center caliper, near actuator	1	g
CTRCALPVERT1	11	Vertical Acceleration, center caliper, near actuator	1	g
CTRCALPLONG1	12	Longitudinal Accel, center caliper, near actuator	1	g
CYLPRESS1	13	Brake Cylinder Pressure, center caliper	1	psi
CTRDSKTEMP1	14	Thermocouple, center rotor	1	°F
SYNC	15	File Synchronization signal		volts
AXLELAT2	16	Lateral Acceleration, axle mounted	2	g
TRFLLAT2	17	Lateral Acceleration, Truck Frame Left	2	g
TRFLVERT2	18	Vertical Acceleration, Truck Frame Left	2	g
TRFLLONG2	19	Longitudinal Acceleration, Truck Frame Left	2	g
BRMTLAT2	20	Lateral Acceleration, Brake Mounting Tube	2	g
BRMTVERT2	21	Vertical Acceleration, Brake Mounting Tube	2	g
BRMTLONG2	22	Longitudinal Acceleration, Brake Mounting Tube	2	g
CTRCALPLAT2	23	Lateral Acceleration, center caliper, near actuator	2	g
CTRCALPVERT2	24	Vertical Acceleration, center caliper, near actuator	2	g
CTRCALPLONG2	25	Longitudinal Accel, center caliper, near actuator	2	g
CTRDSKTEMP2	26	Thermocouple, center rotor	2	°F
CYLPRESS2	27	Brake Cylinder Pressure, center caliper	2	psi
CTRSPK6F1	28	Strain gage, center disc spoke 6, F1	1	uε
CTRSPK6F2	29	Strain gage, center disc spoke 6, F2	1	uε
CTRSPK6R1	30	Strain gage, center disc spoke 6, R1	1	uε
CTRSPK6R2	31	Strain gage, center disc spoke 6, R2	1	uε
BAD	32	Bad channel, unused		

Table 2.5. Channel Designation During Phase 3 Test Runs, June 17-18, 2005 (NOTE: Axle 1–WABTEC/SAB-WABCO Supplied Brake Discs, Axle 2–Knorr Brake Discs) (Cont'd)

Channel Short Name	Chan No.	Parameter	Axle	Units
CTRSPK3R1	33	Strain gage, center disc spoke 3, R1	1	uε
CTRSPK3R2	34	Strain gage, center disc spoke 3, R2	1	uε
AXLECSPK6	35	Strain gage, axle near center disc, adjacent spoke 6	1	uε
AXLECSPK3	36	Strain gage, axle near center disc, adjacent spoke 3	1	uε
AXLEOSPK6	37	Strain gage, axle near ¼ location, adjacent spoke 6	1	uε
AXLEOSPK3	38	Strain gage, axle near ¼ location, adjacent spoke 3	1	uε
AXLE1LLINK	39	Strain gage, center caliper left	1	uε
AXLE1RLINK	40	Strain gage, center caliper right	1	uε
CTR2SPK6R1	41	Strain gage, center disc spoke 6, R1 (SG1)	2	uε
CTR2SPK6R2	42	Strain gage, center disc spoke 6, R2 (SG2)	2	uε
CTR2SPK3R1	43	Strain gage, center disc spoke 3, R1 (SG3)	2	uε
CTR2SPK3R2	44	Strain gage, center disc spoke 3, R2 (SG3a)	2	uε
CTR2SPK6_4	45	Strain gage, center disc spoke 6 face, upper gage (SG4)	2	uε
CTR2SPK6_5	46	Strain gage, center disc spoke 6 face, lower gage (SG5)	2	uε
CTR2SPK6_6	47	Strain gage, center disc spoke 4, R2 position (SG6)	2	uε
AXLE2CSPK6	48	Strain gage, axle near center disc, adjacent spoke 6	2	uε
AXLE2CSPK3	49	Strain gage, axle near center disc, adjacent spoke 3	2	uε
AXLE2CSPK6+90	50	Strain gage, axle near ¼ location, adjacent spoke 6	2	uε
AXLE2CSPK6-90	51	Strain gage, axle near ¼ location, adjacent spoke 3	2	uε
AXLE2OSPK6	52	Strain gage, axle near center disc adjacent spoke 6 +90°	2	uε
AXLE2OSPK3	53	Strain gage, axle near center disc adjacent spoke 6 -90°	2	uε
LBOXLAT1	54	Lateral Acceleration, Axle Box left	1	g
LBOXVERT1	55	Vertical Acceleration, Axle Box left	1	g
RBOXLAT1	56	Lateral Acceleration, Axle Box right	1	g
RBOXVERT1	57	Vertical Acceleration, Axle Box right	1	g
LBOXLAT2	58	Lateral Acceleration, Axle Box left	2	g
LBOXVERT2	59	Vertical Acceleration, Axle Box left	2	g
RBOXLAT2	60	Lateral Acceleration, Axle Box right	2	g
RBOXVERT2	61	Vertical Acceleration, Axle Box right	2	g
AXLELAT1-2	62	Lateral Acceleration 2, axle mounted	1	g
AXLELAT1-3	63	Lateral Acceleration 3, axle mounted	1	g
AXLE1LLONG	64	Longitudinal Acceleration, axle mounted	1	g
Speed	65	Calculated Speed for SINE 1		mph

3.0 TEST RESULTS

This section will provide an overview of the results determined from analysis of the data collected and events observed during this test program. More detailed results, as well as the original data sets, are contained in the various appendices to this report. Appendix D provides logs generated during each of these test runs.

Section 3.1 presents results determined during Phase 1 testing; Section 3.2 provides results from Phase 2 testing; and Section 3.3 includes results from Phase 3 testing. Each section provides information of the various quantities studied during the over-the-road testing, as well as results from any component level testing conducted during a particular phase of the investigation. Section 3.4 provides results compiled from data collected from multiple phases of testing.

3.1 Phase 1 Test Results

Phase 1 involved the instrumentation of two WABTEC/SAB-WABCO supplied discs, the center and an outer disc of a single axle, their calipers, and the accelerations observed on the axle and its bearings. The objective of Phase 1 was the characterization of the mechanical and thermal load environment associated with the WABTEC/SAB-WABCO supplied discs. Following a shakedown run, a round-trip test was conducted between Washington and Boston on May 16 and 17. An FEA focusing on the WABTEC/SAB-WABCO supplied disc and a spreader bar test were also part of this phase of the effort.

3.1.1 Finite Element Analysis

During the preparation for the first set of over-the-road tests, ENSCO conducted an FEA of the WABTEC/SAB-WABCO supplied disc to gain insight into the response of the disc to various loadings. ENSCO developed a solid model of the WABTEC/SAB-WABCO supplied disc based on measurements made on removed brake discs using AutoDesk Inventor v. 9.0. This model was then turned into a finite element model, and ENSCO engineers used COSMOS DesignSTAR v. 4.5 to analyze its response to mechanical loading. The different modes of vibration and the frequencies associated with that vibration were then identified. ENSCO then provided the model to MSC Software Ltd. to confirm the results of ENSCO's mechanical response analysis and to conduct an analysis of the response of the disc to heat input that would result from braking, as well as stresses that would result from high rotational speeds.

ENSCO and MSC identified two different fundamental modes of vibration associated with the model of a single WABTEC/SAB-WABCO supplied disc. One fundamental frequency was calculated to be 206 Hz and was associated with the situation in which the hub of the brake disc was fixed (i.e., prevented from moving). This frequency was associated with a motion in which the disc vibrates outside of the plane of rotation; Figure 3.1 illustrates this vibration. The other fundamental frequency that was identified was 585 Hz and was associated with the situation in which the hub of the brake disc was free to move. The motion associated with this frequency resembles the opening and closing of an umbrella.

The second fundamental frequency associated with the case in which the hub of the disc was fixed was calculated to be 269 Hz. The motion associated with this frequency also resembled the opening and closing of an umbrella. Because this was determined using a model with a fixed hub, it is likely that the motion associated with this frequency is associated with excitation in the lateral direction.

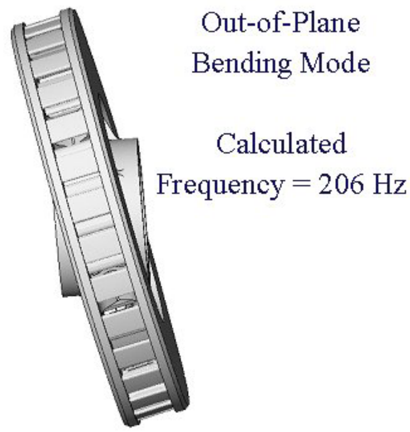


Figure 3.1. Out-of-Plane Bending Mode Determined from FEA

An important result of the analysis was the identification of the location on the spoke at which the highest strains could be expected. This location is highlighted in red in Figure 3.2. This finding was important for two reasons–this location was close to the location of many of the cracks observed on the brake discs identified to date, and it corresponded to the location in which discontinuities arising from a mold parting line found on the surface of some spokes was observed.

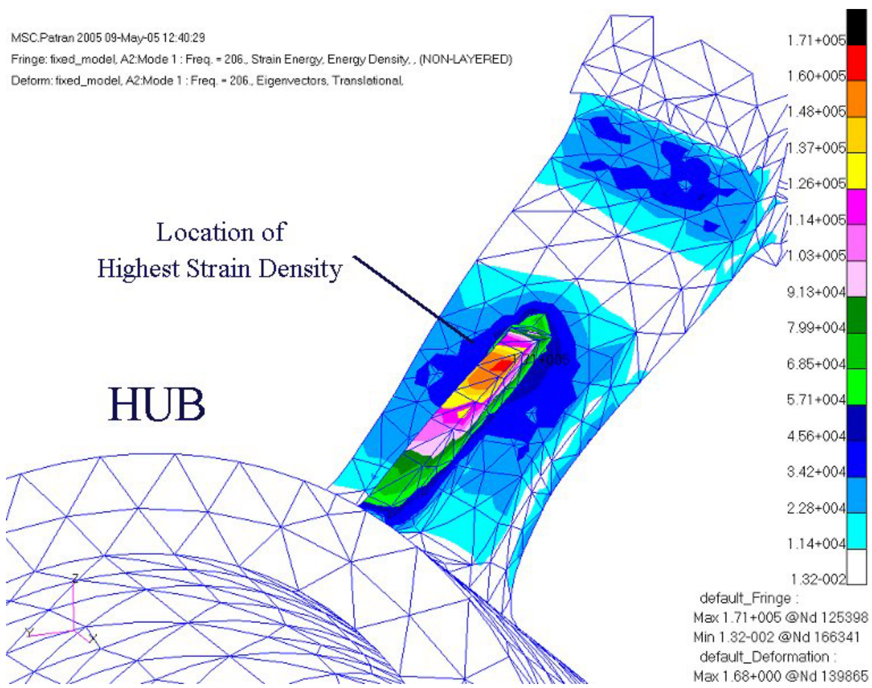


Figure 3.2. Location of Highest Strain for Out-of-Plane Bending Mode Determined from FEA

The FEA predicted tensile strains in the spokes as a result of the increase in temperature due to heat conduction from the friction ring during braking. In this analysis, the disc was stationary and not subjected to mechanical loads. The analysis also predicted a relatively low level of strain due to the rotation of the disc. Appendix E provides additional details associated with the FEA.

Although the numerical studies highlighted above considered only a single disc and did not account for the entire brake disc/axle assembly or any effects of the mounting process or long-term usage, information provided by the FEA was very useful during the analysis of data collected during over-the-road testing.

3.1.2 Axle Accelerations

The test plan for Phase 1 testing called for the characterization of the dynamic environment of the wheelset and consequently the brake disc, in typical revenue service. Accelerometers were mounted to each end of the test axle, on the axle itself near the center brake disc, and on the calipers over the center and one outboard brake disc. Appendix F provides detailed analyses of accelerations measured throughout the test effort. In general, accelerations recorded during the tests were analyzed using percentile levels, peak levels, and PSDs.

As discussed in Chapter 2, the vertical load environment associated with the test axle was measured with accelerometers mounted on the bearing end caps located at both ends of the axle. During the early part of the initial test run between Washington and Boston on May 16, the accelerometers oriented in the lateral and vertical directions on the left end of the test axle displayed an unsatisfactory signal-to-noise ratio. Figure 3.3 provides an illustration of vertical accelerations measured between MP 8 and MP 9 south of Philadelphia.

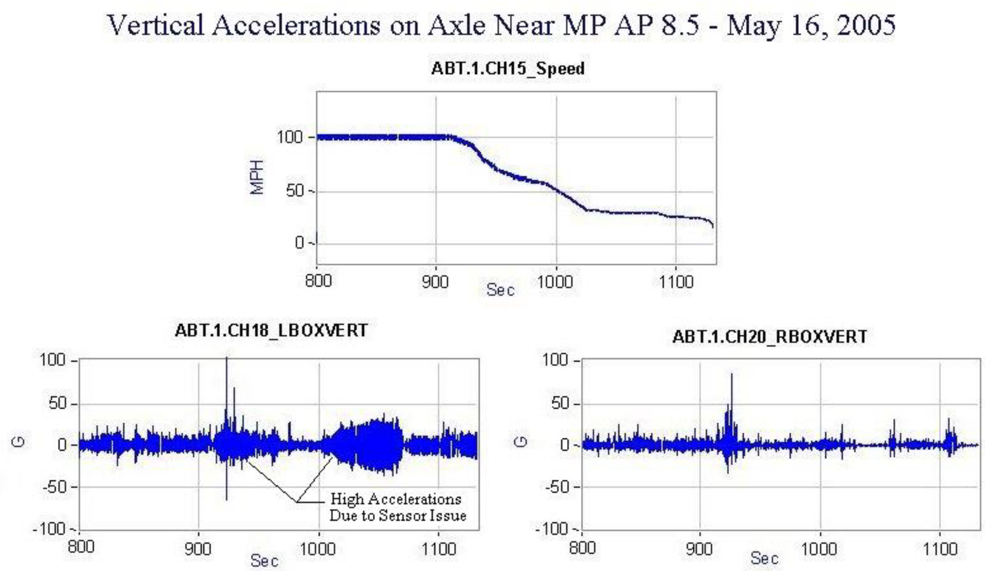


Figure 3.3. Vertical Accelerations Measured on Instrumented Axle 1 Near MP AP 8.5 (File 051605_08.ABT)–May 16, 2005

Figure 3.4 illustrates lateral accelerations measured on the axle at the same geographic location.

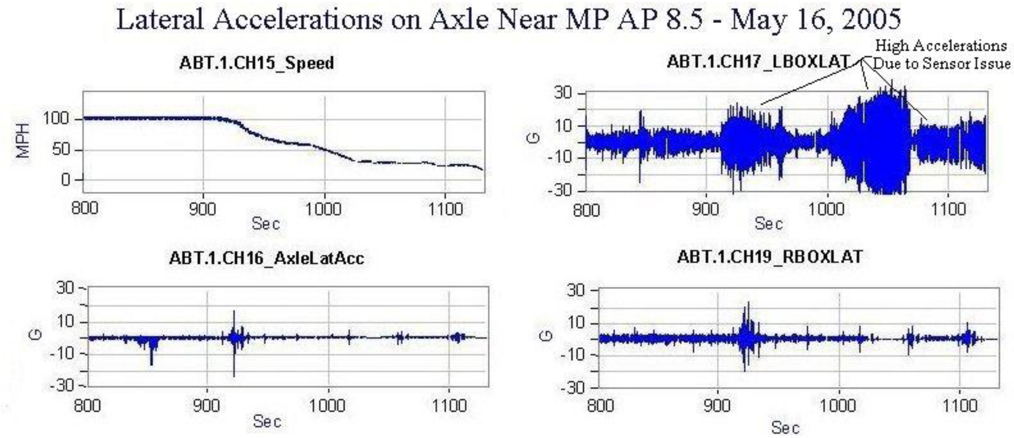


Figure 3.4. Lateral Accelerations Measured on Instrumented Axle 1 Near MP AP 8.5 (File 051605_08.ABT)–May 16, 2005

To address the issue observed on the accelerations measured on the left end of the axle, ENSCO's data acquisition hardware was modified upon arrival in Newark, NJ, to allow for the recording of the Amtrak accelerometers previously mounted on the left end of the test axle for Amtrak's monitoring purposes. The test was then able to proceed with satisfactory results.

Another issue associated with measured axle accelerations was identified during the initial phases of the test–an apparent saturation of the signal produced by the axle mounted accelerometer intended to measure lateral accelerations, resulting in extremely high accelerations not observed at other locations on the axle. This effect is noticeable in Figure 3.4 between t=800 and t=900; Figure 3.5 shows a more severe example of this effect.

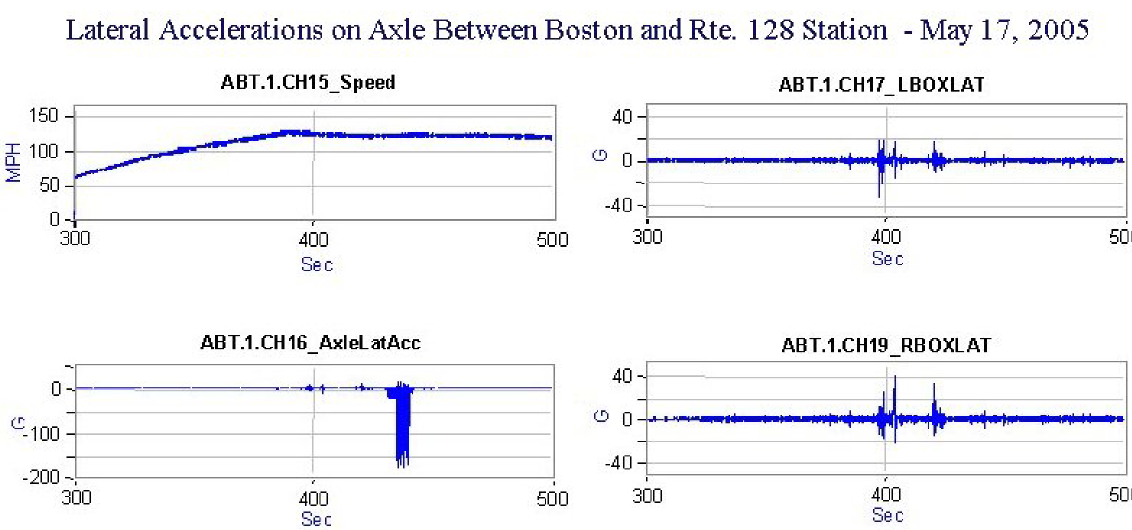


Figure 3.5. Lateral Accelerations Measured on Instrumented Axle 1 Between Boston and Rte 128 Station (File 051705_02.ABT)–May 17, 2005

Consideration of the issue with the axle-mounted accelerometer led to the observations that this high amplitude signal only appeared while the test vehicle was moving through a curve and was usually accompanied by an audible, high-pitched squealing. It was decided that these particular instances of high amplitude lateral accelerations should be disregarded and that lateral accelerations on the axle would be measured using sensors of alternative design during subsequent testing.

With these issues in mind, a significant amount of information still existed regarding the load environment associated with the revenue service operations that was learned from the axle-mounted accelerometers. High magnitude shocks were identified by counting all the cases in which one or more consecutive data values exceed a given acceleration threshold. Each acceleration channel was analyzed independently, and values appearing to result from electrical noise or other instrumentation issues were neglected. Figure 3.6a illustrates the distribution of vertical accelerations above 50 g recorded on the test axle from Washington to Boston on May 16 with the test axle in a trailing position; Figure 3.6b illustrates the corresponding information for the data collected between Boston and Washington on May 17 with the test axle in a leading position. The data illustrated in Figure 3.6 is tabulated in Appendix F. Accelerations above 50 g were reviewed to ensure that any acceleration affected by the noise-related issue highlighted in Figure 3.2 was disregarded.

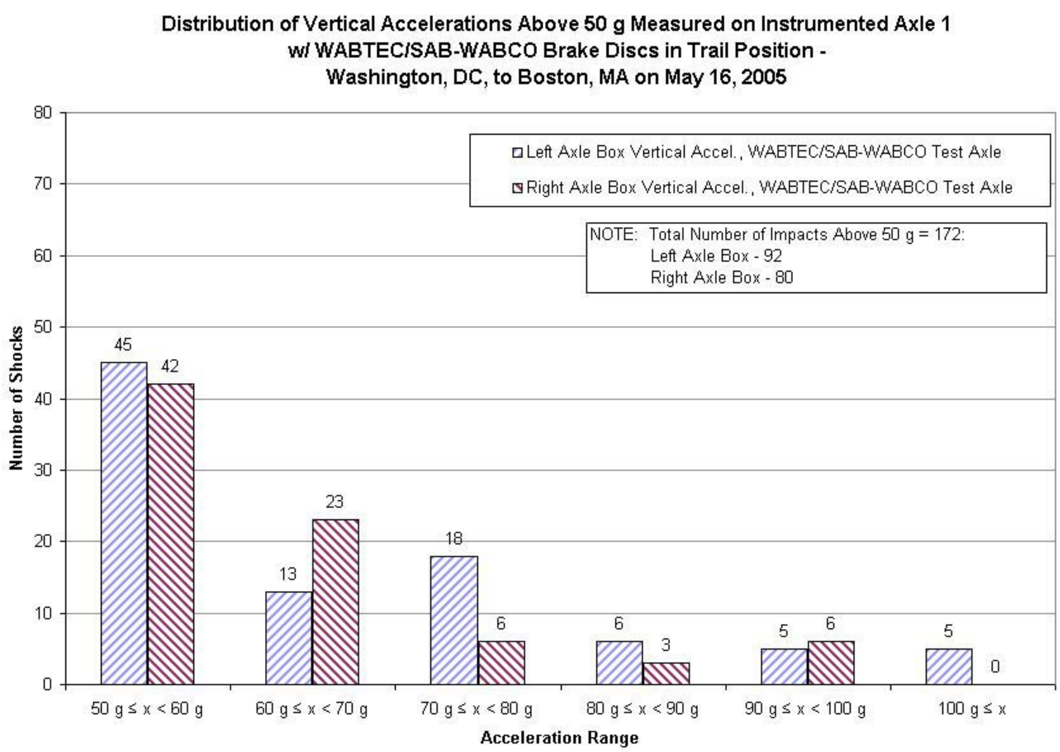


Figure 3.6a. Distribution of Vertical Accelerations Above 50 g Measured on Instrumented Axle 1 with WABTEC/SAB-WABCO Supplied Brake Discs in Trail Position– Washington, DC, to Boston, MA, on May 16, 2005

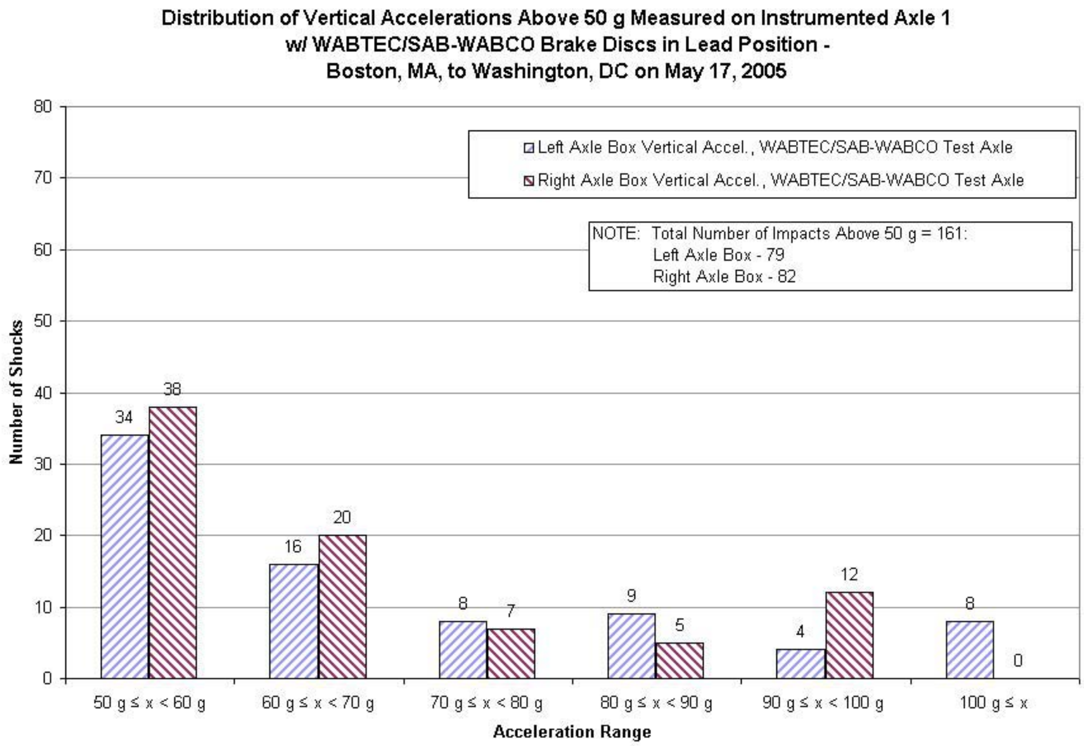


Figure 3.6b. Distribution of Vertical Accelerations Above 50 g Measured on Instrumented Axle 1 with WABTEC/SAB-WABCO Supplied Brake Discs in Lead Position– Boston, MA, to Washington, DC, on May 17, 2005

As indicated in the plots provided in Figure 3.6, 172 vertical shocks above 50 g were measured on the WABTEC/SAB-WABCO test axle during the northbound test conducted on May 16, 92 on the left end axle box and 80 on the right end axle box, and 161 vertical shocks above 50 g were measured during the southbound test conducted on May 17, 79 on the left end axle box and 82 on the right end axle box.

The highest vertical acceleration observed in Phase 1 testing was 126 g, measured on the left end of the axle on May 16 near Ham Interlocking at MP AN 55.5 while the test train was traveling at almost 111 mph. Appendix F provides the details associated with all the accelerations above 100 g, including location, speed of the test train, and information regarding the measured strains at the particular location, in tabular form.

Regarding lateral accelerations, six lateral shocks above 30 g were measured on the right end axle box of the WABTEC/SAB-WABCO test axle during Phase 1 testing; two were observed during the northbound test conducted on May 16, and four were observed during the southbound test conducted on May 17. Although many lateral accelerations above 30 g were measured on the left end axle box and on the middle of the test axle itself, these were affected by the signal quality issues highlighted in Figures 3.4 and 3.5 and were deemed unreliable.

The highest lateral acceleration observed on the right end axle box during Phase 1 testing was 39.1 g, measured on May 17 between Boston's South Street Station and the Route 128 Station while the test train was traveling at a speed near 120 mph.

The following key observations were made regarding the accelerations measured on the axle during Phase 1 testing:

- The load environment associated with vertical impacts was much more severe than that associated with lateral impacts. The maximum vertical acceleration was almost three times that of the maximum lateral acceleration. In addition, the number of high amplitude vertical impacts was significantly higher than the number of high amplitude lateral impacts.
- Based on analysis of the lateral acceleration measurements made on the WABTEC/SAB-WABCO test axle during Phase 1, the accelerometer mounted on the middle of the axle was subject to a signal quality issue from time to time that suggested saturation of the sensor. When the sensor was working properly, the accelerations measured on the middle of the axle were lower than the accelerations measured on the axle boxes on either end of the axle.

3.1.3 Spoke Strains

The analysis of strains collected during the test program was based the analysis of combinations of individual measurements to identify the effects of spoke tension, in-plane bending (BIP) of the spokes, and out-of-plane bending (BOP) of the spokes. These three types of spoke strain are used to characterize the response of the spokes throughout the test effort. Figure 3.7 illustrates the strain gage arrangement employed with spoke 6 on the instrumented brake discs in the center and outer positions.

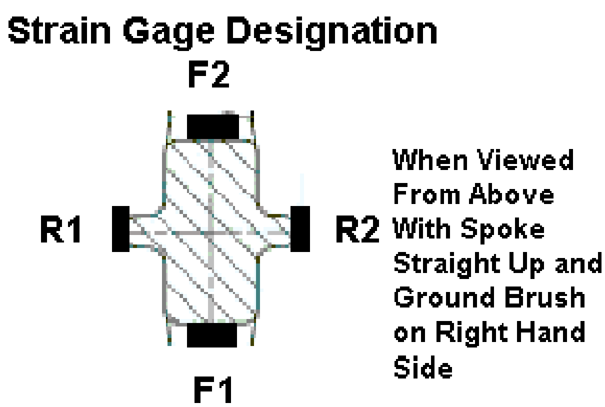


Figure 3.7. Designation of Strain Gages Used on Spoke 6 of Center and Outer Instrumented WABTEC/SAB-WABCO Supplied Discs During Phase 1 Testing

The tensile strain in the spoke is produced by averaging the output of the four strain gages around the circumference of the spokes. In equation form, the tensile strain is given by:

$$\text{Average Tensile Strain } \varepsilon_T = (\varepsilon_{F1} + \varepsilon_{F2} + \varepsilon_{R1} + \varepsilon_{R1}) / 4$$

where:

ε_{F1} is the strain measured by gage F1 $\quad$ ε_{F2} is the strain measured by gage F2

ε_{R1} is the strain measured by gage R1 $\quad$ ε_{R2} is the strain measured by gage R2

Combining the readings of the strain gages in this manner effectively cancels the effects of BIP and BOP.

Strain due to BIP of the spoke is calculated using the output from the two strain gages located within the plane of the disc, gages F1 and F2. The formulation of the BIP strain is given by:

$$\text{In-Plane Bending Strain } \varepsilon_{BIP} = (\varepsilon_{F1} - \varepsilon_{F2}) / 2$$

Similarly, strain associated with BOP of the spoke is calculated from the two strain gages located on the sides of the spoke, gages R1 and R2. The formulation of the BOP strain is given by:

$$\text{Out-of-Plane Bending Strain } \varepsilon_{BOP} = (\varepsilon_{R1} - \varepsilon_{R2}) / 2$$

Zero-to-peak strain levels are preserved in each of these formulations.

Throughout this report, the strains presented are as measured and have not been corrected for existing strains, as defined in Figure 2.27, unless otherwise stipulated.

Two types of strain clearly dominated the data collected during Phase 1 testing, tensile strains in the spoke resulting from the buildup of heat in the disc during braking and a BOP of the spoke produced both in braking and non-braking scenarios. BIP was generally small compared to the other types of strain. Figure 3.8 illustrates this observation, where the average tensile strain, BIP strain, and BOP strain measured on spoke 6 of both the center and outer WABTEC/SAB-WABCO supplied discs is illustrated for a series of brake applications on May 16 between Philadelphia, PA, and MP AN 60.

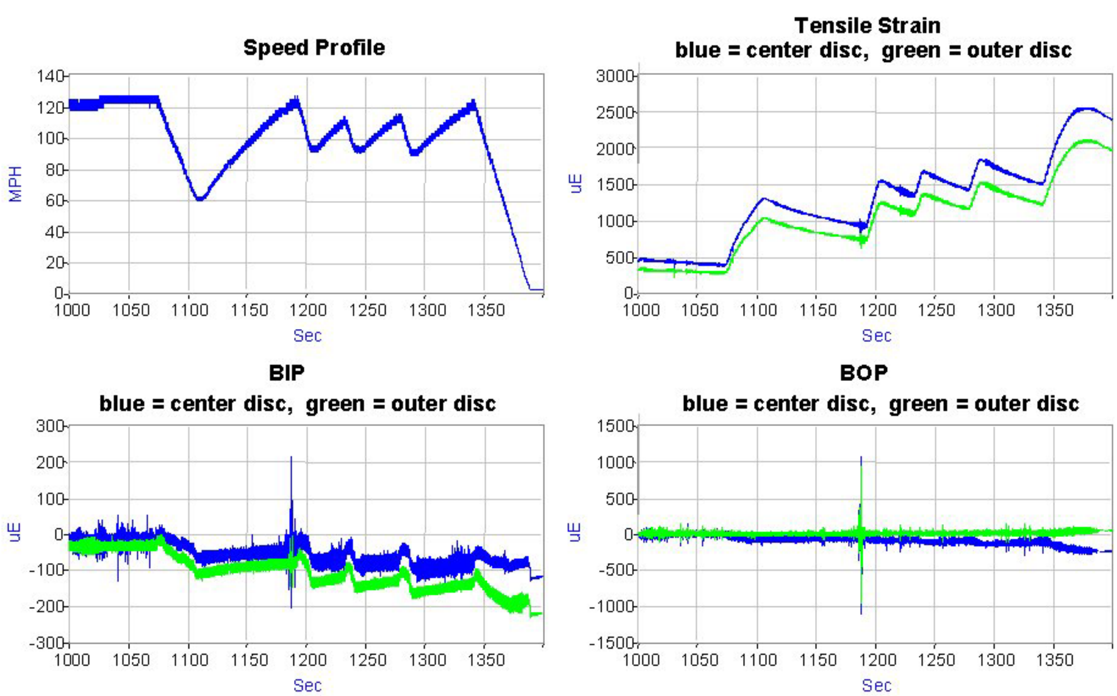


Figure 3.8. Strains on Spoke 6 of Center and Outer WABTEC/SAB-WABCO Supplied Brake Discs During Brake Applications (File 051605_09.ABT)–May 16, 2005

Brake applications illustrated in Figure 3.8 are not presented as typical brake applications but were chosen to illustrate the general behavior of the measured strains.

One can observe several items of interest in Figure 3.8, including the following:

- As the brakes are applied and the speed of the train decreases, the average tensile strain increases, reflective of the fact that the disc is being heated up and the spoke is affected by the tensile strain resulting from the thermal expansion of the material.
- The BOP strain for this braking scenario is relatively low, save for the spike observed in the middle of the time history of the strains. This resulted from a vertical impact that was measured on the test axle at that instance. The BOP strain does not exhibit the gradual rise observed on the average tensile strains during the brake applications–the same rise in strain is observed on both sides of the spoke and is removed in the subtraction of the two strains.
- The BIP strain is small compared to average tensile and BOP strains.

Upon review of the data, it was found that, although the average tensile strain experienced large changes only during braking, BOP strain could be relatively large in two different scenarios–when the test axle experienced a vertical impact and under selected brake applications.

BOP Strains Due to Vertical Impacts

Figure 3.9 illustrates the BOP strain responses of the center disc and outer disc to a 117.5 g vertical shock on the left end axle box (with a 39.5 g vertical shock on the right end axle box) between Newark, NJ, and Philadelphia, PA, on May 17 while traveling at a speed of 119 mph.

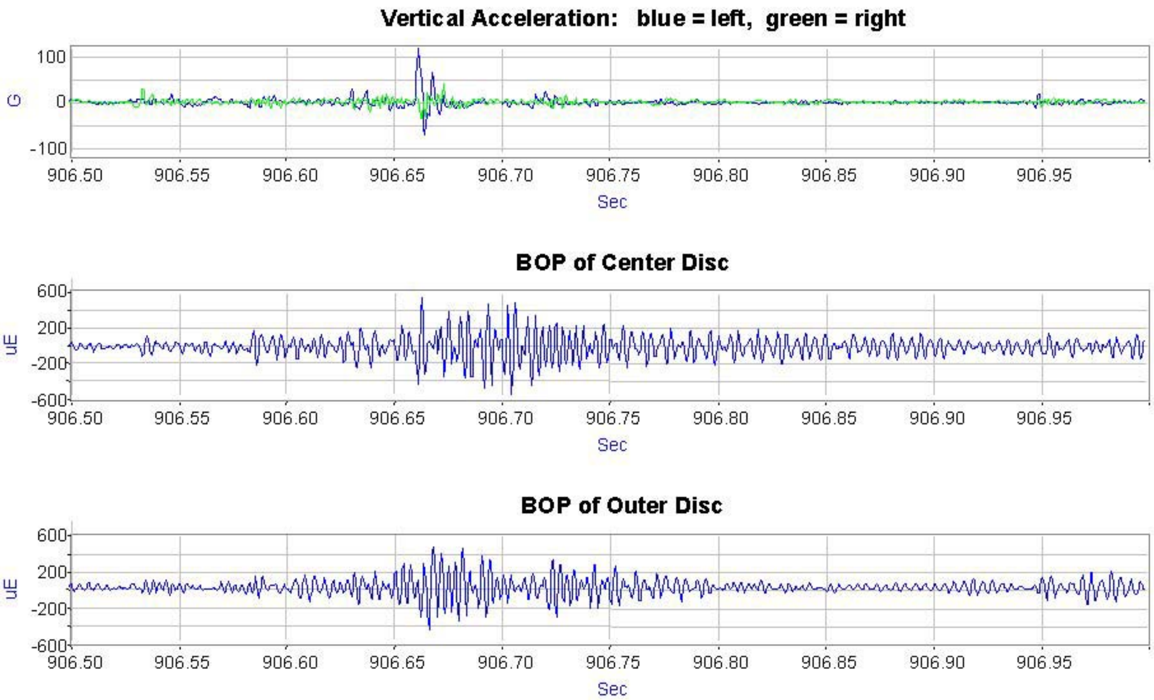


Figure 3.9. Vertical Accelerations and BOP Strains on Spoke 6 of Center and Outer WABTEC/SAB-WABCO Supplied Brake Discs During Vertical Shock (File 051705_19.ABT)– May 17, 2005

One can see the relatively large levels of strains that are measured on both discs as a result of the impact. Further analysis of this response of the discs to vertical shocks revealed that the frequency associated with this oscillating BOP strain was approximately 227 Hz. The frequency associated with BOP strain resulting from vertical impacts was close to the frequency associated with the BOP motion identified in the FEA for the single disc with a fixed hub, calculated to be 206 Hz. A natural frequency for the disc/axle assembly was not calculated using FEA, but the proximity of the measured frequency to that calculated for the single brake disc suggests a correlation.

In this particular case, the strains measured on the center disc are comparable to those measured on the outer disc. In order to assess the relative response of the two discs to shocks, shocks greater that 50 g measured on either end of the test axle on May 17 were analyzed to determine the relative amplitude of BOP on the center disc to that found on the outer disc. Figure 3.10 illustrates this analysis. The maximum peak-to-peak strain of the center disc is plotted against the maximum peak-to-peak strain of the outer disc for selected impacts.

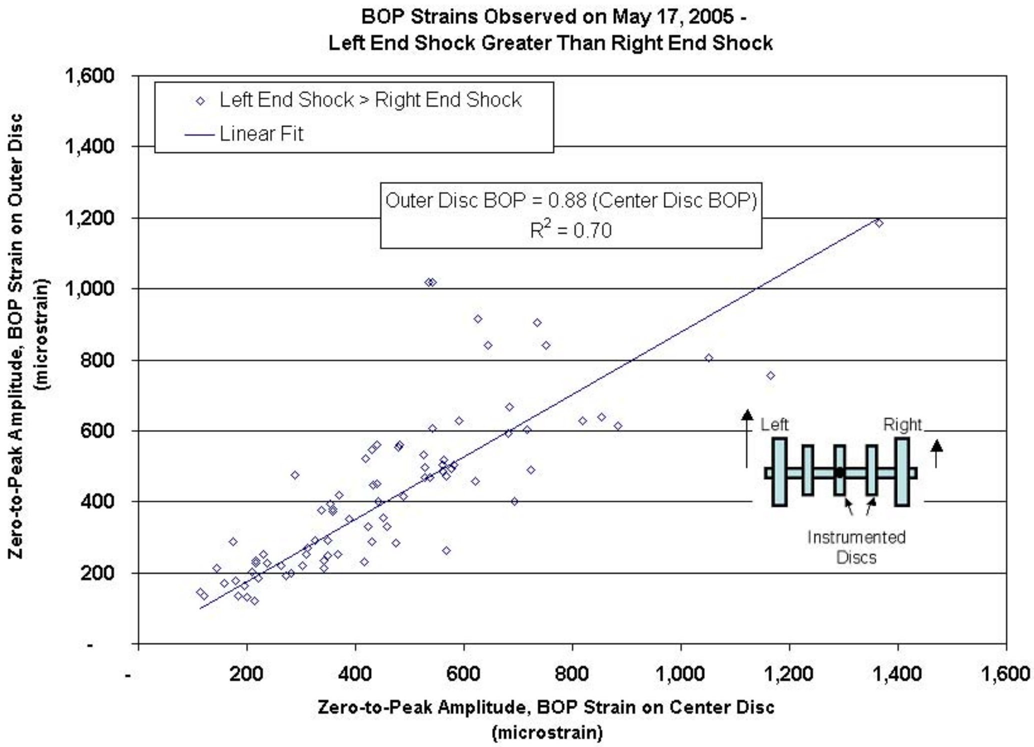


Figure 3.10a. Comparison of BOP Amplitudes of WABTEC/SAB-WABCO Supplied Center and Outer Discs Measured During Vertical Impacts, Left End Shock Greater Than Right End Shock– May 17, 2005

It can be seen that the responses of the center and outer discs are similar but that the amplitudes of the BOP strain oscillations on the center disc were generally a bit higher than those on the outer disc when the higher amplitude shock is at the opposite end of the axle from the outer instrumented disc.

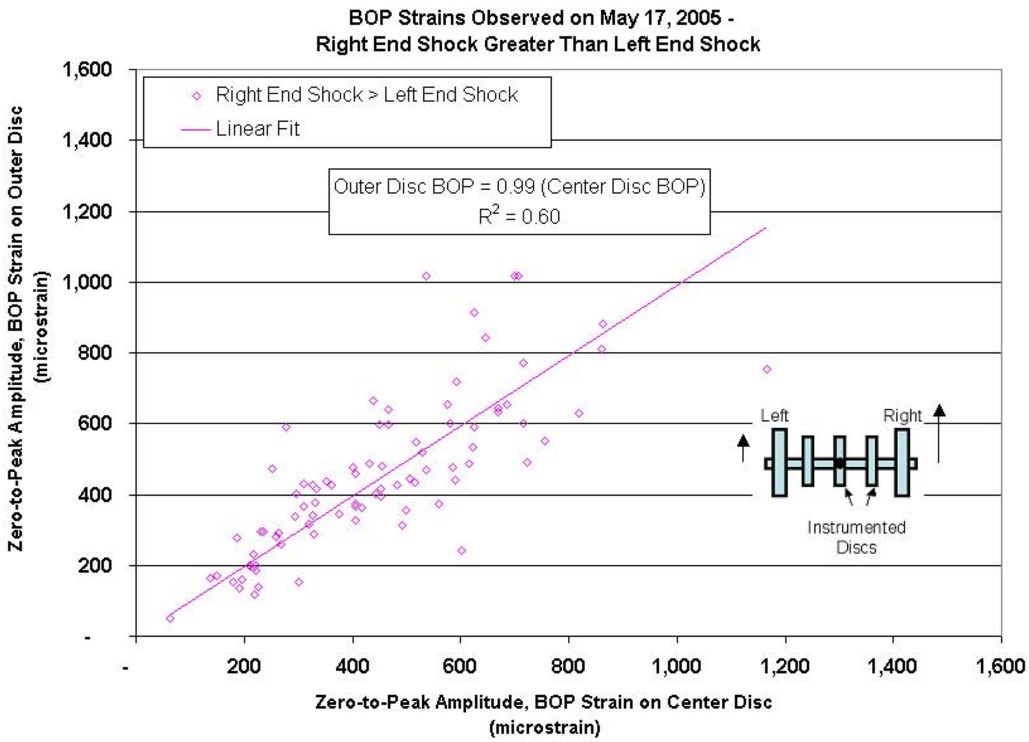


Figure 3.10b. Comparison of BOP Amplitudes of WABTEC/SAB-WABCO Supplied Center and Outer Discs Measured During Vertical Impacts, Right End Shock Greater Than Left End Shock– May 17, 2005

When the higher amplitude shocks were seen on the right end of the axle (i.e., closer to the outer disc), the response of the outer disc was generally equal to the response of the center disc, as indicated by the slope of the linear fit to the data points contained in Figure 3.10b.

The highest strains on both discs resulting from vertical impacts were observed on May 17 approximately 1700' southwest of MP AN 79, near the Gunpow Interlocking, while traveling at 119 mph. The amplitude of the BOP strains on the center disc reached 1,365 microstrain, zero-to-peak. The amplitude of the BOP strains on the outer disc was 1,186 microstrain, zero-to-peak, at the same location. As stated earlier, the strains presented are as measured and have not been corrected for pre-load strains in the spoke.

BOP Strains During Particular Braking Events

During the test run from Boston to Washington on May 17, high BOP strains were observed on the WABTEC/SAB-WABCO supplied brake discs, especially the one in the center position, under several brake applications. Figure 3.11 illustrates the output of the R1 strain gage on the center disc recorded near MP E17 as the test train was slowing down from 100 mph. The figure also provides a detailed plot of the strain gage activity. The oscillatory nature of the strain is similar to the one illustrated in Figure 3.9; however, it is superimposed over an increasing average tensile strain resulting from the buildup of heat during braking, and the oscillations persist for a much longer period of time than that seen in the response to the vertical shock shown in Figure 3.9.

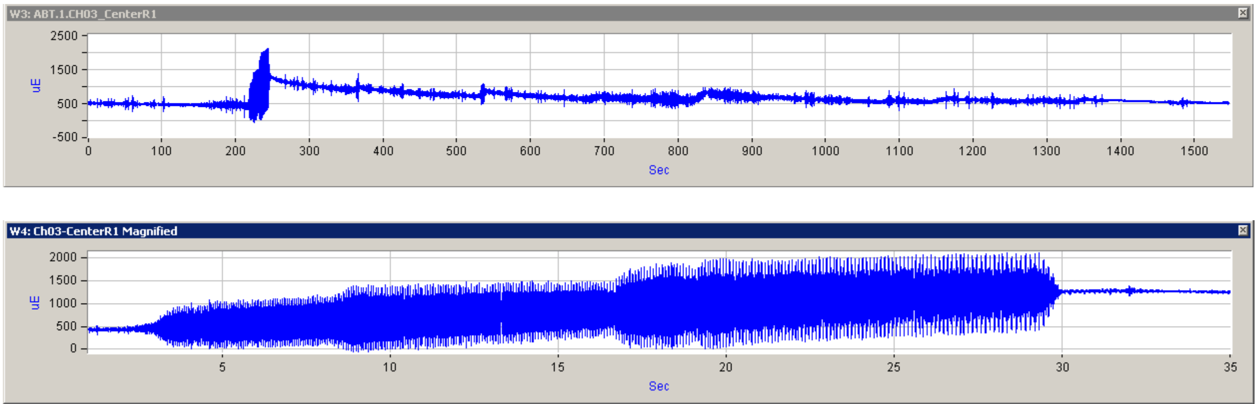


Figure 3.11. Strain Recorded on Gage R1 of Center WABTEC/SAB-WABCO Supplied Brake Disc During Braking Near MP E17 (File 051705_17.ABT)–May 17, 2005

The strain illustrated in Figure 3.11 is that measured on the side of the spoke of the center brake disc. Figure 3.12 provides the BOP strain measured on both the center and outer brake disc during this particular brake application. The upper portion of the illustration is the BOP strain measured on the two discs; the plot in the lower portion of the illustration is indicative of the amplitude of the oscillatory strains measured on each of the discs. It can be seen that the BOP strains measured on the center disc are between three and four times that of the strains recorded on the outer disc at the same time. It should be kept in mind that the overall rise in tensile strain experienced by the spoke is not observed in the BOP strains. The BOP strains represent the differences between the strains measured on either side of the spoke of interest.

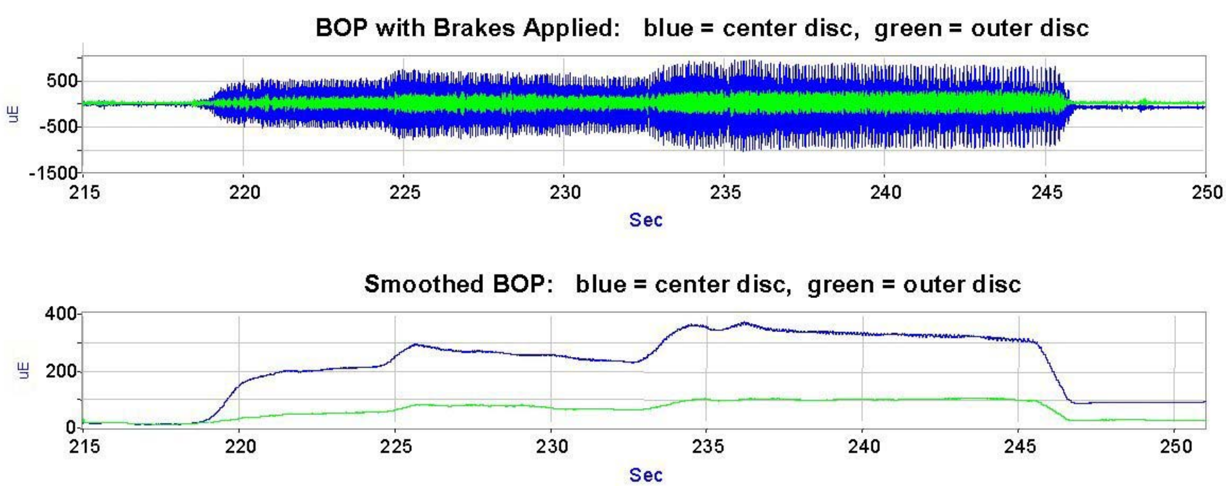


Figure 3.12. BOP Strain Recorded on Center and Outer WABTEC/SAB-WABCO Supplied Brake Discs During Braking Near MP E17 (File 051705_17.ABT)–May 17, 2005

Eight brake applications occurred during the test run conducted on May 17 that exhibited this type of substantial strain. Table 3.1 provides details associated with each of the events in which this behavior was observed. Appendix G provides additional details associated with these events. Figure 3.13 illustrates the terminology employed in Table 3.1.

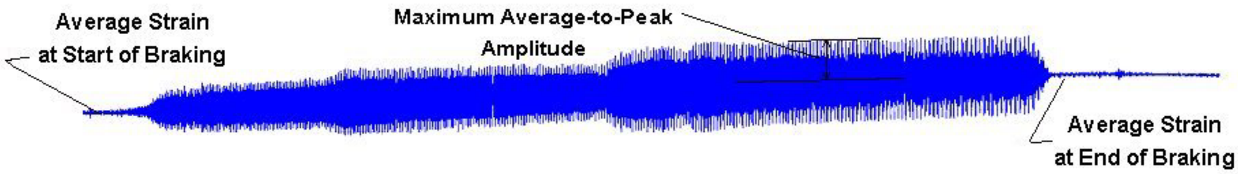


Figure 3.13. Terminology Used to Describe Sustained Oscillations During Braking

Table 3.1. Summary of Measurements Collected from Center WABTEC/SAB-WABCO Supplied Brake Disc During Brake Applications Exhibiting Signs of High BOP Strain–May 17, 2005

Geographic Location	Duration (s)	Measurements from Center Disc						Brake Cyl Press (psi)	Speed at Start of Braking (mph)
		Max Avg-to-Pk Amplitude (με)	Avg Strain @ Start (με)	Avg Strain @ End (με)	Disc Temp @ Start (°F)	Disc Temp @ End (°F)	Peak Disc Temp (°F)		
1685 SW of MP E17	28	850	445	1329	136.7	184.6	229.0	45	101
190 SW of MP AN13	22	711	350	887	116.0	163.5	189.9	35	103
Near N. Philadelphia	7	502	11	32	183.3	187.7	193.0	45	14
516 SW of MP AP25	6	623	476	659	109.9	122.6	172.8	36	94
2303 NE of MP AP65	20	700	785	1368	127.5	186.4	242.2	40	110
947 NE of MP AP71	32	591	950	1702	172.3	227.3	283.1	37	119
471 SW of MP AP79	3	576	875	958	160.9	161.8	171.9	31	123
1573 W of MP AP91	12	502	617	886	131.4	136.7	181.5	32	70

The highest amplitude of oscillations on the center disc was seen during the brake application near MP E 17 during braking from 101 mph. In this case, BOP strain oscillations reached an average-to-peak amplitude of ± 850 microstrain or a peak-to-peak amplitude of 1,700 microstrain. These strains are as measured and have not been corrected for pre-load strains in the spoke.

Several key observations were made during these particular brake applications:

- No brake applications occurred on the May 16 test run in which this behavior was observed. The main difference between the two test runs was the direction of travel of the test vehicle and therefore the direction of rotation of the test axle. The test run conducted on May 16 was with the test axle in a trailing position, and the test run conducted on May 17 was with the test axle in a leading position. This behavior was investigated during a subsequent stage of the test program.
- During these brake applications, the frequency associated with the oscillatory BOP strains was approximately 186 Hz. This was lower than the frequency of 227 Hz associated with the oscillatory strains resulting from vertical impacts.
- In each of these brake applications, the amplitude of the BOP strain measured on the center brake disc was higher than the BOP strain measured on the outer brake disc, just as Figure 3.12 shows.
- Because these oscillatory BOP strains occur during braking, they are superimposed on average tensile strains built up during the heating of the brake discs. The example provided in Figure 3.11 illustrates this action.

3.1.4 Caliper Accelerations

As described in Section 2.3.2, accelerations were recorded near one of the brake pads and near the actuator on the test axle's center caliper assembly and near one of the brake pads of the caliper used with the outer brake disc used for the test effort. Analysis of these signals indicated that little was of interest in the various caliper accelerations at times other than brake applications. Therefore, this section will present examples of the caliper accelerations collected during braking.

Figure 3.14 illustrates the three accelerations measured at each of the locations on the center caliper during a brake application from 135 mph to a near stop made while the test train was moving southbound near MP AN 41 on May 17. It can be seen that no significant level of activity occurs at either location; lateral accelerations on the actuator reached a peak level of 15 g, but accelerations at other locations on the caliper did not exceed approximately 8 g. Considering that the caliper is mounted to the truck, this is not an excessive level of excitation.

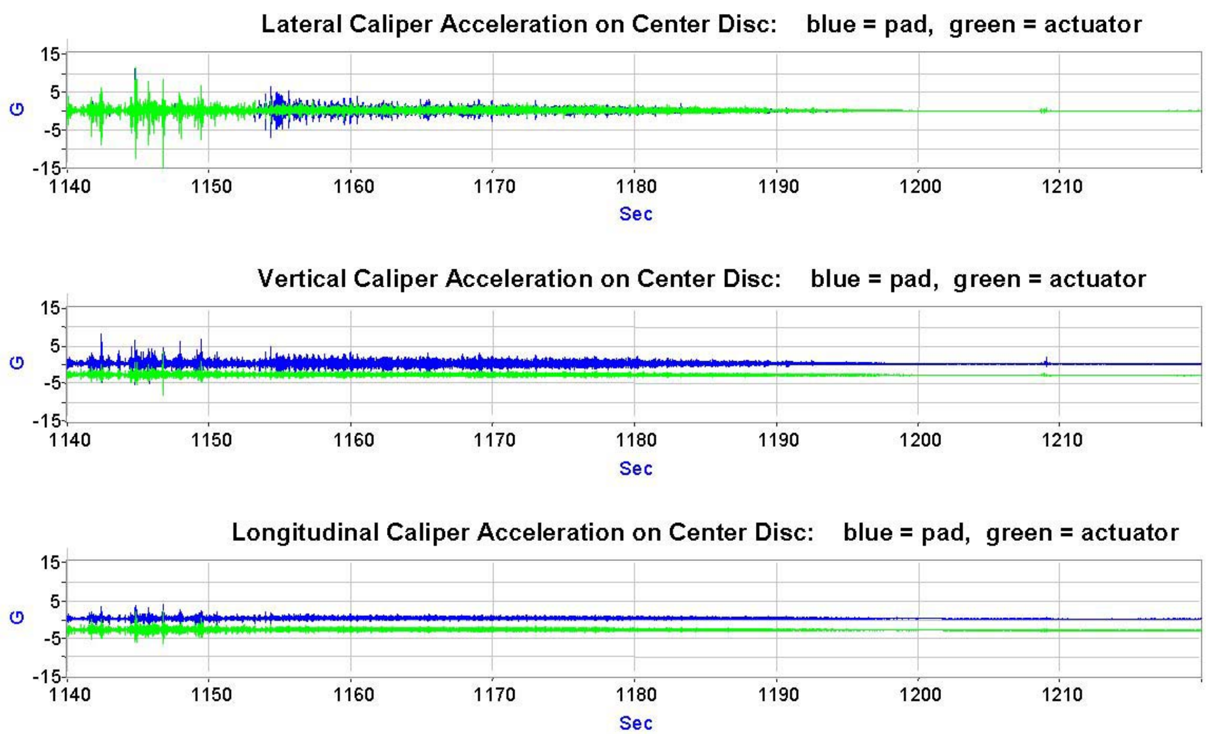


Figure 3.14. Accelerations Measured on Center Caliper During Normal Brake Application (File 051705_19.ABT)–May 17, 2005

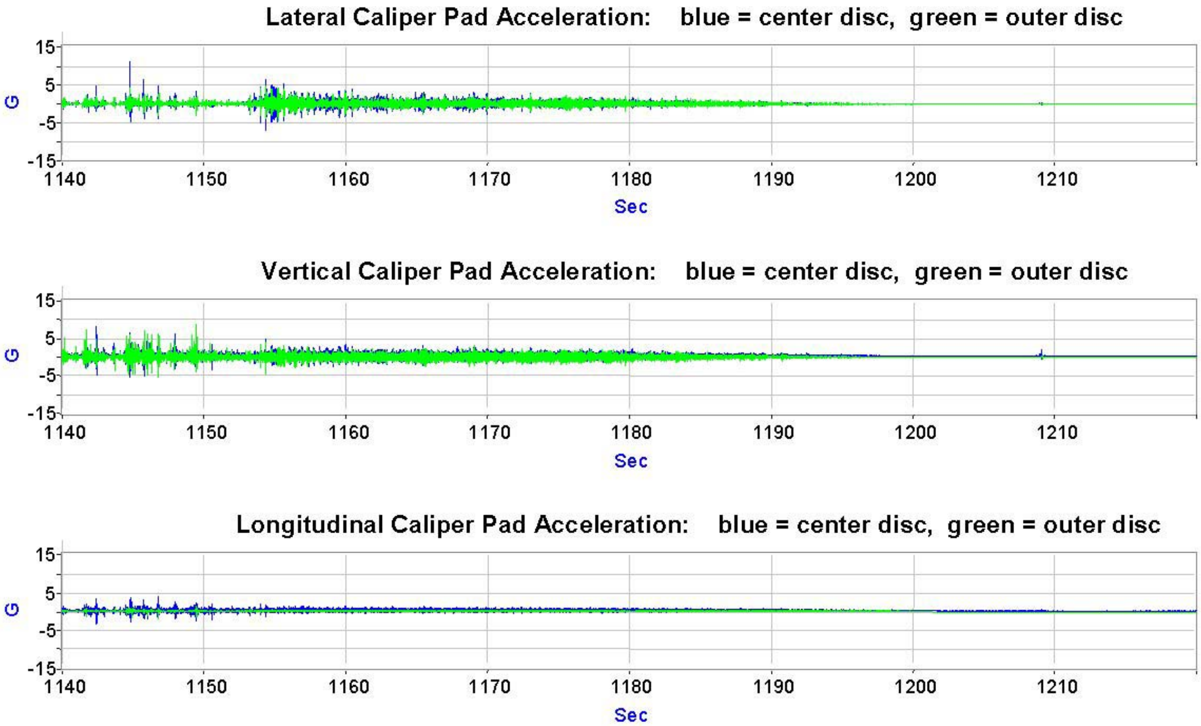


Figure 3.15. Accelerations Measured on Center and Outer Calipers Near Pads During Normal Brake Application (File 051705_19.ABT)–May 17, 2005

Figure 3.15 illustrates the three accelerations measured near the pads on both the center and outer caliper assembly during the same brake application pertaining to Figure 3.14. Again, it can be seen that no significant level of activity occurs on either caliper assembly.

Figure 3.16 illustrates the three accelerations measured at each of the locations on the center caliper during the brake application illustrated in Figures 3.11 and 3.12 where high BOP strains were observed on the center WABTEC/SAB-WABCO supplied disc while the test train was slowing down from 100 mph near MP E17 on May 17. Clearly the accelerations measured near the pads are much higher than those measured near the actuator. In addition, it can be seen that the lateral accelerations measured on the pad while the brake disc in question is experiencing high BOP strains can reach high levels, in this case up to approximately 30 g. The lateral accelerations measured near the pad are higher than vertical accelerations and much higher than longitudinal accelerations measured at the same location; accelerations measured in the longitudinal direction are relatively low during this type of phenomenon. The frequency associated with these accelerations is 186 Hz, the same as that observed in the BOP strains of the brake disc.

Figure 3.17 illustrates the three accelerations measured near the pads on the center and outer caliper assemblies during a brake application near MP AN 13 from 100 mph. Accelerations measured on the center caliper assembly are much higher than those measured on the outer caliper assembly in this situation, and the relative levels of acceleration are very similar to the relative levels of BOP strain illustrated in Figure 3.12.

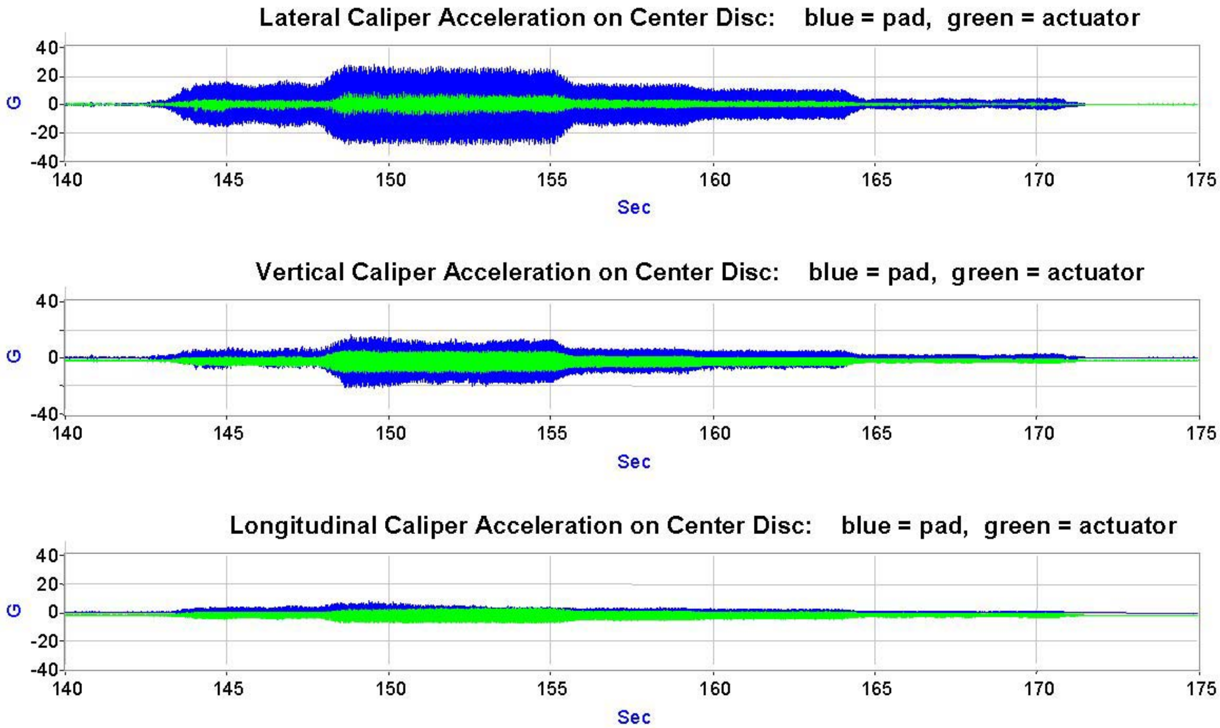


Figure 3.16. Accelerations Measured on Center Caliper During Brake Application with High BOP Strains (File 051705_19.ABT)–May 17, 2005

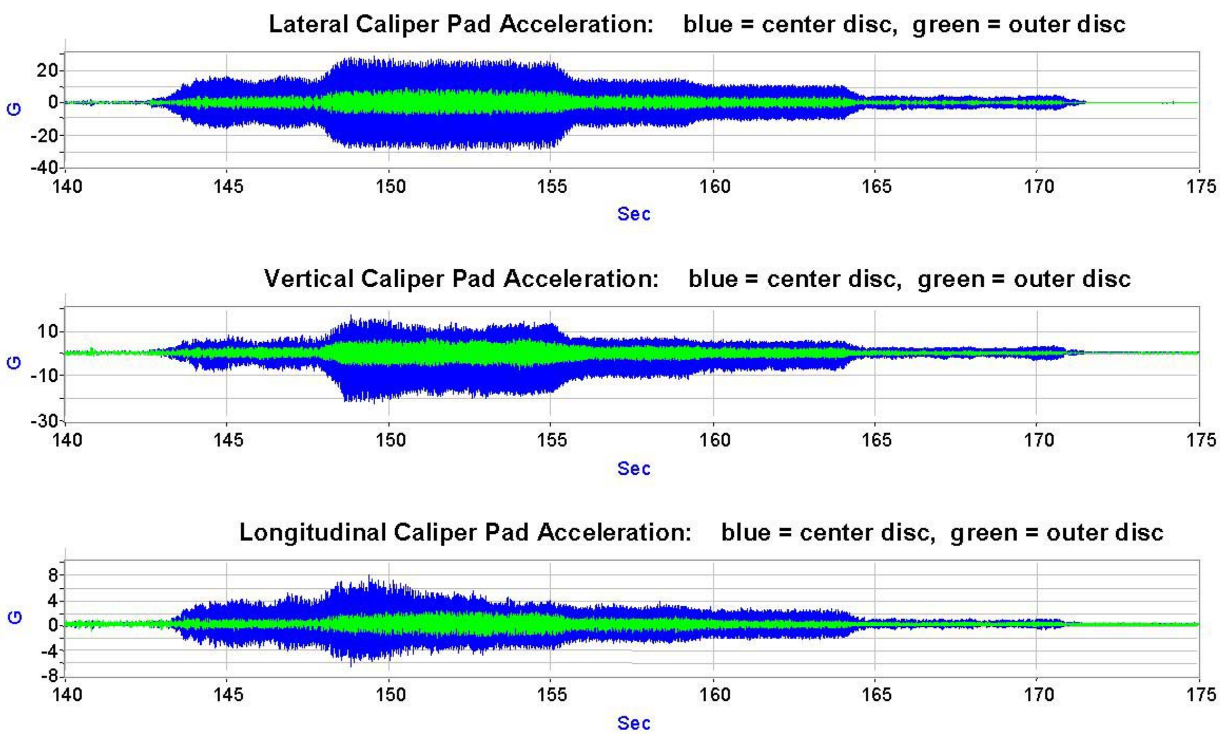


Figure 3.17. Accelerations Measured on Center and Outer Calipers Near Pads During Brake Application with High BOP Strains (File 051705_19.ABT)–May 17, 2005

From these illustrations and review of the caliper accelerations recorded during Phase 1 testing, the following observations were made:

- Accelerations on the calipers can get quite high during incidents in which the brake disc is experiencing high levels of BOP strains if the brakes are applied. The highest accelerations were observed to be lateral accelerations recorded near the pad.
- During typical brake applications in which high levels of strain are not observed on the brake discs, the accelerations measured on the caliper assemblies are relatively low.
- Based on a review of the test data (print outs of which are provided in Appendix L) the calipers experience relatively low levels of excitation when the brakes are not applied.

3.1.5 Temperatures

As described in Section 2.3.3, temperature measurements were made on the center disc using the IR sensors mounted in either side of the disc and with a thermocouple located on the disc itself. On May 16, the thermocouple was attached to spoke 6 in the vicinity of the strain gages. During testing on May 16, the initial location of the thermocouple was deemed unsatisfactory because the temperature of the spoke was not yielding useful information. Figure 3.18 illustrates the spoke temperature measured on the center WABTEC/SAB-WABCO supplied disc by the thermocouple and the temperature of the left side of the disc on the friction ring measured by one of the IR sensors during a series of brake applications on May 16 between Philadelphia, PA, and MP AN 60. The speed profile during this series of brake applications is provided for reference.

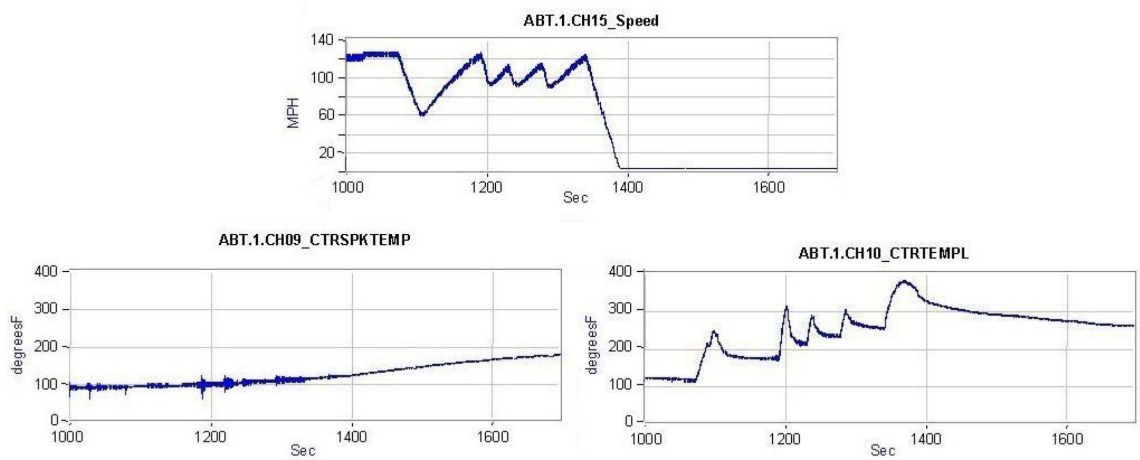


Figure 3.18. Friction Ring and Spoke Temperatures Measured on Center WABTEC/SAB-WABCO Supplied Brake Disc During Brake Applications (File 051605_09.ABT)–May 16, 2005

Brake applications illustrated in Figure 3.17 are not presented as typical brake applications but were chosen to illustrate the general behavior of the measured strains.

One can observe that the spoke temperature is well below the temperature measured on the left friction ring. The highest spoke temperature recorded on May 16 was 185.5 °F following a brake application near MP AB215. This was not considered to be an excessive temperature by the brake vendors.

During the test run on May 16, thermocouple measurements were collected from the center disc on the left side friction ring following several brake applications. These measurements have been compared; Appendix I provides these results. In general, hand thermocouple measurements were lower than the temperatures measured with the IR sensor with the highest difference being close to 100 °F but the average difference being approximately 25 °F.

Upon review of the data from the May 16 test run, it was decided that the thermocouple should be moved to the back of the friction ring for the remainder of testing to monitor higher disc temperatures. On the evening on May 16, the thermocouple was removed from spoke 6 of the center disc and relocated to the back of the friction ring as illustrated in Figure 2.19.

Figure 3.19 illustrates the temperatures measured with the IR sensors on both sides of the center and outer brake discs and the temperature measured on the back of the center disc's friction ring during the test run between Newark, NJ, and Philadelphia, PA, on May 17. As evidenced by the large temperature increase in the middle of this data sample, a full-service brake application was made during this portion of the test.

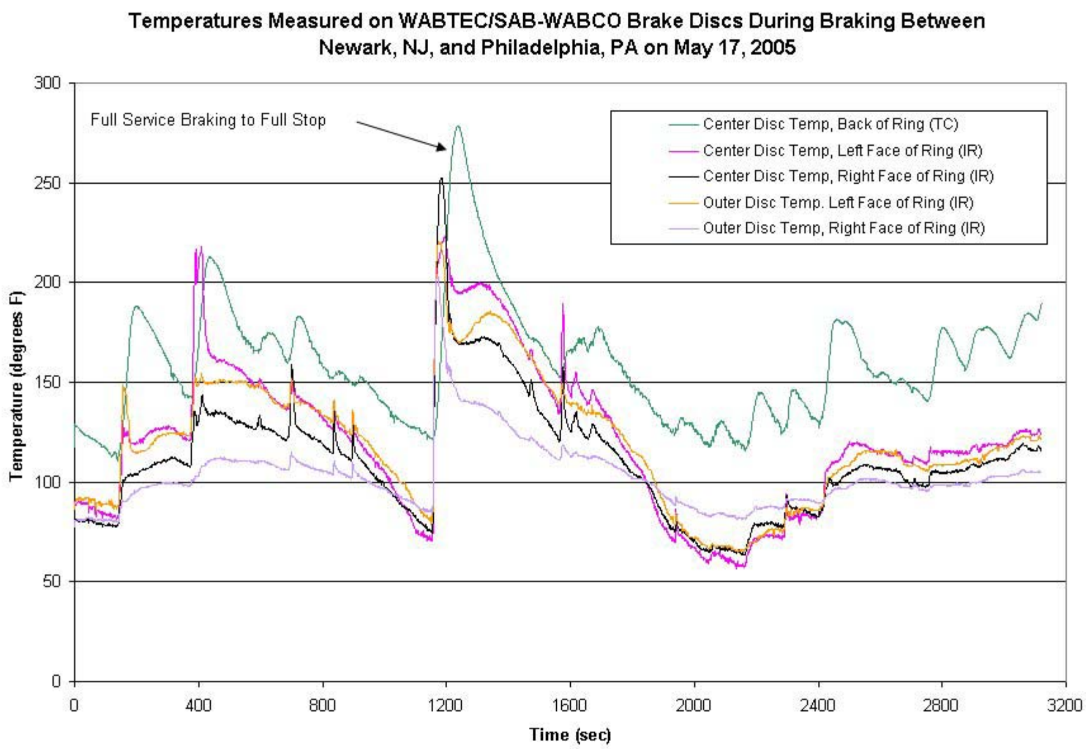


Figure 3.19. Temperature Measurements Made During Testing Between Newark, NJ, and Philadelphia, PA–May 17, 2005

In general, the trends of the various temperature measurements agree with each other. The temperature measured on the back of the friction ring tends to be higher than the temperatures measured by the IR sensors. Many factors influenced this difference, including the IR sensors' sensitivity to orientation or angle, with respect to the surface upon which measurements are made; the IR sensors' sensitivity to surface finish; and the proper selection of emissivity settings. Two separate corrections that can be applied to temperatures measured by the IR sensors on the friction rings to bring them into agreement with temperatures measured by the thermocouple on the back of the center disc's friction ring were developed based on the data illustrated in Figure 3.19. Appendix I provides these corrections. One of these corrections involves a simple bias, or offset, shift while the other involves the application of both a scale factor and an offset shift.

With these statements in mind, the IR sensor measurements, in combination with the temperatures measured on the back of the friction ring using the thermocouple, provided sufficient information to be able to make an assessment of the brake disc temperatures. The highest temperatures on the brake discs were observed between Wilmington, DE, and Baltimore, MD, on May 17 following the second of two brake applications from 125 mph to 30 mph between MP AP 65 and MP AP 72; Figure 3.20 shows this occurrence. The maximum temperature measured on the back of the friction ring of the center disc was close to 280 °F and was observed following the last of the brake applications shown in the illustration. The temperature measured on the left friction ring of the center brake disc reached a value of approximately 255 °F. The brake vendors did not identify these temperatures as excessive.

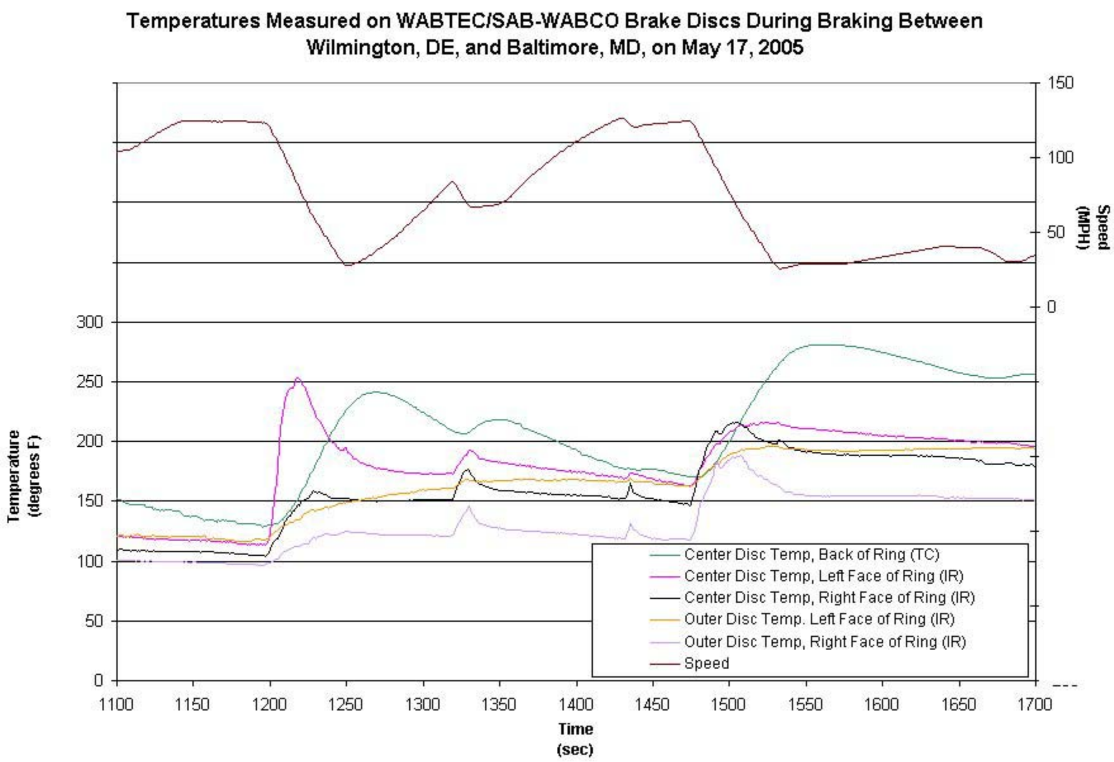


Figure 3.20. Extreme Temperature Measurements Made During Testing Between Wilmington, DE, and Baltimore, MD–May 17, 2005

The temperatures measured at the single location on the back of the center disc's friction ring were used to estimate the state of thermal stress in the spokes of the disc. It is recognized that the distribution of the temperature in the friction plates of the brake discs is expected to be complex and dependent on many aspects, including the geometry of the friction plate. It must be recognized that analyses conducted on data collected with the thermocouple data were conducted to extract meaningful observations from temperature data, and the results of these analyses are only considered to be approximations. Temperatures measured on May 17 on the back of the friction ring before brake application were compared with the corresponding tensile strain in spoke 6. No direct measure of spoke temperature occurred following tests conducted on May 16. Figure 3.21 illustrates the comparison of temperature and spoke strain. Choosing to consider the temperatures before the brake applications allows for equalization of temperatures throughout the disc. By establishing a relationship between these two quantities, an *estimate* of the thermal strains in the spoke can be arrived at without a direct measurement of spoke temperature. These estimated thermal strains would not account for any existing pre-load strains in the spoke.

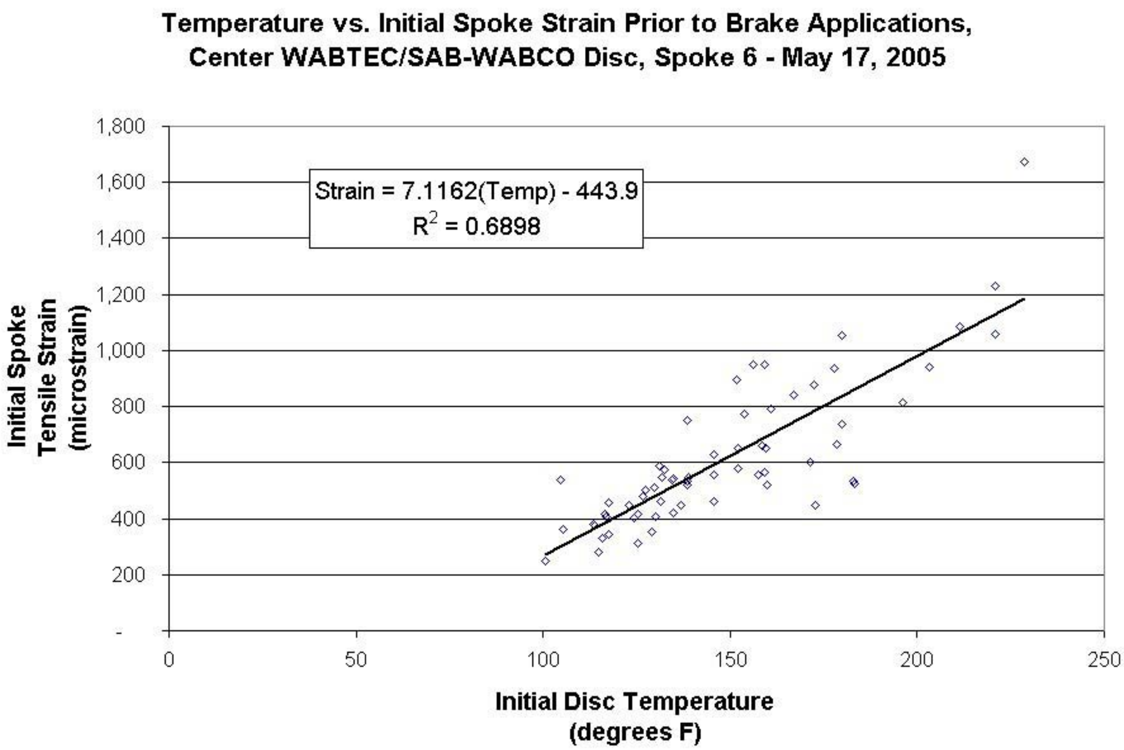


Figure 3.21. Brake Disc Temperature versus Initial Spoke Tensile Strain Before Brake Applications, Center WABTEC/SAB-WABCO Supplied Disc, Spoke 6–May 17, 2005

3.1.6 Brake Pressures

As described in Section 2.3.4, three pressures within the brake system were monitored during Phase 1 testing. In general, the pressures varied as follows:

- Brake cylinder pressure was typically 0 psi until the brakes were applied. Brake cylinder pressure reached a maximum of 56 psi during full service brake applications.
- Brake pipe pressure was typically 110 psi, falling to a minimum of 90 psi during brake applications.
- Parking brake pressure measurements were reflective of the main reservoir pressure, 140 to 145 psi, when the brakes were released. When the brakes were applied, the parking brake pressure measurement was the same as the brake cylinder pressure.

Upon review of the data, nothing of particular interest was observed in brake pipe and parking brake pressure. According to the brake vendors, the brake system appeared to function to an acceptable level.

Review of brake cylinder pressure measurements revealed that the amplitude of the high BOP strains measured during seven brake applications on May 17 correlated with the brake application pressure reflected in the brake cylinder pressure. Figure 3.22 illustrates the BOP strains recorded on the center and outer WABTEC/SAB-WABCO supplied discs provided in Figure 3.12 along with the brake cylinder pressure recorded during the same time frame. It can clearly be seen that the amplitude of the strain oscillations increase with increasing brake pressure; the maximum amplitude oscillation is reached when the brakes are at full service pressure of 56 psi. Brake pressure, however, does not appear to be the trigger for this dynamic behavior. Based on the brake pressures at the start of this activity in the seven examples highlighted in Table 3.1, this activity can be initiated over a range of brake cylinder pressures, (31–45 psi).

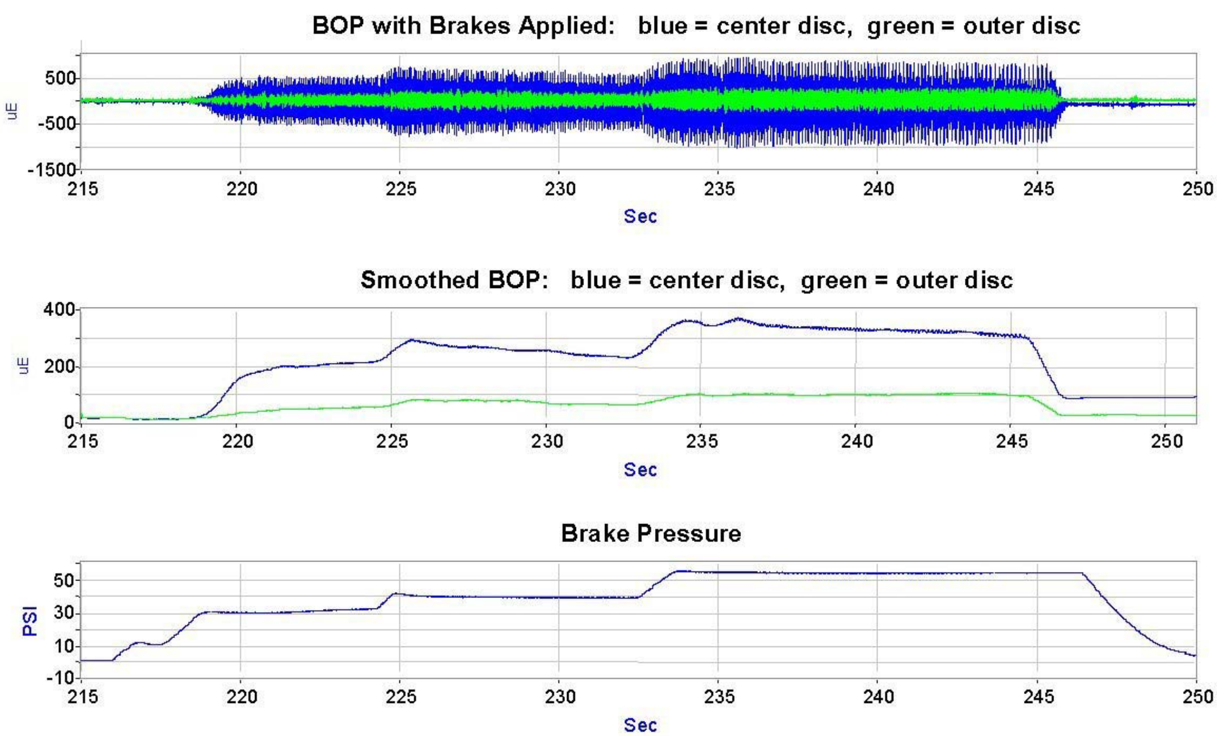


Figure 3.22. Brake Cylinder Pressure and BOP Strains Recorded on WABTEC/SAB-WABCO Supplied Brake Discs During Braking Near MP E17 (File 051705_17.ABT)–May 17, 2005

3.1.7 Spreader Bar Test

Following the completion of the test run conducted on May 17, a series of tests was conducted on Instrumented Axle 1 in which a spreading force was placed at various locations between the center and outer WABTEC/SAB-WABCO supplied instrumented discs. Section 2.4.1 provides a description of the procedure followed for this investigation.

Figure 3.23 provides strain measurements recorded from the instrumented spokes on each of the discs during both loadings. The graph in Figure 3.23a pertains to loadings aligned with spokes on the center disc, while Figure 3.23b pertains to loadings aligned with spokes on the outer disc. Part A of Appendix J includes strain readings illustrated in Figure 3.23.

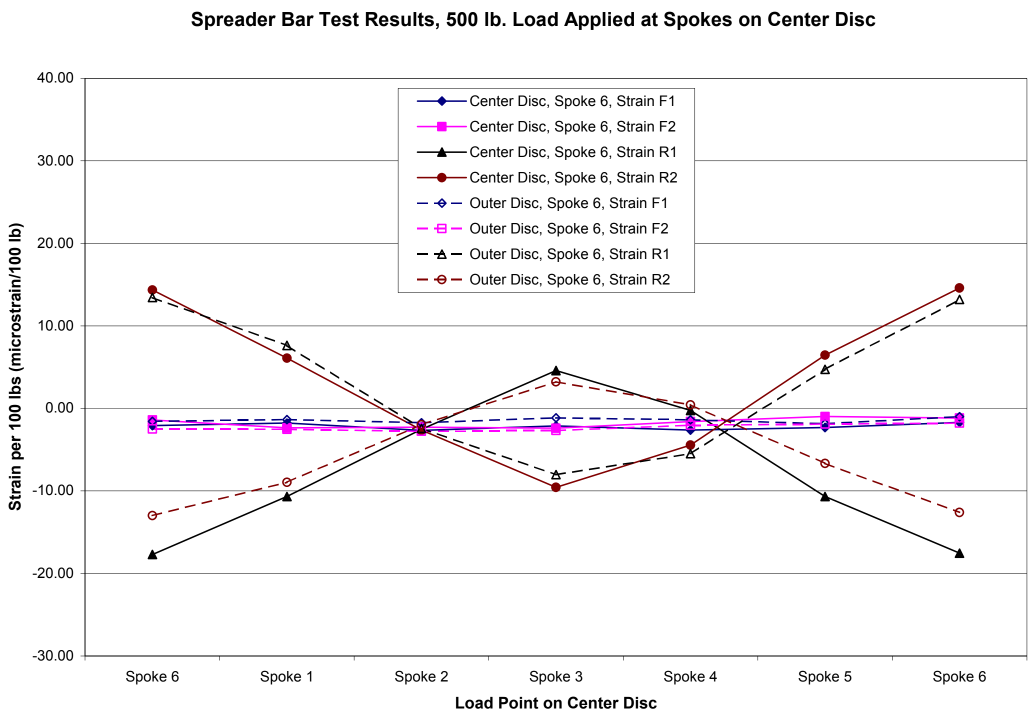


Figure 3.23a. Strains Measured During Spreader Bar Test, Load Aligned with Spokes of Center Disc

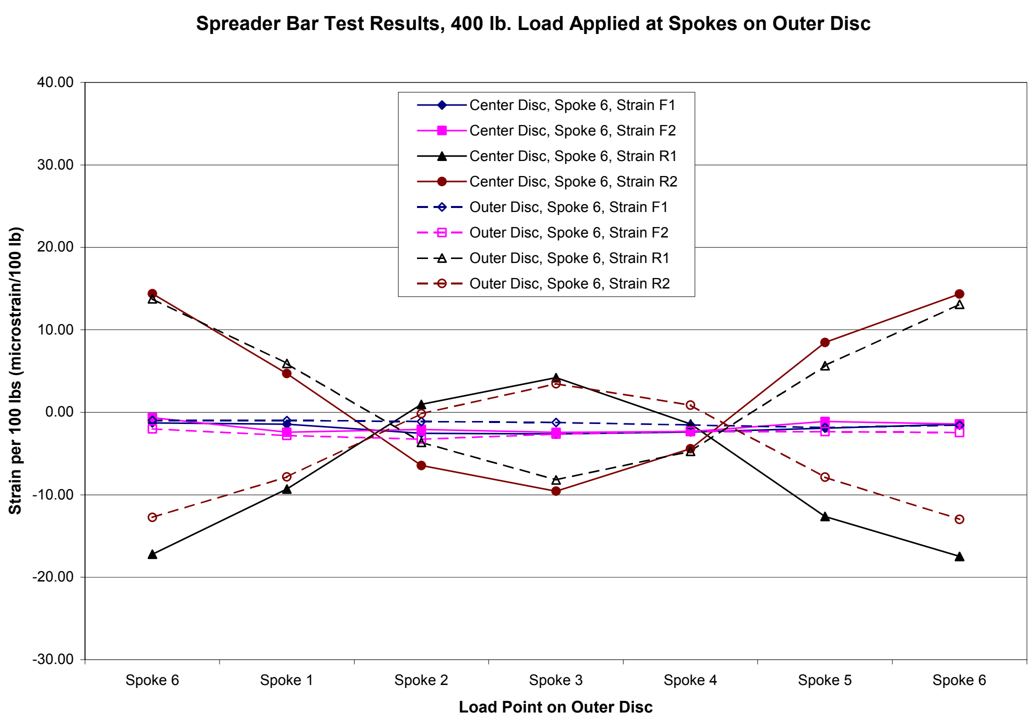


Figure 3.23b. Strains Measured During Spreader Bar Test, Load Aligned with Spokes of Outer Disc

Based on the results presented in Figure 3.22, the following observations were made:

- The strain gages on each of the instrumented spokes were working as expected following the first portion of the over-the-road testing. The lateral spreading force resulted in little strain on the faces of the spokes and strains of opposite nature (i.e., tension versus compression) on the web/rib of the spokes.
- The strains measured by the R2 gage on spoke 6 of the outer disc tended to be approximately 20 percent lower than strain measured by the R1 gage on spoke 6 of the center disc. This difference is largely reflective of the variability of strain measurements in individual spokes and is not significant enough to affect the results provided for the outer disc in this section.

3.1.8 Concluding Comments

Important information was learned from the results of Phase 1 testing, including the following:

- Based on a preliminary FEA, a frequency associated with a BOP was calculated to be 206 Hz.
- High magnitude shocks occurring in accelerations measured on the axle were identified by counting cases in which one or more consecutive data values exceed a given acceleration threshold. Accelerations appearing to result from electrical noise or other instrumentation issues were neglected.

  It was found that the load environment experienced by the typical axle was more influenced by high vertical accelerations than by high lateral accelerations.

  During Phase 1 testing, 172 vertical shocks above 50 g were recorded on May 16, 5 of which were above 100 g. There were 161 vertical shocks above 50 g recorded on May 17, 8 of which were above 100 g. The highest vertical acceleration observed in Phase 1 testing was 126 g.

  Six lateral shocks above 30 g were measured on the WABTEC/SAB-WABCO test axle during Phase 1 testing; two were observed during the test conducted on May 16, and four were observed during the test conducted on May 17. The highest lateral acceleration measured during Phase 1 testing was 39.1 g, measured on May 17.
- Two types of strain dominated the data collected during Phase 1 testing, tensile strains in the spoke resulting from the buildup of heat in the disc during braking and BOP of the spoke produced in response to vertical shocks and in certain braking scenarios.

  The highest BOP strains on both the center and outer WABTEC/SAB-WABCO supplied discs resulting from vertical shocks reached 1,365 microstrain, zero-to-peak, and 1,186 microstrain, zero-to-peak, respectively at the same location. The frequency associated with oscillating BOP strains resulting from vertical shocks was approximately 227 Hz. The responses of the center and outer discs are similar, but the amplitudes of the BOP strain oscillations on the center disc were generally a bit higher than those on the outer disc when the higher amplitude shock is at the opposite end of the axle from the outer instrumented disc. When the higher amplitude shocks were seen on the right end of the axle (i.e., closer to the outer disc), the response of the outer disc was generally equal to the response of the center disc.

  High BOP strains were observed on the WABTEC/SAB-WABCO supplied brake discs, especially the one in the center position, under eight brake applications during the test run from Boston to Washington on May 17. This phenomenon was not observed on the northbound test on May 16. The nature of the strain is characterized by an oscillating strain superimposed over an increasing average tensile strain resulting from the buildup of heat during braking. These oscillations persist for a much longer period of time than that seen in the response to vertical shocks and have a frequency of 186 Hz associated with them. The amplitude of the oscillations on the center brake disc was between three and four times that of the outer brake disc; the maximum amplitude of oscillating strain on the center disc observed during Phase 1 tests was 1,700 microstrain, peak-to-peak. The amplitude of these oscillations was proportional to the brake pressure measured throughout the application.

Specified strains are as measured and have not been corrected for pre-load strains in the spoke.

- Accelerations measured on the caliper assemblies near the brake pad were higher than those measured near the actuators. The highest accelerations near the caliper pads were measured during those braking events in which the high BOP strains were observed and appeared to correlate with the amplitude of the oscillations of the particular brake disc. Consequently, accelerations measured on the center caliper assembly during these incidents were higher than those measured on the outer caliper assembly.
- Temperatures measured at several locations on the brake discs did not exceed temperatures expected by the brake vendors.

In addition, several issues associated with instrumentation were identified, including the following:

- The low signal-to-noise ratio exhibited in the output of the accelerometers on the left end axle box in the beginning of the test run conducted on May 16.
- The intermittent saturation of the lateral accelerometer mounted directly to the test axle.
- The discrepancy in temperatures measured by the IR sensors with those measured by the thermocouples.

Although many things were learned during Phase 1 testing, several questions remained unanswered, including the following:

- What was the mode of vibration experienced by the brake discs? Although the frequencies associated with the various motions suggested an out-of-phase bending motion identified in the initial FEA, insufficient data existed to confirm this.
- What was the exact value of the natural frequency of the WABTEC/SAB-WABCO supplied brake disc?
- What were the contributing factors to the high BOP strains observed during several brake applications, and why were they not observed during the northbound test conducted on May 16?

These questions, in addition to questions raised by the results provided during Phase 1 testing, served as motivation for testing conducted during Phase 2 of the effort.

3.2 Phase 2 Test Results

To better characterize the strains associated with BOP, focus shifted to the center WABTEC/SAB-WABCO supplied disc in Phase 2 testing where additional strain measurements were made on the spoke opposite that monitored during the initial test efforts. Strain gages were mounted to the axle at the request of the brake system suppliers to determine the contribution of axle bending to the results observed in Phase 1 testing. The sampling rate employed with the ENSCO-based data collection hardware was increased from 2,000 Hz to 3,000 Hz for Phase 2 testing so that all relevant information, especially those quantities that change quickly such as accelerations, was captured in an accurate manner. Amtrak provided a second data collection system that employed a sampling rate of 10,000 Hz to record selected parameters.

A round trip test was conducted between Washington and Boston on May 26 and 27. The test run conducted on May 26 was a northbound run with the test axle in a leading position within the test vehicle; the test run conducted on May 27 was a southbound run with the test axle in the trailing position within the test vehicle.

During the second phase of testing, sound levels under the test vehicle were recorded to attempt to capture and analyze the high frequency noise heard during times in which signs of saturation were observed on some or all of the accelerometers mounted directly to the axle. The sound recording equipment was also used to attempt to capture and analyze a moaning noise heard above many axles of the test train during braking in Phase 1 testing.

3.2.1 Axle Accelerations

As described in Chapter 2, the sampling rate employed with the ENSCO data collection hardware was increased from 2,000 Hz to 3,000 Hz for Phase 2 testing; an anti-alias filter with a cut-off frequency of 750 Hz was used during Phase 2 testing. Amtrak provided a second data collection system that employed a sampling rate of 10,000 Hz to record axle accelerations and other selected parameters; no anti-alias filter was used with the Amtrak data collection system. Figure 3.24 illustrates a vertical shock measured on the left end axle box and corresponding BOP strain recorded on spoke 6 of the center disc, while the test train traveled through the Forest Interlocking near MP AB 223 at 120.4 mph during the May 26 test run. The ENSCO-based collection system recorded the amplitude of this shock as 116.6 g. As can be seen in the figure, the Amtrak-based collection system was able to record a higher acceleration during this event. This highlights an important consequence of the proper selection of a sampling rate–increasing the rate at which data is recorded, or increasing the bandwidth of the data, can result in higher recorded amplitudes of acceleration.

Further analysis of acceleration data collected at the two sampling rates by test personnel and the brake vendors indicated that no additional information critical to the study was provided by the data collected with the 10,000 Hz sampling rate. This is evidenced by the negligible difference in strains recorded spoke 6 at the two different sampling rates shown in Figure 3.24. Subsequent testing in Phase 3 did not employ the data collected with 10,000 Hz in the official test record. In light of the decisions made regarding the data collected with the higher sampling rate, discussion of results in this section will be limited those based on data recorded at 3,000 Hz.

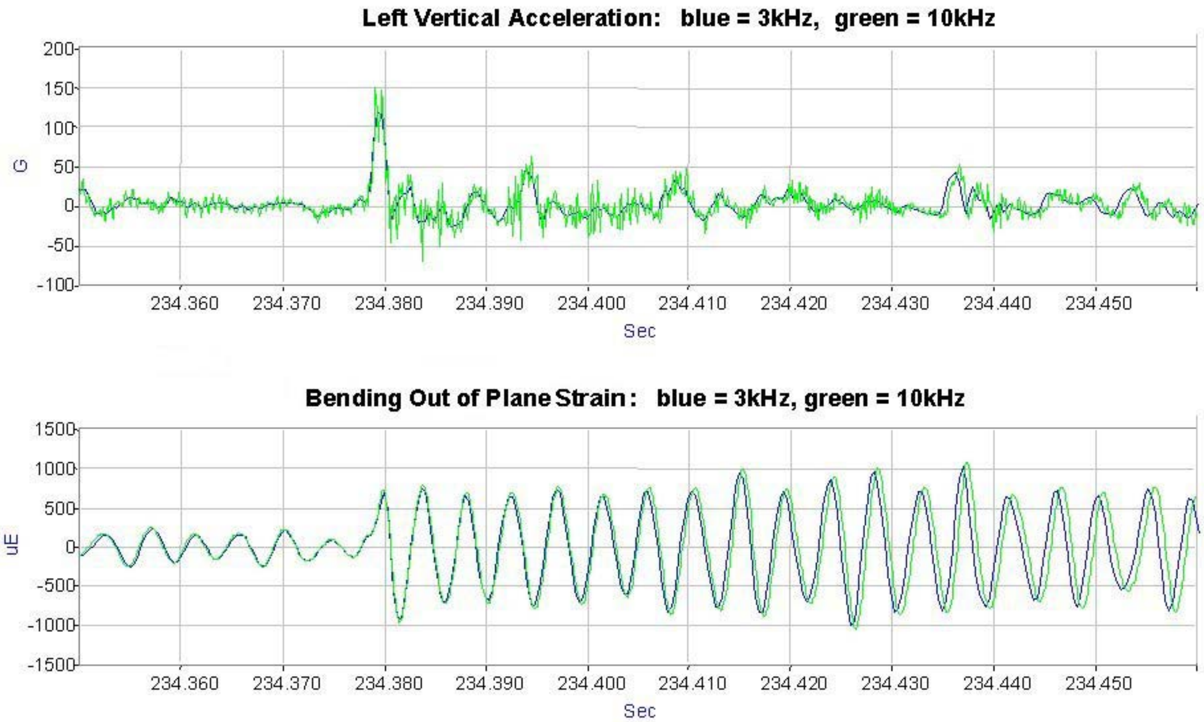


Figure 3.24. Comparison of Vertical Shock and BOP Strains Recorded with 3,000 Hz and 10,000 Hz Sampling Rates (Files 052605_18.AB2 [3,000 Hz Data] and File 052605_18.001 [10,000 Hz Data])–May 26, 2005

Figure 3.25a illustrates the distribution of vertical accelerations above 50 g recorded on the test axle from Washington to Boston on May 26 with the test axle in a leading position. Figure 3.25b illustrates the corresponding information for the data collected between Boston and Washington on May 27 with the test axle in a trailing position. Appendix F tabulates the data illustrated in Figure 3.25.

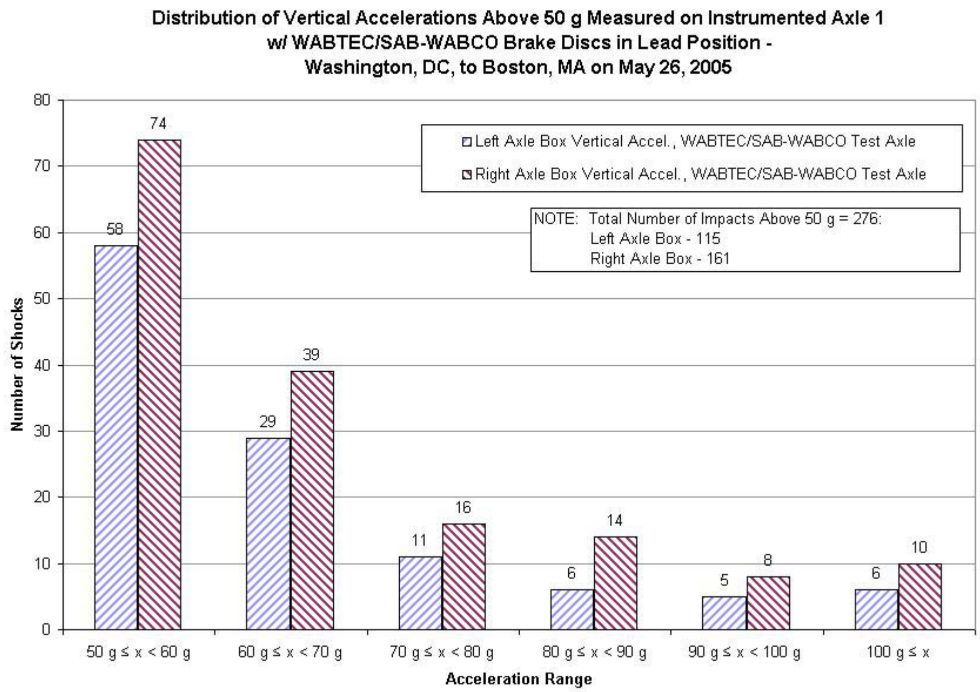


Figure 3.25a. Distribution of Vertical Accelerations Above 50 g Measured on Instrumented Axle 1 with WABTEC/SAB-WABCO Supplied Brake Discs in Lead Position–Washington, DC, to Boston, MA, on May 26, 2005

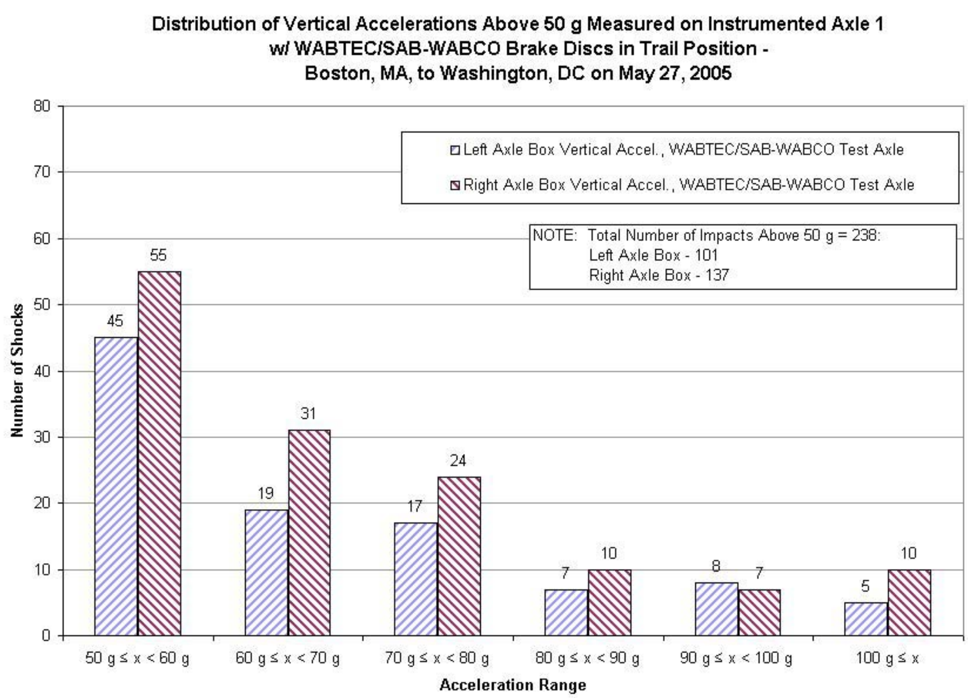


Figure 3.25b. Distribution of Vertical Accelerations Above 50 g Measured on Instrumented Axle 1 with WABTEC/SAB-WABCO Supplied Brake Discs in Trail Position–Boston, MA, to Washington, DC, on May 27, 2005

As shown in Figure 3.25, 276 vertical shocks above 50 g were measured on the WABTEC/SAB-WABCO test axle during the northbound test conducted on May 26, 115 on the left end axle box and 161 on the right end axle box, and 238 vertical shocks above 50 g were measured during the southbound test conducted on May 27, 101 on the left end axle box and 137 on the right end axle box. Regarding results from May 26, 16 shocks above 100 g were measured. Fifteen shocks over 100 g were measured on May 27.

The highest vertical acceleration observed in Phase 2 testing was 156 g, measured on the left end of the axle on May 26 near Union Interlocking near MP AN 20 while the test train was traveling at 113 mph. Appendix F provides the details associated with accelerations above 100 g in tabular form.

As discussed in Section 2.3.2, two additional accelerometers were mounted to the axle in an attempt to improve the reliability of the measurement of the lateral accelerations on the axle. Upon review of the data, it was determined that neither of the two new accelerometers provided improved performance. Results pertaining to lateral accelerations during this phase of testing will be based upon the axle box-mounted sensors and the Silicon Designs +/- 200 g single-axis accelerometer employed during the first phase of testing.

Figure 3.26a illustrates the distribution of lateral accelerations above 30 g recorded on the test axle from Washington to Boston on May 26 with the test axle in a leading position. Figure 3.26b illustrates the corresponding information for the data collected between Boston and Washington on May 27 with the test axle in a trailing position. Appendix F tabulates the data illustrated in Figure 3.26.

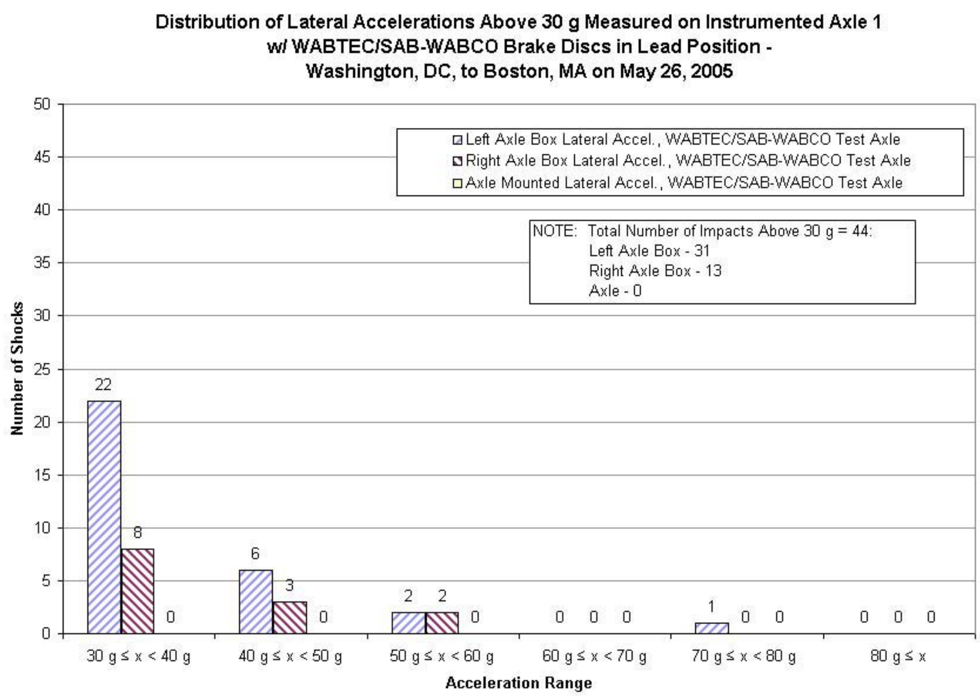


Figure 3.26a. Distribution of Lateral Accelerations Above 30 g Measured on Instrumented Axle 1 with WABTEC/SAB-WABCO Supplied Brake Discs in Lead Position–Washington, DC, to Boston, MA, on May 26, 2005

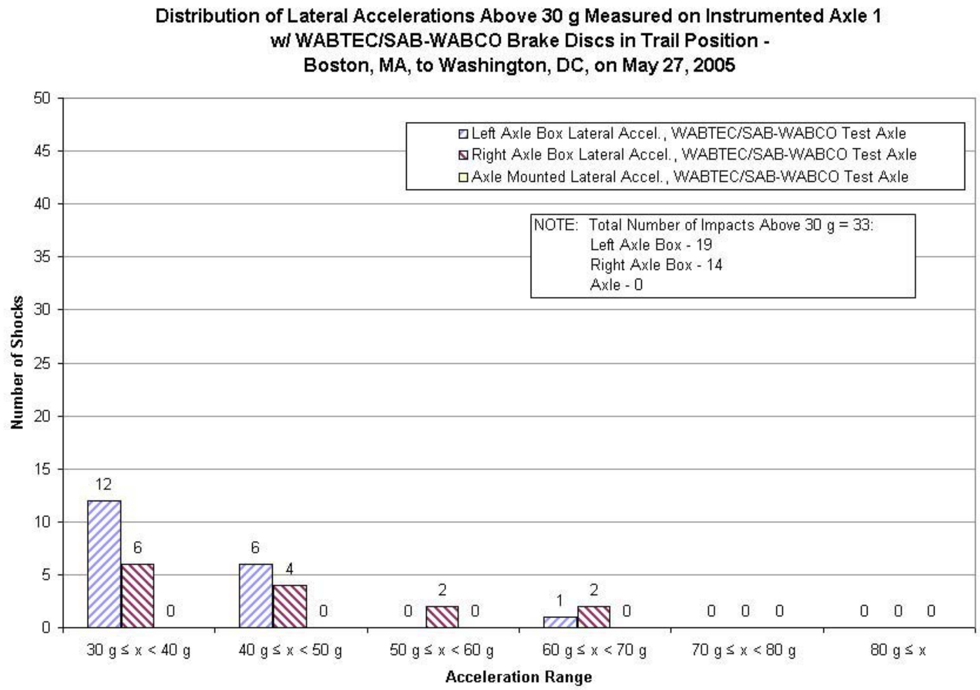


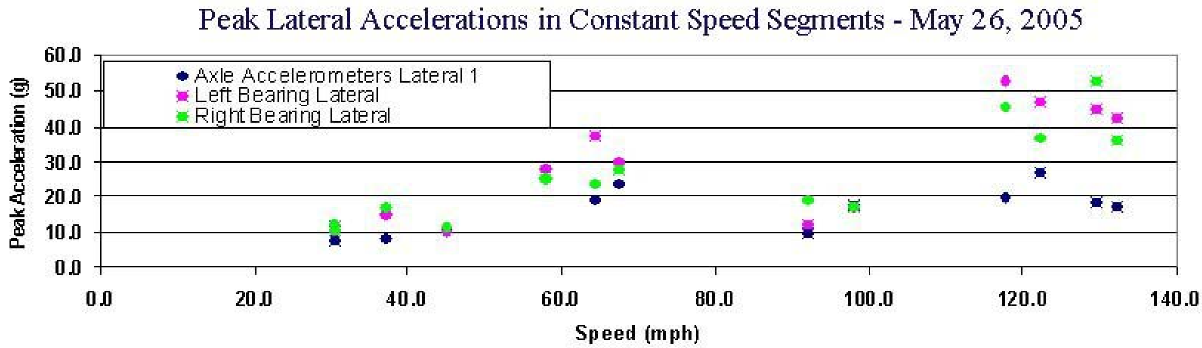
Figure 3.26b. Distribution of Lateral Accelerations Above 30 g Measured on Instrumented Axle 1 with WABTEC/SAB-WABCO Supplied Brake Discs in Trail Position–Boston, MA, to Washington, DC, on May 27, 2005

Forty-four lateral shocks above 30 g were measured on the WABTEC/SAB-WABCO test axle during the northbound test conducted on May 26, 31 on the left end axle box and 13 on the right end axle box. No accelerations were measured above 30 g on the axle that were reliable measurements. Thirty-three lateral shocks above 30 g were measured on the WABTEC/SAB-WABCO test axle during the southbound test conducted on May 27, 19 on the left end axle box and 14 on the right end axle box. No accelerations were measured above 30 g directly on the axle that were considered reasonable.

The highest lateral acceleration observed during Phase 2 testing was on the left end axle box. A 75.3 g shock was measured on May 26 at the Union Interlocking near MP AN20 while the test train was traveling at a speed near 112 mph.

During Phase 1 testing, the observation was made that the load environment associated with vertical impacts was much more severe than that associated with lateral impacts, with peak vertical accelerations measuring almost three times the level of peak lateral accelerations. Accelerations measured during Phase 2 testing were analyzed in detail to see if this relationship between lateral and vertical accelerations extended beyond accelerations associated with large impacts.

In order to characterize the typical load environment affecting the test axle, a number of segments of the data collected on May 26 and May 27 were identified in which near-constant speeds were maintained. Within each of these zones, the highest lateral and vertical accelerations were identified. Figure 3.27 provides the results of this analysis conducted with data collected on May 26. Lateral accelerations identified in this process are shown in the upper portion of the figure, and the corresponding information for vertical accelerations is shown in the lower portion of the figure. The results contained in these plots do not represent the entire run but only those constant speed segments selected for consideration.



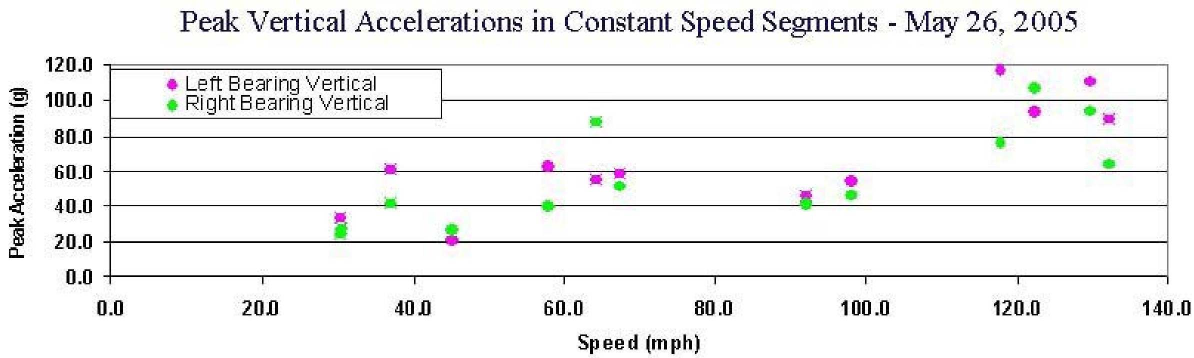


Figure 3.27. Peak Lateral and Vertical Accelerations Observed in Near-Constant Speed Segments as a Function of Speed–May 26, 2005

A similar consideration was made for data collected on the southbound portion of the trip conducted on May 27. The results based on data collected on May 27 were similar to those shown in Figure 3.27 and are included in Appendix F.

In addition to the peak lateral and vertical accelerations calculated in each near-constant speed data segment, several percentile values of acceleration were calculated. As an example, the 99.9 percentile value is the acceleration value below which 99.9 percent of all accelerations within the data segment reside. Calculating several percentile values of acceleration for each data segment considered in this analysis allowed for a more general characterization of the accelerations. Figure 3.28 illustrates the ratios of vertical to lateral accelerations for several percentile levels of acceleration determined within near-constant speed segments recorded at 122 mph. In this illustration, vertical accelerations measured on the axle boxes were typically 2 to 3.7 times as large as the lateral accelerations measured at the same location. Similar results were found for other data segments considered.

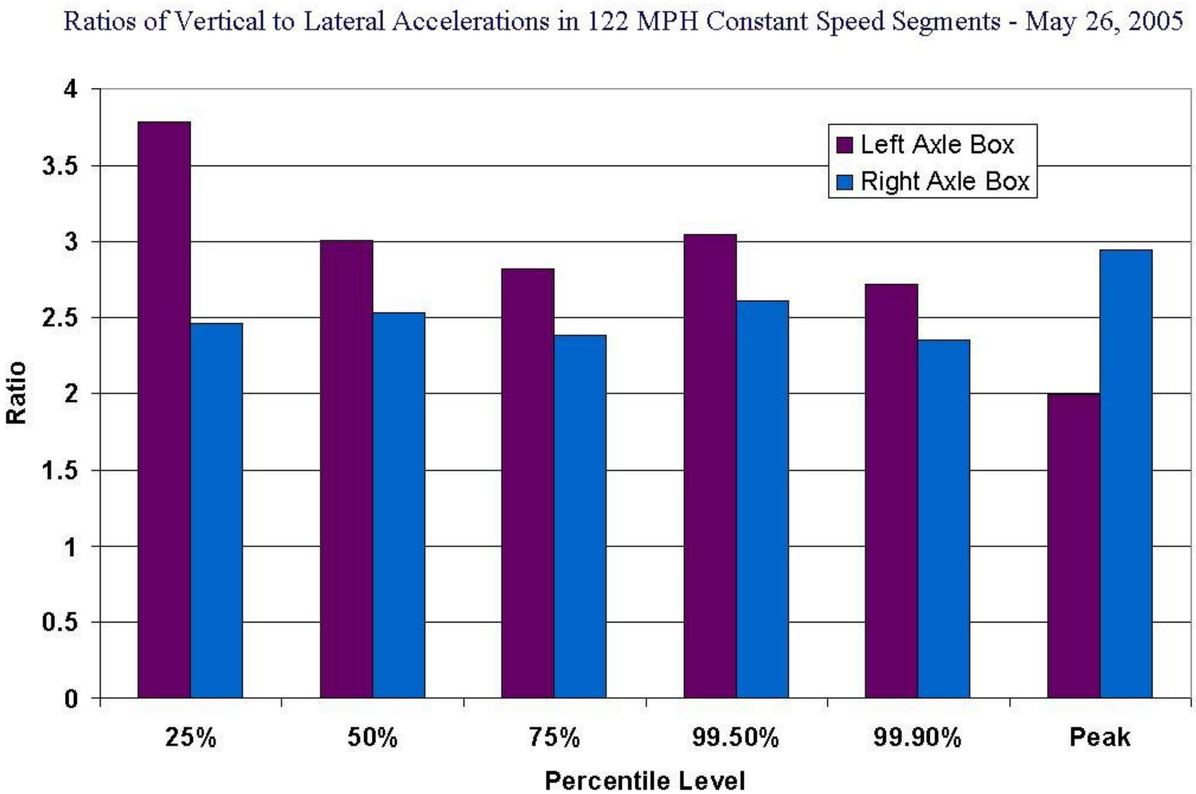


Figure 3.28. Vertical to Lateral Acceleration Ratios Determined for Data Collected in Near-Constant Speed Segments at 122 MPH–May 26, 2005

In summary, results from Phase 2 testing confirmed that the load environment associated with vertical impacts was much more severe than that associated with lateral impacts. It was established that vertical accelerations are typically between 2 and 3.7 times lateral accelerations, regardless of the level of accelerations considered.

3.2.2 Spoke Strains

One of the goals of Phase 2 testing was to collect strain measurements on the WABTEC/SAB-WABCO supplied disc mounted in the center position of the axle from the spoke opposite the one that was subject of measurements in Phase 1. This was done so that sufficient information was available to be able to specify the motion of the brake disc. Figure 3.29 illustrates the arrangement of the strain gages on the spokes of the WABTEC/SAB-WABCO supplied disc mounted in the center position of the axle.

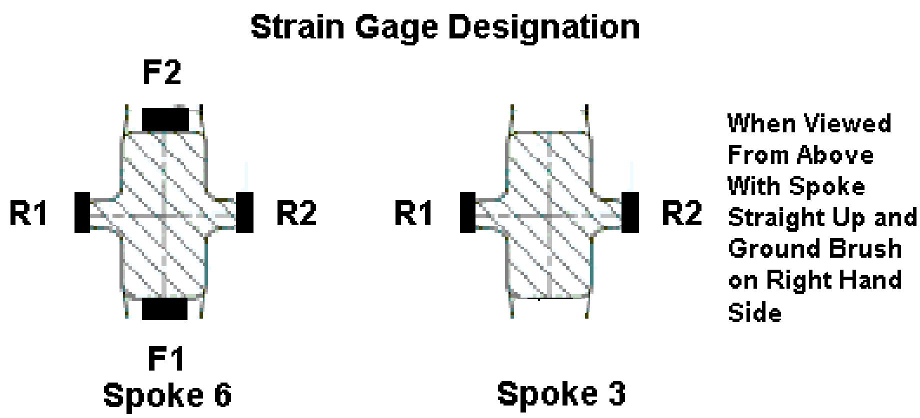


Figure 3.29. Designation of Strain Gages Used on Spoke 6 and Spoke 3 of Instrumented Center WABTEC/SAB-WABCO Supplied Disc During Phase 2 Testing

During Phase 2 testing, noise spikes were observed on the signals from the F1 and F2 strain gages on spoke 6. Caution had to be exercised when considering results that made use of these gages to ensure that the noise spikes did not adversely affect findings.

Figure 3.30 illustrates the BOP strains determined for spoke 6 and spoke 3 as a result of a vertical impact. In this particular example, a vertical shock on the left end axle box of 116.6 g was measured while the test train traveled through the Forest Interlocking near MP AB 223 at 120.4 mph during the May 26 test run (Figure 3.24 illustrates this shock). The plot in the upper portion of the figure illustrates the vertical accelerations on the test axle. Based on the behavior of the BOP strains on the opposing spokes, it is clear that an out-of-plane vibration of the brake disc is taking place.

Figure 3.31 illustrates BOP strains observed during a brake application. In this example, the disc exhibited high BOP strains during a brake application from 150 mph near MP AB 158 during the northbound test run on May 26. Based on the relationship between the BOP strains recorded on the opposite spokes during this brake application, it is clear that the disc is vibrating out of the plane of rotation, just as exhibited by the disc in response to the vertical shock illustrated in Figure 3.30.

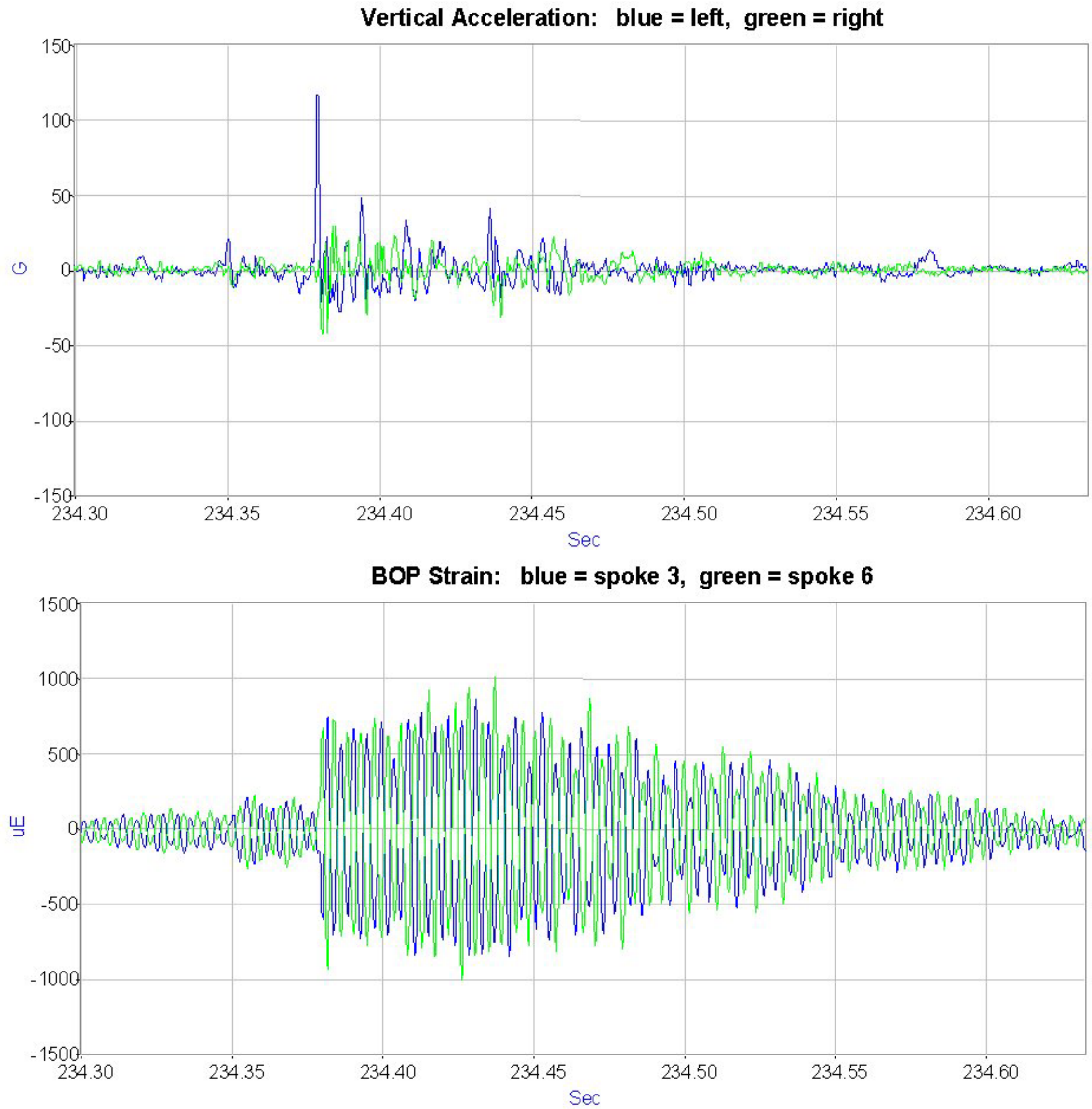


Figure 3.30. Vertical Shock and BOP Strains Recorded on Center WABTEC/SAB-WABCO Supplied Brake Disc During Phase 2 Testing (File 052605_18.AB2)–May 26, 2005

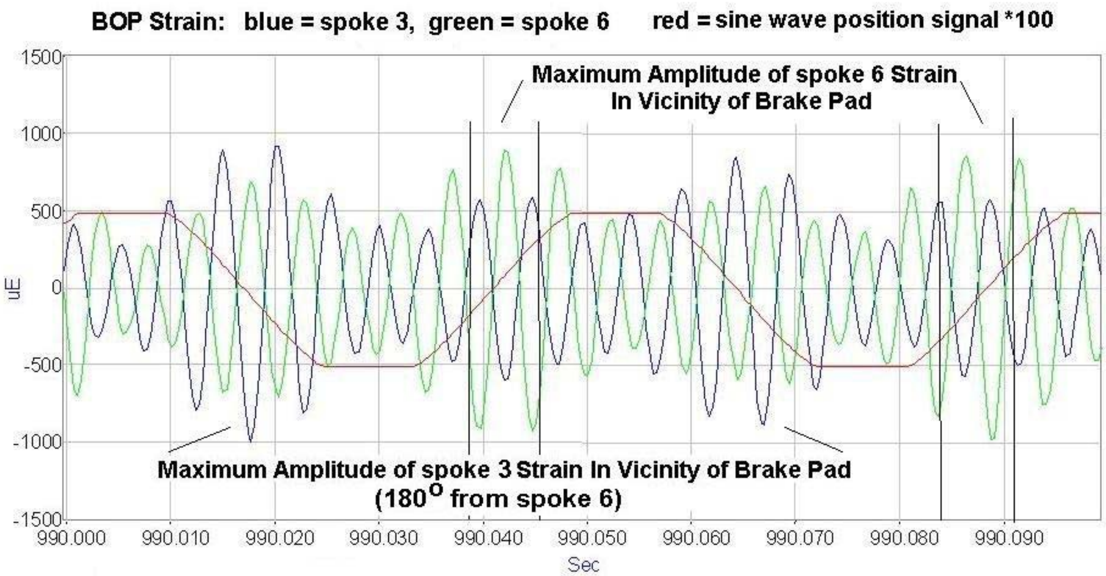


Figure 3.31. BOP Strains Recorded During Braking on Center WABTEC/SAB-WABCO Supplied Brake Disc Near MP AB 158 During Phase 2 Testing (File 052605_15.AB2)–May 26, 2005

Figure 3.31 includes the wheel position signal generated by the slip ring indicating the rotational position of the brake discs. Figure 2.22 establishes the position of the axle with respect to this sine wave. The position of the brake disc indicated that a spoke experiences the largest strains when it is in the vicinity of the brake pads. This indicates that the calipers play a role in these high oscillations during particular brake applications.

Eleven brake applications occurred during the test run conducted on May 26 that exhibited substantial BOP strains. Table 3.2 provides details associated with each of the events in which this behavior was observed. Appendix G provides additional details associated with these events. Terminology used in Table 3.2 is defined in Figure 3.13.

During the southbound test conducted on May 27 with the test axle in the trailing position, no braking events in which high, sustained BOP strains were observed. This appeared to confirm the results observed during Phase 1 testing pertaining to the correlation of the high BOP strains observed during selected braking events when the test axle was in a leading position. No strong evidence presented itself to indicate that truck dynamics played a role in this phenomenon, so attention turned to the direction of the axle's rotation and the disc's interaction with the brake hardware. This was pursued in Phase 3 testing.

Table 3.2. Summary of Measurements Collected from Center WABTEC/SAB-WABCO Supplied Brake Disc During Brake Applications Exhibiting Signs of High BOP Strain–May 26, 2005

Geographic Location	Duration (s)	Measurements from Center Disc						Brake Cyl Press (psi)	Speed at Start of Braking (mph)
		Max Avg-to-Pk Amplitude (με)	Avg Strain @ Start (με)	Avg Strain @ End (με)	Disc Temp @ Start (ºF)	Disc Temp @ End (ºF)	Peak Disc Temp (ºF)		
1429 SW of MP AN11	16	706	701	1142	107.3	134.1	161.8	40	103
15 NW of MP E13	5	483	393	503	82.6	102.9	137.6	32	64
2139 NE of MP E17	20	665	432	869	93.2	117.8	145.9	34	77
195 SW of MP MN59	4	262	353	453	77.4	90.1	140.7	30	65
642 E of MP AB84	30	793	257	1129	74.3	126.2	162.6	35	122
1108 E of MP AB89	32	784	697	1617	134.1	186.8	217.2	36	89
1240 E of MP AB116	6	540	734	873	129.2	138.9	156.9	32	79
1936 NE of MP AB158	44	972	391	1764	85.3	185.9	222.9	40	150
2230 S of MP AB179	17	796	650	1301	109.0	128.8	161.8	38	137
1939 SW of MPAB204	5	766	409	657	80.0	83.5	96.7	33	130
1732 NE of MP AB216	22	542	678	1124	87.5	145.5	187.3	36	84

Regarding the extreme strains observed during Phase 2 testing, the highest strains on the center disc resulting from a vertical impact were observed on May 27 approximately 1000' northeast of MP AB 224, near the Plains Interlocking, while traveling at 119 mph. The amplitude of the BOP strains on the center disc reached 2,258 microstrain, zero-to-peak, on spoke 6. The amplitude of the BOP strains on spoke 3 was 1,785 microstrain, zero-to-peak, at the same location. This particular case was extremely high, especially when it is considered that the vertical shock on the left end of the axle was 102 g. High BOP strains resulting from impacts during Phase 2 testing were typically on the order of 1,400 microstrain, zero-to-peak.

The highest amplitude of sustained BOP oscillations on the center disc during a brake application was observed 1936' northeast of MP AB 158 during braking from 150 mph. In this case, BOP strain oscillations reached average-to-peak amplitudes of ± 972 microstrain or peak-to-peak amplitudes of 1,944 microstrain. These oscillations were superimposed on a mean measured strain that reached 1,764 microstrain.

As stated earlier, the strains presented are as measured and have not been corrected for pre-load strains in the spoke.

Asymmetric Vertical Shocks

As shown in both Figure 3.9 and Figure 3.30, vertical shocks elicit large BOP strain amplitudes in the WABTEC/SAB-WABCO supplied brake disc that damp out within a short period of time. A common feature to the shocks illustrated in both of these figures is that the vertical shock on one end of the test axle is higher than that observed on the other end, referred to as an asymmetric shock. The vast majority of impacts observed during the test program were of this nature. Occasionally, impacts were measured on both ends of the test axle at nearly the same instant that did not elicit as large a BOP strain as some responses to asymmetric shocks. Figure 3.32 illustrates the response of the WABTEC/SAB-WABCO supplied disc to shocks of similar magnitude on both ends of the axle. In this case, vertical impacts of 88.8 g and 66.5 g were recorded on the left and right ends of the test axle, respectively, while traveling southbound at 60 mph approximately 1400' northwest of MP AB 117. A lateral shock of approximately 40 g was recorded at the same location.

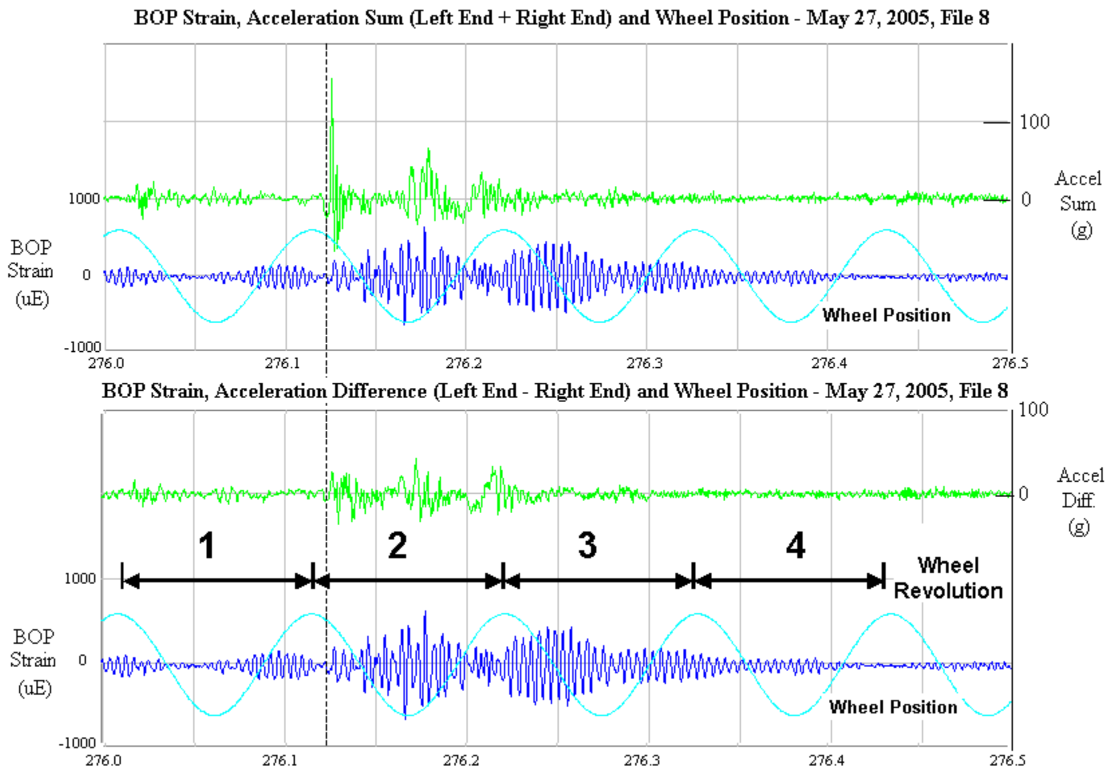


Figure 3.32. BOP Strains on WABTEC/SAB-WABCO Supplied Center Disc Resulting from Vertical Shocks on Both Ends of Test Axle (File 052705_08.AB2)–May 27, 2005

The BOP strain response of the brake disc is illustrated in two separate plots, one showing the sum of the accelerations recorded at both ends of the axle and one showing the difference in accelerations recorded at both ends of the axle. One can observe that the maximum sum of the accelerations, indicated by the dashed line at the beginning of the second wheel revolution, reaches a value near 150 g but elicits little BOP strain response. The BOP strain response increases during the middle stage of the second wheel revolution and the third wheel revolution, which correlates well with the increase in the difference in the axle accelerations.

An important aspect of the response of the WABTEC/SAB-WABCO supplied brake disc to vertical impacts is the orientation of the brake disc and, in particular, the position of the spoke from which strains are being collected. Review of the test data indicated that, for a given level of the difference in accelerations on both ends of the test axle (originating at either end), a variation in the amplitude of the BOP strain resulting from the impact was observed. An analysis was conducted on accelerations recorded on the May 26 test run to arrive at an explanation for this observation.

For the analysis of asymmetric shocks, impacts were selected and the BOP strain measured on spoke 6 was plotted against the arithmetic difference in accelerations measured on the ends of the test axle. Only

21 cases in which the acceleration difference was greater than 100 g were initially considered and only those cases with a single peak acceleration difference were analyzed, resulting in 17 examples included in this brief analysis. Figure 3.33 illustrates the results of this consideration. Any meaningful correlation does not appear to exist, as indicated by the low correlation factor.

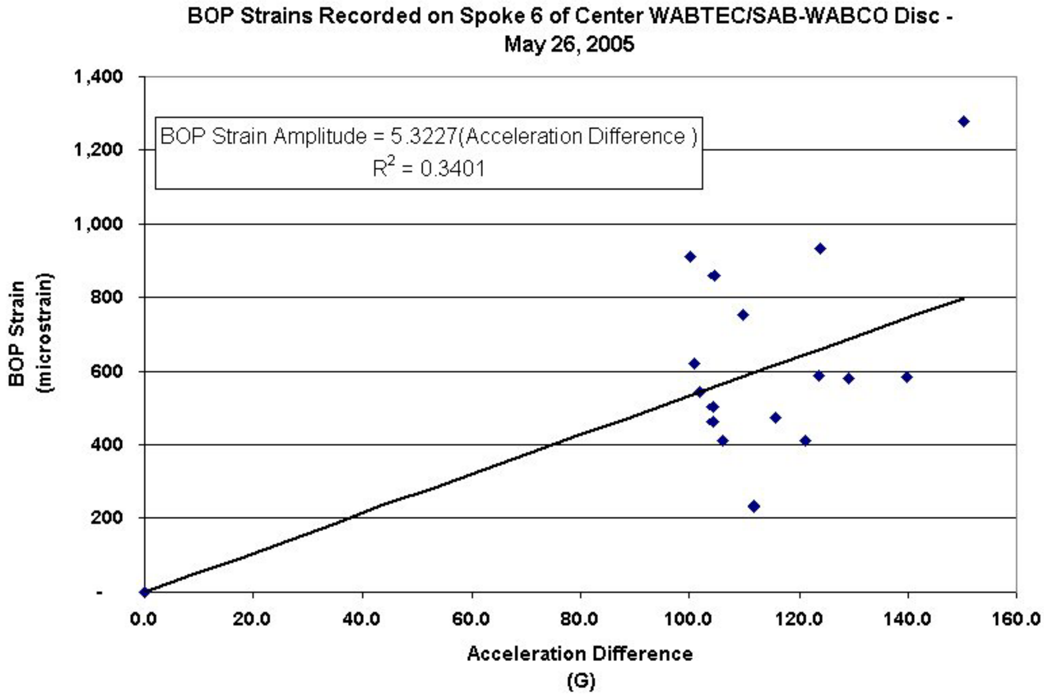


Figure 3.33. BOP Strains as a Function of Acceleration Differences Measured on May 26, 2005

If the BOP strain on spoke 6 is plotted against the product of the acceleration difference and the trigonometric sine of the angular position of the spoke (as defined in Figure 2.22), however, a better correlation is realized. Figure 3.34 illustrates the results of this consideration. A correlation between the amplitude of acceleration differences and the amplitude of the response in terms of BOP strain emerges. Although the results illustrated in Figure 3.34 are based on a limited sample size, the relationship between the difference in loads measured at either end of the test axle and the BOP strains is important to the behavior of the brake disc.

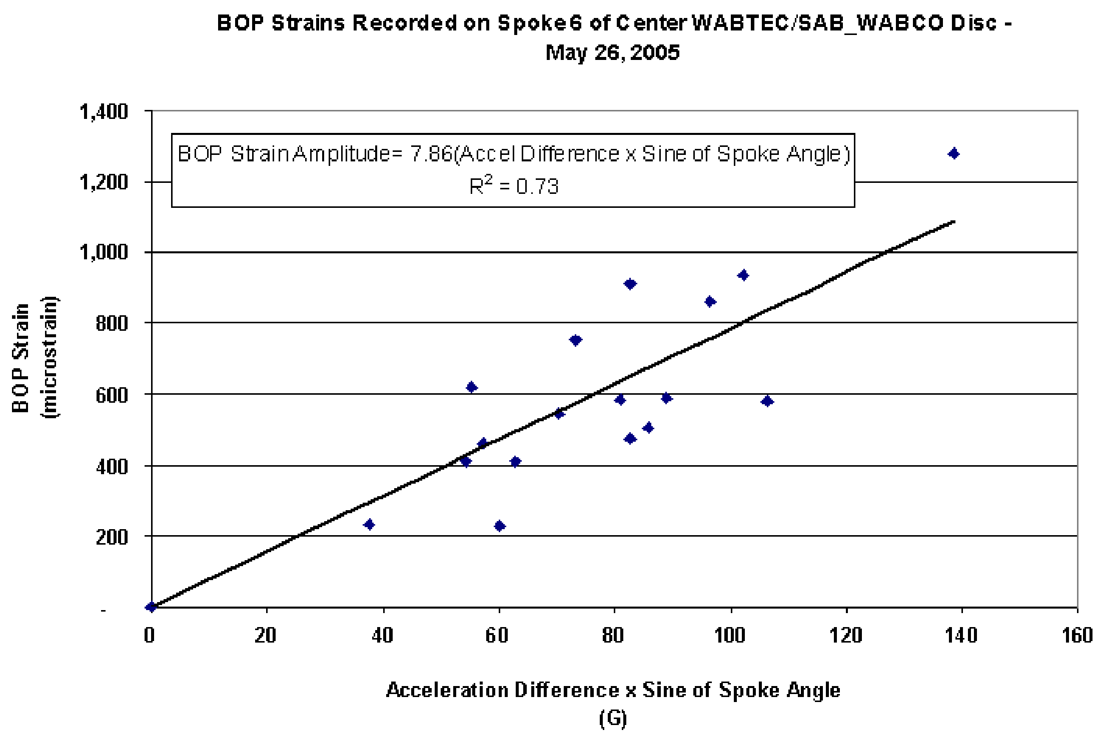


Figure 3.34. Correlation of BOP Strain Amplitudes and Acceleration Differences Based on Measurements Collected on May 26, 2005

In the development of Figures 3.33 and 3.34, it was pointed out that only those cases with a single peak acceleration difference were analyzed. This was an important criterion to keep in mind. Many different loading conditions were observed in which the amplitude of the BOP strains did not vary linearly with the accelerations measured on the ends of the axle. As presented here, the angular position of the instrumented spoke is important but so is the acceleration time history associated with the peak accelerations. It can be shown that several peak accelerations experienced in rapid succession can actually diminish the peak BOP strains observed on the spokes. Appendix G treats this subject in more detail.

The observation that the BOP strain correlates with the difference in accelerations measured at the ends of the axle suggests that it is a “rotation of the axle in a vertical plane” of the axle that has the greatest effect on the disc.

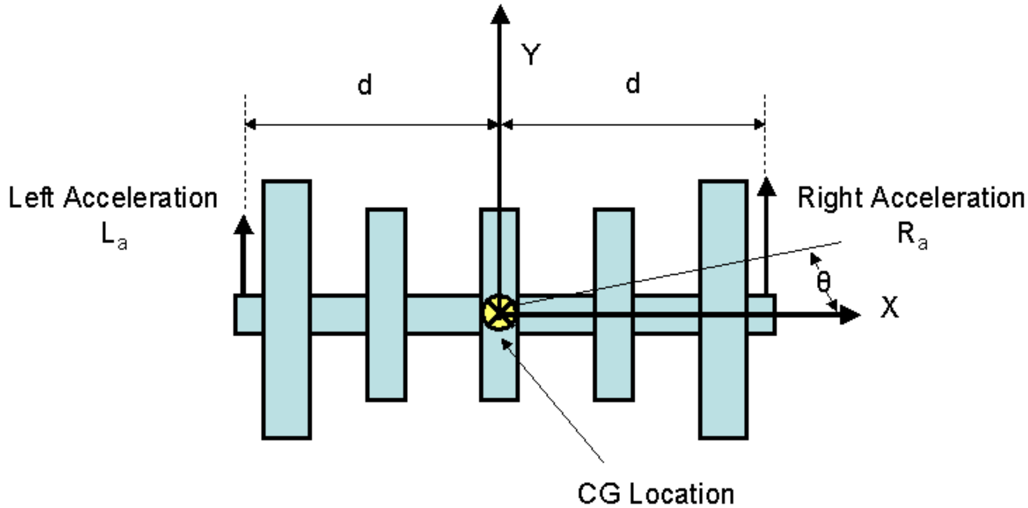


Figure 3.35. Definition of Wheelset Acceleration Terminology

Figure 3.35 illustrates an idealized wheelset. If one assumes that the wheelset/brake disc assembly is rigid and is limited to two degrees of freedom, vertical translation and rotation, then the accelerations measured on the ends of the axle can be used to specify the acceleration of any point on the rigid body through the following relationships:

$$A(\mathrm{X}) = \text{Acceleration at a point along axle}$$
$$A(\mathrm{X}) = A(0) + \ddot{\theta}\mathrm{X}$$
$$A(0) = \text{Translational Acceleration at CG}$$
$$A(0) = (\mathrm{L_a} + \mathrm{R_a})/2$$
$$\ddot{\theta} = \text{Rotational Acceleration}$$
$$\ddot{\theta} = (\mathrm{L_a} - \mathrm{R_a})/2$$

Using this formulation, it can be seen that the acceleration difference reflected in Figures 3.33 and 3.34 is indicative of the rotational acceleration of the axle, which is constant over the length of the axle. The actual measured acceleration will depend on the location of the sensor along the axle. This leads to the conclusion that all three brake discs on the axle will respond in a similar fashion to a given difference in accelerations observed at each end of the axle. This is supported by some of the observations regarding relative responses of the inner and outer brake discs presented in Section 3.1.3.

Several key findings regarding strains in the WABTEC/SAB-WABCO supplied brake discs resulted from Phase 2 testing:

- The vibration of the WABTEC/SAB-WABCO supplied brake disc during responses to vertical shocks, as well as during some brake applications, was a BOP oscillation in which the motion of the spokes on one side of the disc was out-of-phase with the motion of the spoke on the opposite side of the disc.

- When experiencing sustained oscillations during braking, the maximum BOP strains were observed to occur while the particular spoke was in the vicinity of the brake pad, indicating that the calipers play a role in these oscillations.
- It was confirmed that high BOP strain oscillations observed during braking only occurred when the test axle was in the leading position of the test vehicle. Consideration of the interaction of the rotating brake disc with the brake mounting hardware was discussed as a possible explanation for this behavior.
- Analysis of the data recorded during Phase 2 testing showed that the WABTEC/SAB-WABCO supplied disc's response to asymmetric vertical impacts was more severe than that resulting from impacts of similar magnitude being inflicted upon the ends of the axle. The amplitude of the BOP strains resulting from asymmetric vertical shocks correlate well with the tilt acceleration, reflective of the difference between the two impacts, when it is corrected for the angular position of the instrumented spoke.

3.2.3 Axle Strains

As discussed in Section 2.3.1, several axle-mounted strain gages were employed during Phase 2 testing to investigate the behavior of the axle. Two gages were placed 180º apart as close to the center disc as possible, and two additional gages were placed 180º apart at a location approximately ¼ of the distance between the two wheels adjacent to the S brake disc (the non-instrumented brake disc). Appendix H examines axle strains collected throughout the test program. This section will examine the basic characteristics of these signals and observations made during Phase 2 testing.

Figure 3.36 illustrates a wheelset, without disc brakes, under equilibrium conditions. The axle strain data is dominated by a bending moment produced by the vehicle's weight applied at the bearings and the vertical rail forces applied at the wheel rail interface.

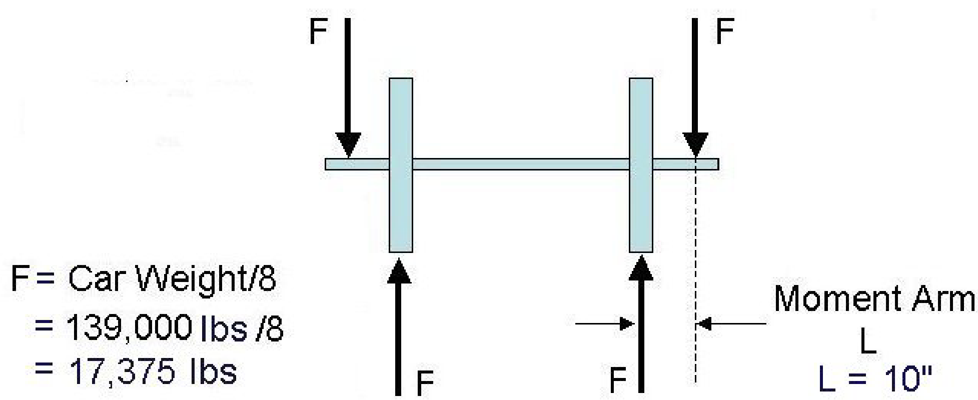


Figure 3.36. Bending Moments in Generic Wheelset

Figure 3.37 shows the calculated bending strain for a range of applied forces and moment arms between the midpoint of the bearing and the wheel/rail contact point. The published weight for the Acela coach is 139,000 pounds. Based on the drawing for the Acela wheelset, the distance between the midpoint of the bearing and the wheel/rail contact point is approximately 10 inches. Based on these values, the predicted axle bending strains are approximately 200 microstrain.

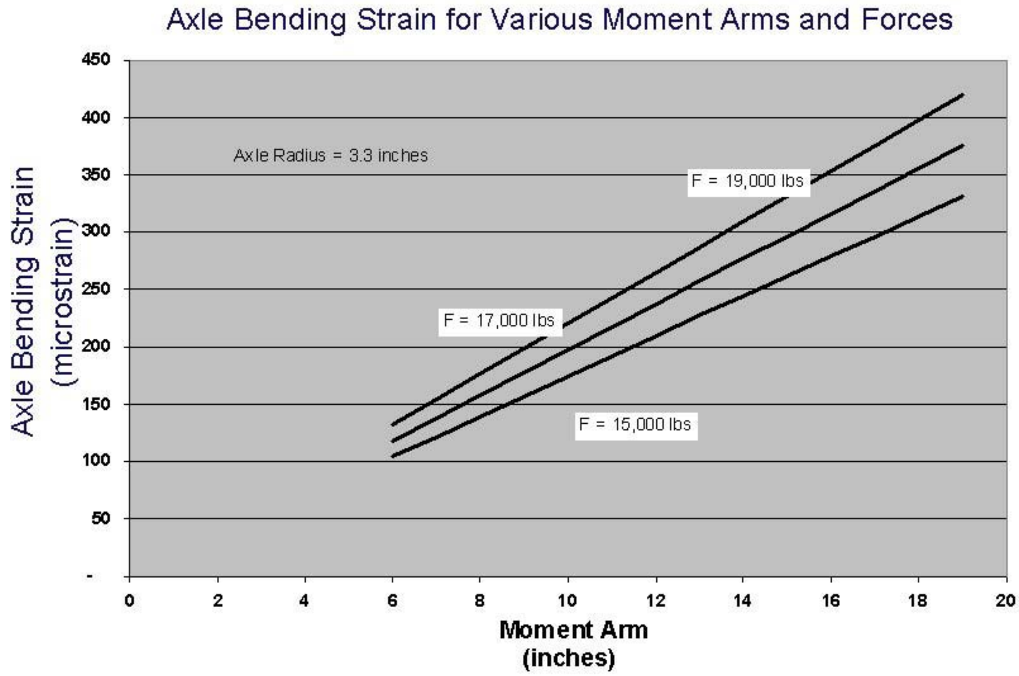


Figure 3.37. Axle Bending Strain as a Function of Bearing Force and Moment Arm

Figure 3.38 shows the output from a pair of axle-mounted strain gages as the test vehicle was moving over tangent track near MP AB 221 at 115 mph on May 26. The output from the strain gages have had the offset, or average reading, removed for presentation purposes. The output from the slip ring resolver is also plotted in this figure to illustrate the rotational rate of the axle.

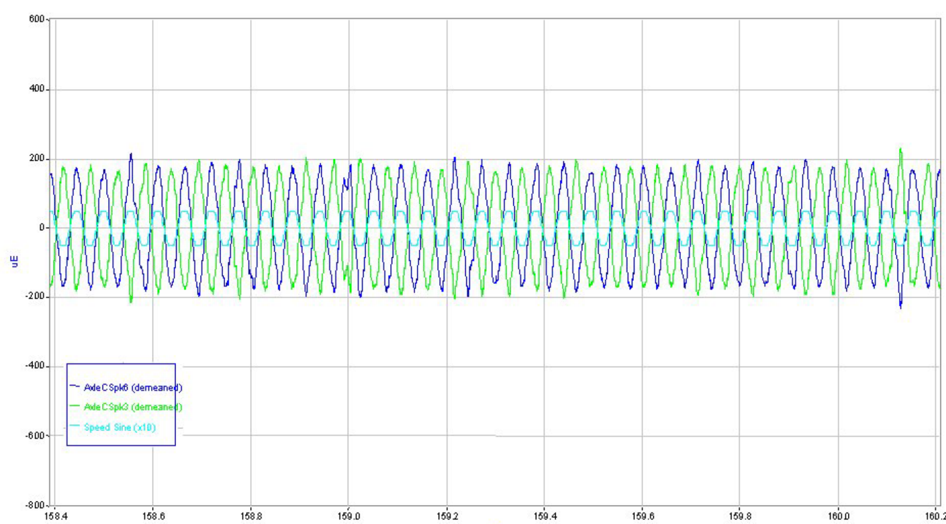
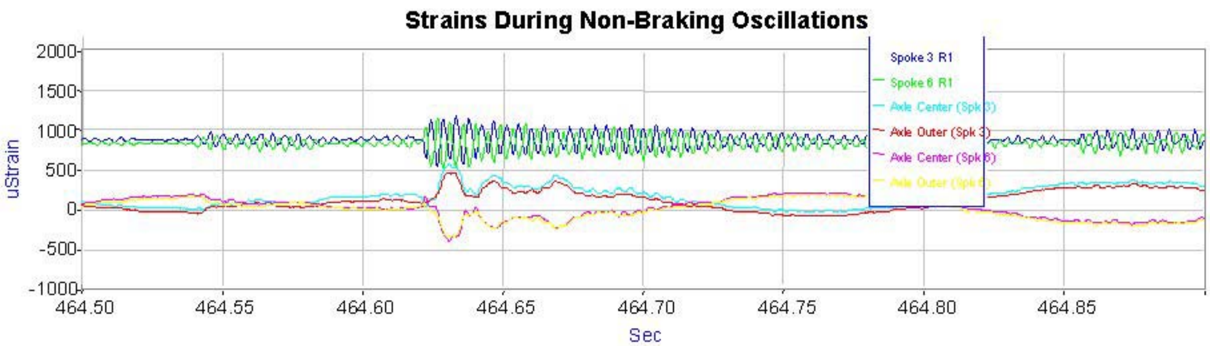


Figure 3.38. Typical Axle Bending Strains Recorded Over Tangent Track (File 052605_18.AB2)–May 26, 2005

The behavior of the axle strains depended on many factors. The amplitude of the strains increased in proportion to the lateral accelerations exerted on the axle as a result of navigating through a curve. As the axle rotates, this bending moment is modulated by the wheel rotation rate. Figure 3.39 illustrates the axle strains and spoke strains recorded during a case of sustained oscillations during a brake application from 120 mph near MP AB 225.5 AB. In this particular case, the amplitude of the BOP oscillations is not considered to be high, and this case has not been identified as a case with high BOP strains, but it does serve to illustrate the behavior of the axle strain gages. The effects of the higher frequency content associated with the BOP strains on the brake disc are evident in the axle bending strains.

Figure 3.39. Axle Bending Strains Recorded During Case of Small Oscillating BOP Strains During Brake Application (File 052605_18.AB2)–May 26, 2005

Figure 3.40 illustrates the strains recorded during a response to a vertical impact of 55.5 g experienced on the left end of the axle while traveling near the Route 128 Station at 30 mph on May 26. The effects of the impact can be seen on the axle. This illustration appears to indicate that the WABTEC/SAB-WABCO supplied brake disc responds to the impact and that the axle subsequently reacts to the motion of the disc.



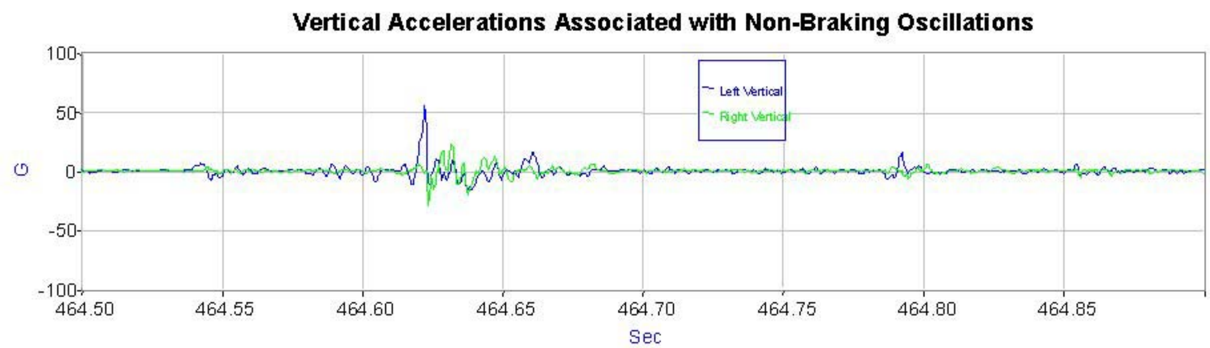


Figure 3.40. Axle Bending Strains Recorded During Response of WABTEC/SAB-WABCO Supplied Brake Disc to Vertical Impact (File 052605_18.AB2)–May 26, 2005

The frequency associated with the axle bending strain measurements are important, yet they are difficult to arrive at because, when the individual strain gages are at or near the neutral axis of the axle at particular times in the rotation cycle, the gages will see little bending and therefore very small strains. The frequency content of the axle strains will be considered in more detail during the discussion of Phase 3 testing.

3.2.4 Temperatures

The maximum temperature measured on the back of the friction ring of the WABTEC/SAB-WABCO supplied brake disc located in the center of the test axle was 336 °F. This was measured following a series of brake applications made from high speeds between Providence, RI, and MP AB 160 on May 27 (File 052705_05.AB2).

As done with temperature measurements collected from the back of the center disc's friction ring during Phase 1 testing, friction ring temperatures were used to estimate the state of thermal stress in the spokes of the disc. Based on the analysis method described in Section 3.1.5, estimates of the thermal strains in the spoke were derived from data collected during testing on May 26 and 27. Figures 3.41 and 3.42 provide the results of this analysis with additional details in Appendix I. Results provided in these figures are similar to those determined during Phase 1 testing. These estimated thermal strains would not account for any existing pre-load strains in the spoke.

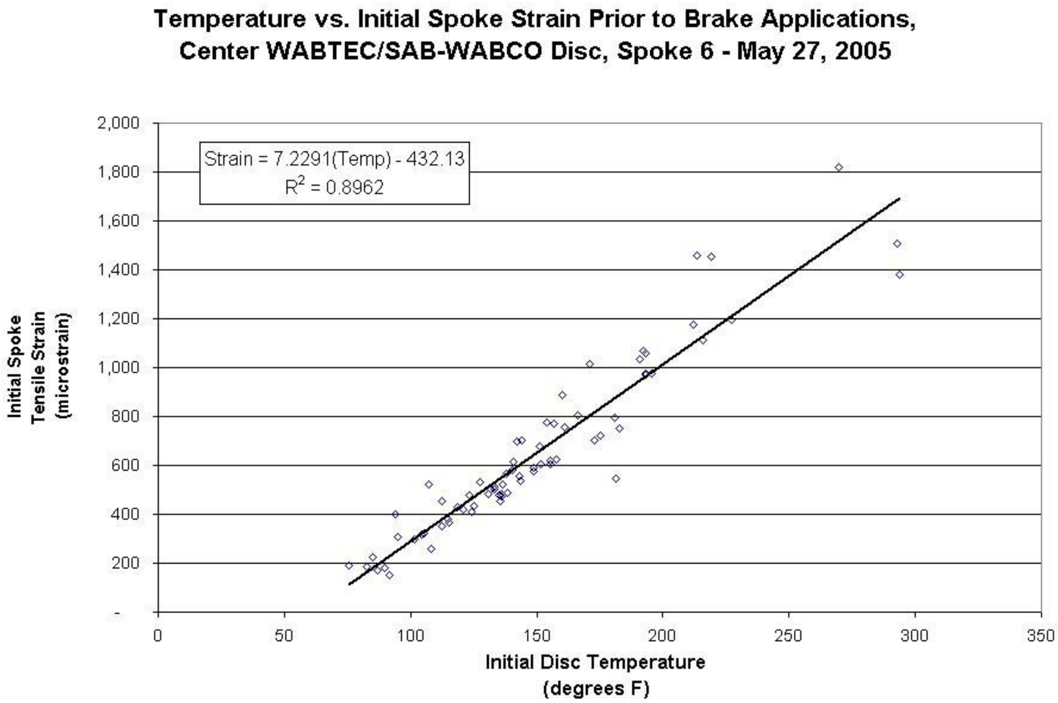


Figure 3.41. Brake Disc Temperature versus Initial Spoke Tensile Strain Before Brake Applications, Center WABTEC/SAB-WABCO Supplied Disc, Spoke 6–May 26, 2005

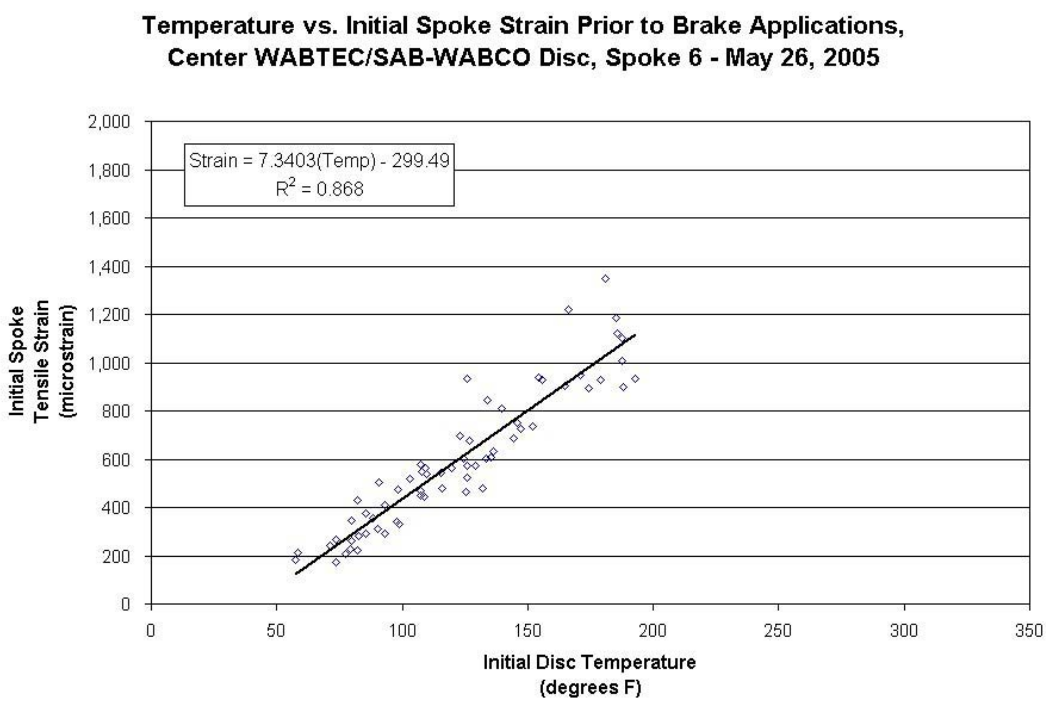


Figure 3.42. Brake Disc Temperature versus Initial Spoke Tensile Strain Before Brake Applications, Center WABTEC/SAB-WABCO Supplied Disc, Spoke 6–May 27, 2005

3.2.5 Brake Pressures

The only brake pressure that was analyzed during Phase 2 testing was the brake cylinder. Results pertaining to brake cylinder pressures in Phase 2 were similar to those from Phase 1 testing–namely that the amplitude of the strain oscillations in episodes of sustained oscillations during braking increases with increasing brake pressure. Because this was demonstrated so clearly in Section 3.1.6, no additional results will be presented here.

3.2.6 Sound Level Measurements

As discussed in Section 2.3.8, sound levels under the test vehicle were recorded in order to attempt to capture and analyze two different noises. The first noise was the high frequency noise, or squeal, heard during times in which signs of saturation existed on the axle-mounted accelerometer. The second noise was the moaning noise heard above many of the axles of the test train during braking.

Figure 3.43 illustrates the frequency analysis of sound measurements collected while the center WABTEC/SAB-WABCO supplied brake disc was exhibiting high BOP strains during a brake application from 137 mph near MP AB179 on May 26. In this analysis, the sound level expressed in decibels (dB) is plotted as a function of the frequency associated the particular component of the sound.

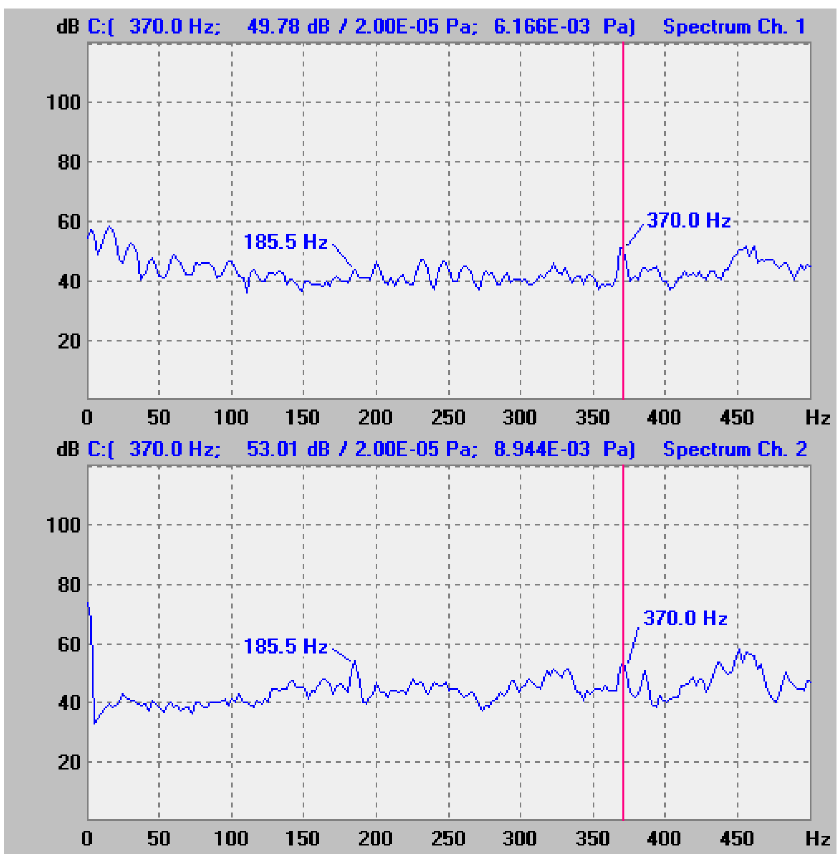


Figure 3.43. Analysis of Sound Recorded During Sustained Oscillations While Braking Near MP AB 179–May 26, 2005

Within this recording, the sound on Channel 1 (the upper graph) and Channel 2 (the lower graph) has its strongest component of sound at a frequency of approximately 450 Hz. On both channels, a component of sound with a frequency of 370 Hz can be observed. In the sound recorded on Channel 2, evidence of contribution from a component with a frequency of 185.5 Hz exists. The 185.5 Hz frequency is close to the frequency associated with the sustained oscillations during braking observed in the strains.

Analysis of sound recordings made when a high-pitched squeal was heard while navigating through curves did not reveal any one particular component of sound that could lend insight into the saturation of the axle mounted sensors. Aside from the observations cited above, no other useful information resulted from the noise testing conducted during Phase 2 testing.

3.2.7 Concluding Comments

Several items were learned from the results of Phase 2 testing, including the following:

- The load environment associated with vertical impacts was confirmed to be more severe than that associated with lateral impacts. It was established that vertical accelerations are typically between 2 and 3.7 times lateral accelerations, regardless of the level of accelerations considered.

  There were 276 vertical shocks above 50 g measured on the WABTEC/SAB-WABCO test axle during the northbound test conducted on May 26, 16 of which were above 100 g. During the southbound test conducted on May 27, 238 vertical shocks above 50 g were measured, 15 of which were over 100 g. The highest vertical acceleration observed in Phase 2 testing was 156 g, measured on the left end of the axle on May 26 near Union Interlocking near MP AN 20 while the test train was traveling at 113 mph.

  There were 44 lateral shocks above 30 g measured on the WABTEC/SAB-WABCO test axle during the northbound test conducted on May 26. Thirty-three lateral shocks above 30 g were measured on the WABTEC/SAB-WABCO test axle during the southbound test conducted on May 27. The highest lateral acceleration observed during Phase 2 testing was a 75.3 g shock, measured on May 26 at the Union Interlocking near MP AN 20 while the test train was traveling at a speed near 112 mph.

- The vibration of the WABTEC/SAB-WABCO supplied brake disc during responses to vertical shocks, as well as during some brake applications, was confirmed to be a BOP oscillation in which the motion of spokes on one side of the disc were out-of-phase with the motion of spokes on the opposite side of the disc.

  When experiencing sustained oscillations during braking, the maximum BOP strains were observed to occur while the particular spoke was in the vicinity of the brake pad, indicating that the calipers play a role in these oscillations.

  It was confirmed that high BOP strain oscillations observed during braking only occurred when the test axle was in the leading position of the test vehicle.

  The WABTEC/SAB-WABCO supplied disc's response to asymmetric vertical impacts was more severe than that resulting from impacts of similar magnitude being inflicted upon both ends of the axle at the same time. The amplitude of the BOP strains resulting from asymmetric vertical shocks correlate well with a measure of these asymmetric loads when the angular position of the wheel is accounted for.

  The highest strains on the center disc resulting from a vertical impact reached 2,258 microstrain, zero-to-peak, on spoke 6; the amplitude of the BOP strains on spoke 3 was 1,785 microstrain, zero-to-peak, at the same location. These values were extremely high. High BOP strains resulting from impacts during Phase 2 testing were typically on the order of 1,400 microstrain, zero-to-peak.

The highest amplitude of sustained BOP oscillations on the center disc during a brake application reached average-to-peak amplitudes of ± 972 microstrain, or peak-to-peak amplitudes of 1,944 microstrain. These oscillations were superimposed on a mean strain that reached 1,764 microstrain.

Specified strains are as measured and have not been corrected for pre-load strains in the spoke.

- Strains recorded on the axle during Phase 2 testing exhibited the effects of the oscillatory motion of the center brake disc resulting from vertical impacts and selected brake applications.
- The maximum temperature measured on the back of the friction ring of the WABTEC/SAB-WABCO supplied brake disc located in the center of the test axle was 336 °F. This was measured following a series of brake applications made from high speeds between Providence, RI, and MP AB 160 on May 27.

Several issues associated with instrumentation were identified, including the following:

- Noise spikes were observed on the signals from the F1 and F2 strain gages on spoke 6.
- New accelerometers mounted to the axle to improve the collection of lateral accelerations did not prove effective. The signals resulting from these sensors were not used in the development of results presented in this document.

Following Phase 2 testing, it was decided that a sufficient amount of information pertaining to the strains measured on the WABTEC/SAB-WABCO supplied disc during over-the-road testing had been collected, and no need existed to continue testing the WABTEC/SAB-WABCO supplied brake disc in this manner any longer. Preparations commenced for a third phase of the test program in which the response of the WABTEC/SAB-WABCO supplied brake disc to over-the-road testing would be compared that of a brake disc of alternative design provided by Knorr. In addition to capturing the behavior of the different brake discs, several other goals for Phase 3 testing existed, including the following:

- The determination of the exact value of the natural frequencies of both the WABTEC/SAB-WABCO supplied brake disc and the Knorr brake disc.
- The determination of the stress levels in the spokes of the brake disc before being exposed to service loads.
- The role of the brake mounting hardware, including the brake mounting tube and caliper links/hangers, in the behavior of the brake discs observed to date.

3.3 Phase 3 Test Results

In Phase 3, axle 4 of Car 3534 (adjacent to Car 3413) was removed from the test trainset, and the existing WABTEC/SAB-WABCO supplied brake discs were removed and replaced with discs provided by Knorr. The newly outfitted axle and center Knorr brake disc were instrumented as specified in Figure 2.8b. Modal testing was conducted on the Knorr test axle, to be described in Section 3.3.2, and the axle was installed under Coach 3534. Figure 3.44 shows the locations of the strain gages on the spoke of the Knorr brake disc, recommended by Knorr. For the sake of comparison, Figure 3.45 illustrates the locations of the strain gages on the spokes of the WABTEC/SAB-WABCO supplied disc.

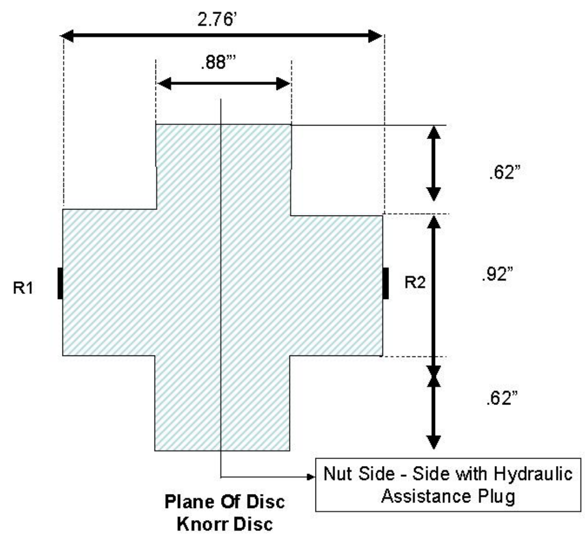


Figure 3.44. Strain Gage Location and Cross Section Associated with Spoke of Knorr Brake Disc

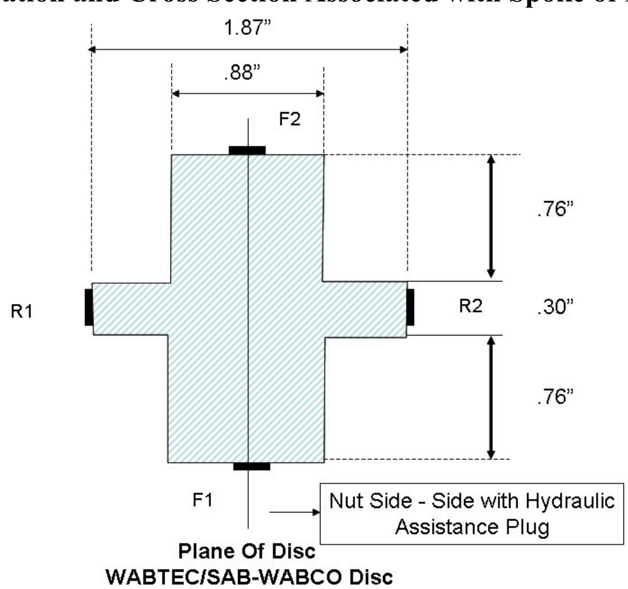


Figure 3.45. Strain Gage Location and Cross Section Associated with Spoke of WABTEC/SAB-WABCO Supplied Brake Disc

Following a shakedown run conducted between Washington, DC, and New York, NY, a final series of tests was run during which direct comparisons were made between the Knorr disc and the WABTEC/SAB-WABCO supplied disc during a round trip between Washington and Boston. Data was collected in a manner that would allow decisions to be made about the potential for success of the Knorr brake disc design in revenue service.

In addition to the over-the-road tests, laboratory tests were performed to investigate the natural frequencies of the WABTEC/SAB-WABCO supplied and Knorr brake discs, as well as the stress levels existing within the spokes of each type of disc before exposure to loads encountered during regular service.

3.3.1 Determination of Pre-Stresses Within Spokes

To prepare for Phase 3 of the test program, one wheelset equipped with WABTEC/SAB-WABCO supplied discs was removed from the test trainset and shipped to the ORX assembly plant in Tipton, PA, for disassembly and re-fit with the Knorr discs. During this changeover process, Mr. Mike Tomas of Amtrak installed strain gages on either side of each spoke of the WABTEC/SAB-WABCO supplied center disc at locations shown in Figure 3.45 before it was pressed off and measured the resultant strain when the disc was removed. The WABTEC/SAB-WABCO supplied disc was reported to have close to 2,000 miles of service life at the time of removal, and no cracked spokes were reported. For this single test specimen, an average resultant compressive strain of 390 microstrain in each spoke was attributed to the pressing operation. Because only one disc was considered in this exercise, it is not clear from the results of this particular study if these stresses are typical for discs with this level of service life. Part B of Appendix J provides the details of this test.

Amtrak also installed strain gages on either side of each spoke on the Knorr brake disc designated for the center of the axle before its installation on the axle; the location of the gages were the same as those shown in Figure 3.44. The spoke strains on the Knorr brake disc were measured prior to and following the pressing of the disc on to the axle. The installation of the Knorr disc results in an average compressive strain of 533 microstrain on the spokes. Part B of Appendix J also provides the details of this investigation.

A test was conducted by Amtrak in which the strain-gaged spokes of the WABTEC/SAB-WABCO supplied brake disc removed from the center position of the axle were cut to relieve any remaining stress in the spokes. Strain measurements were collected prior to and following the cutting of the spokes. Results from this test indicated that an average compressive resultant strain of 600 microstrain in the spokes was present. Part B of Appendix J also provides details of this investigation. This test was not conducted on a brake disc of Knorr design.

Details of the investigation conducted by Amtrak of spoke strain levels present in a WABTEC/SAB-WABCO supplied disc with two cracked spokes are provided in Part B of Appendix J. Measurements indicated that the unbroken spokes of a brake disc with some broken spokes were under more stress than spokes on a brake disc with no broken spokes.

In conclusion, results from this single-sample test indicate that a pre-stress equivalent of approximately 1,000 microstrain may be present as a residual strain in each spoke of a WABTEC/SAB-WABCO supplied brake disc. Appendix M discusses the sources of these existing stresses.

3.3.2 Mode Test Performed on WABTEC/SAB-WABCO Supplied and Knorr Brake Discs

Before the commencement of over-the-road testing in Phase 3, a series of vibration tests was performed to identify fundamental natural frequencies of the Knorr brake disc mounted on the test axle and on a WABTEC/SAB-WABCO supplied brake disc on a typical axle. The WABTEC/SAB-WABCO supplied disc tested in this investigation was not used in the earlier phases of the test program. As described in Section 2.4.3, a force input was provided to each of the discs by striking them with a dead blow hammer, and the response of the discs was measured using accelerometers mounted at various locations around the discs. Each of the discs tested in this investigation were installed on axles that had been removed from under the coach cars.

Table 3.3 lists identifiable modes of vibration of the WABTEC/SAB-WABCO supplied disc over a frequency range up to 1,200 Hz.

Table 3.3. Vibration Frequencies Identified During Impact Tests Conducted on WABTEC/SAB-WABCO Supplied Brake Disc

Frequency (Hz)	Type of Vibration
220	Out-of-Phase
320	In-Phase
360	In-Phase
675	In-Phase
815	In-Phase
905	Out-of-Phase
990	In-Phase

The lowest identifiable frequency for the WABTEC/SAB-WABCO supplied disc was an out-of-phase mode corresponding to BOP mode. The frequency associated with this motion was measured as 220 Hz. This frequency is very close to 206 Hz, the frequency calculated in the FEA conducted at the early stage of the investigation using an idealized model of the WABTEC/SAB-WABCO supplied disc.

Table 3.4 lists frequencies determined for the Knorr disc over a frequency range up to 1,200 Hz. The lowest identifiable frequency for the Knorr disc was an in-phase mode at approximately 420 Hz. No out-of-phase mode could be identified for the Knorr disc. ENSCO did not perform any FEA to determine frequencies of interest in the Knorr disc.

Table 3.4. Vibration Frequencies Identified During Impact Tests Conducted on Knorr Brake Disc

Frequency (Hz)	Type of Vibration
420	In-Phase
675	In-Phase
825	In-Phase
1,020	In-Phase

After completion of the Phase 3 over-the-road testing, a second vibration test using a slightly different approach to the one used in the beginning of Phase 3 was conducted on the Knorr disc to investigate frequencies observed in the test data. For this second vibration test, Instrumented Axle 2 still installed under Coach Car 3534 was used. Excitation was provided to the disc, and the response of the strain gages on spokes 3 and 6 were recorded and analyzed to obtain the frequency at which the spokes would vibrate. Excitation was provided by three hammer blows applied successively at approximately 5-second intervals to the friction ring at the spoke 3 location, with spoke 6 at the position within the brake pads and caliper. The brakes were disengaged throughout the test. Part C of Appendix J provides the details of the analysis of the resulting spoke strains.

Table 3.5 lists results from this test for the Knorr disc over a frequency range up to 1,200 Hz. The lowest identifiable frequency identified in the spoke strain measurements for the Knorr disc was at 351 Hz. By comparing the strain measured simultaneously in spoke 3 with that in spoke 6, the vibration at this frequency corresponded to an out-of-phase mode, suggesting BOP.

Table 3.5. Natural Frequencies Identified by Hammer/Strain Measurement Test for the Knorr Brake Disc

Frequency (Hz)	Phase Between Spoke 3/6
351	Out-of-Phase
460	In-Phase
680	In-Phase

Results from over-the-road testing conducted in Phase 3 will now be presented. This section will focus on the results determined from data collected during the round trip between Washington and Boston. The only data collected during the shakedown run conducted between Washington and New York on June 16 that will be presented will be some temperature measurements that represent the highest temperatures reached during the program and some basic strain data collected from some of the brake mounting hardware.

3.3.3 Axle Accelerations

Figure 3.46a illustrates the distribution of vertical accelerations above 50 g recorded on both the WABTEC/SAB-WABCO and Knorr test axles from Washington to Boston on June 17 with the test axles in a leading position. Figure 3.46b illustrates the corresponding information for the data collected between Boston and Washington on June 18, again with the test axles in a leading position. On these two test days, the accelerometers on the test axles exhibited effects from noise spikes and saturation from time to time, resulting in measurements that appeared similar to the data illustrated in Figure 3.3. Accelerations above 50 g were reviewed to ensure that any acceleration affected by the noise-related or saturation issues was disregarded. Appendix F tabulates the data illustrated in Figure 3.46.

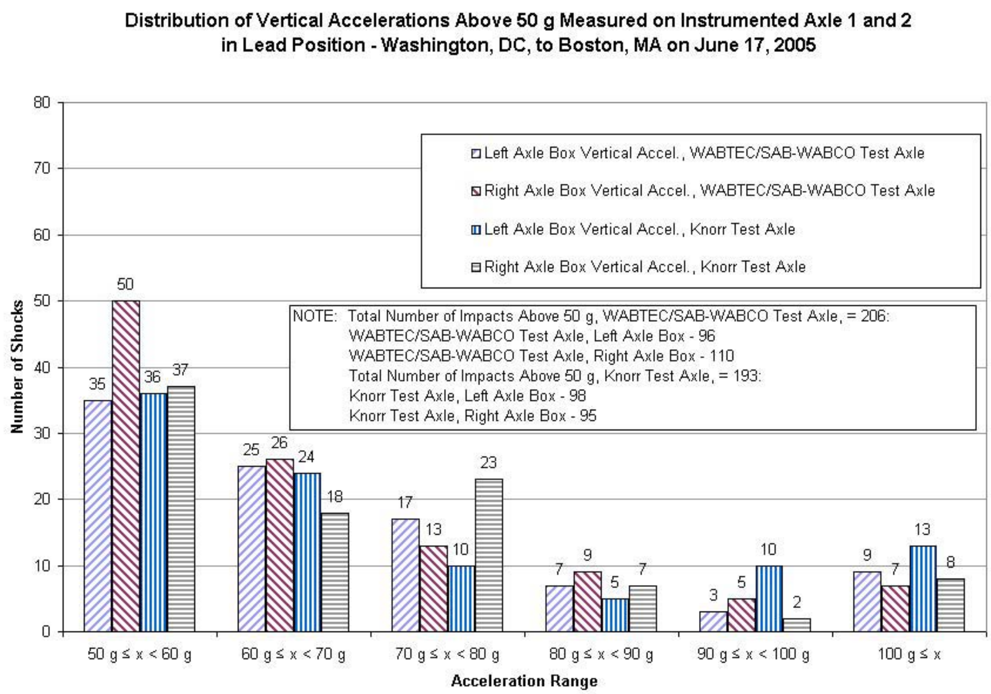


Figure 3.46a. Distribution of Vertical Accelerations Above 50 g Measured on Instrumented Axles 1 and 2 in Lead Position–Washington, DC, to Boston, MA, on June 17, 2005

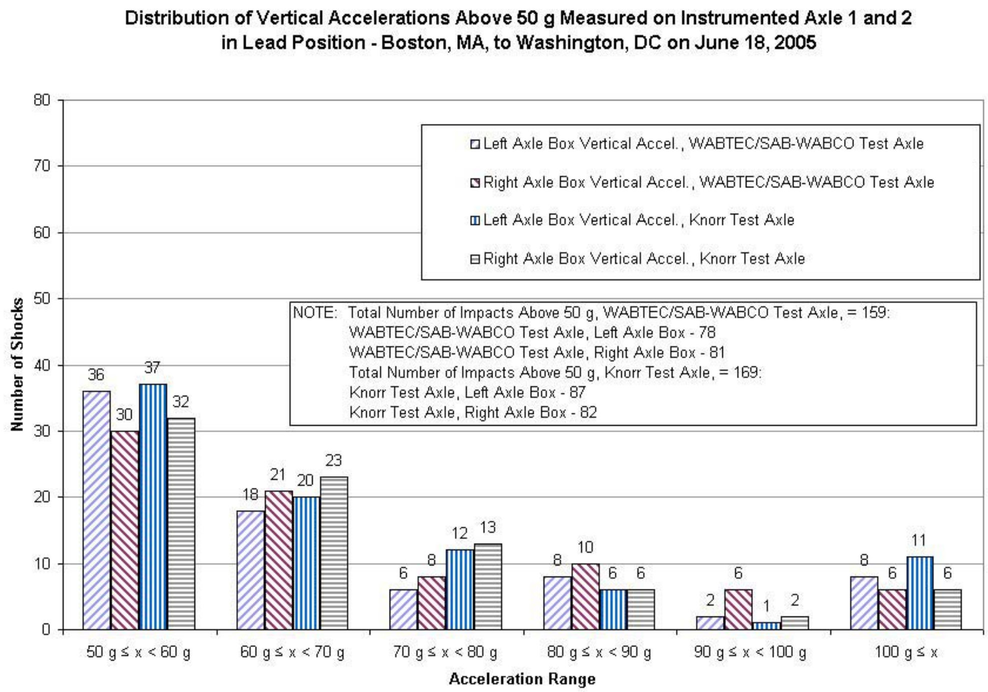


Figure 3.46b. Distribution of Vertical Accelerations Above 50 g Measured on Instrumented Axles 1 and 2 in Lead Position–Boston, MA, to Washington, DC, on June 18, 2005

There were 206 vertical shocks above 50 g measured on the WABTEC/SAB-WABCO test axle during the northbound test conducted on June 17, 96 on the left end axle box and 110 on the right end axle box, and 193 vertical shocks above 50 g were measured on the Knorr test axle during the same test run, 98 on the left end axle box and 95 on the right end axle box. Regarding the southbound test conducted on June 18, 159 vertical shocks above 50 g were measured on the WABTEC/SAB-WABCO test axle, 78 on the left end axle box and 81 on the right end axle box, and 169 vertical shocks above 50 g were measured on the Knorr test axle, 87 on the left end axle box and 82 on the right end axle box.

The highest vertical acceleration observed on the WABTEC/SAB-WABCO test axle during Phase 3 testing was 189 g, measured on the left end of the axle on June 17 near MP 56 of the Metro-North Rail Road while the test train was traveling at 48 mph. At this same location, the Knorr test axle experienced its highest vertical impact on the northbound trip, 172 g. During the southbound test conducted on June 18, the Knorr test axle experienced its highest vertical impact of the test, a 178 g impact on the left end of the axle in the vicinity of Transfer Interlocking near MP AB 218.5 while traveling at 131 mph. At this same location, the WABTEC/SAB-WABCO test axle experienced a vertical impact of 106 g on its left end.

Appendix F provides the details associated with all the accelerations above 100 g in tabular form, including location, speed of the test train, and information regarding the measured strains at the particular location.

As discussed in Section 2.3.2, ENSCO employed accelerometers provided by Vibra-Metrics to monitor the lateral accelerations on the test axles. On the WABTEC/SAB-WABCO test axle, ENSCO employed some of the original axle accelerometers, as well as the Vibra-Metrics accelerometer; the Vibra-Metrics accelerometer was the only accelerometer employed on the Knorr test axle. The performance of the Vibra-Metrics accelerometer on the WABTEC/SAB-WABCO test axle was not satisfactory, and all results pertaining to accelerations measured by axle-mounted accelerations on the WABTEC/SAB-WABCO test axle will be based on the Silicon Designs +/- 200 g single-axis accelerometer employed during the first two phases of testing.

Figure 3.47a illustrates the distribution of lateral accelerations above 30 g recorded on the test axle between Washington and Boston on June 17. Figure 3.46b illustrates the corresponding information for the data collected between Boston and Washington on June 18. Appendix F tabulates the data illustrated in Figure 3.47. On these two test days, the lateral accelerometers on the test axles exhibited effects from noise spikes and saturation from time to time. Accelerations above 30 g were reviewed to ensure that any acceleration affected by the noise-related or saturation issues was disregarded.

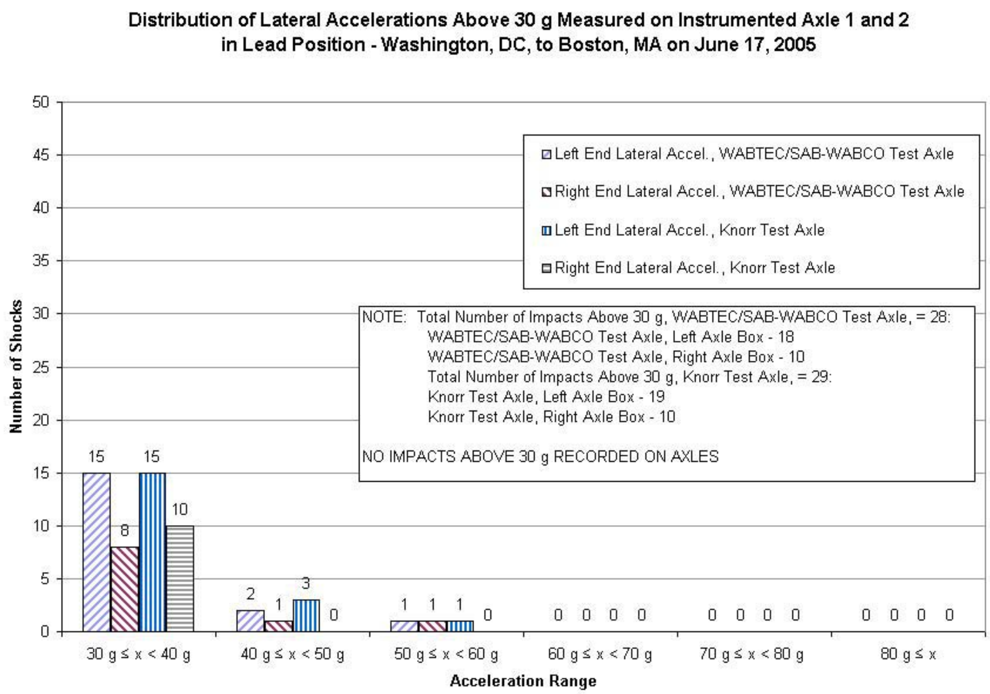


Figure 3.47a. Distribution of Lateral Accelerations Above 30 g Measured on Instrumented Axles 1 and 2 in Lead Position–Washington, DC, to Boston, MA, on June 17, 2005

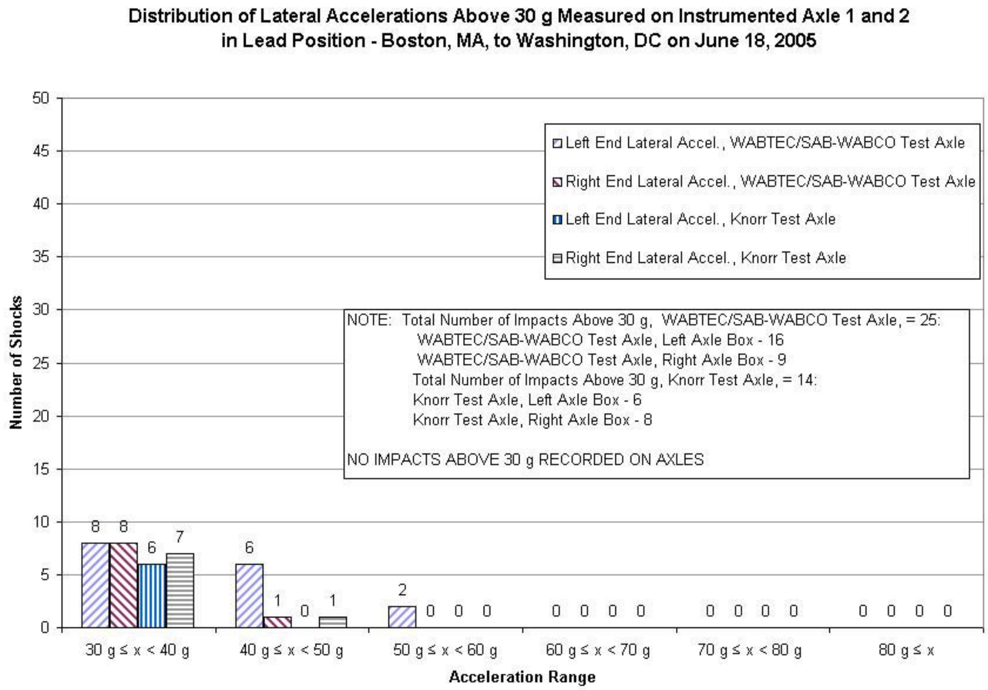


Figure 3.47b. Distribution of Lateral Accelerations Above 30 g Measured on Instrumented Axles 1 and 2 in Lead Position–Boston, MA, to Washington, DC, on June 18, 2005

There were 28 lateral shocks above 30 g measured on the WABTEC/SAB-WABCO test axle during the northbound test conducted on June 17, 18 on the left end axle box and 10 on the right end axle box, and 29 lateral shocks above 30 g were measured on the Knorr test axle during the same test run, 19 on the left end axle box and ten 10 on the right end axle box. These counts represent those shocks in which the measurement was deemed reliable. No lateral shocks were measured directly on either test axle during the June 17 test run that were considered reliable. Regarding the southbound test conducted on June 18, 25 lateral shocks above 30 g were measured on the WABTEC/SAB-WABCO test axle, 16 on the left end axle box and 9 on the right end axle box, and 14 lateral shocks above 30 g were measured on the Knorr test axle, 6 on the left end axle box and 8 on the right end axle box. No lateral shocks were measured directly on either test axle during the June 18 test run that were considered reliable.

The highest lateral acceleration observed on the WABTEC/SAB-WABCO test axle during Phase 3 testing was 58.5 g, measured on the left end of the axle on June 17 in the vicinity of Union Interlocking near MP AN 20 while traveling at 113 mph. The Knorr test axle also experienced its highest lateral impact of the test on the June 17 northbound test run, a 58.4 g impact on the left end of the axle near Bowie Interlocking near MP AP 120.8 while traveling at 125 mph.

In summary, results from Phase 3 testing indicated that the load environment as characterized by high lateral and vertical impacts was similar for each of the test axles. This observation is important because it established the fact that each test axle is subjected to similar loads, allowing for straightforward comparisons of the response of the respective discs for given load conditions.

3.3.4 *Spoke Strains*

Based on observations made during the earlier phases of the test program, one of the issues of interest entering Phase 3 testing was the response of the Knorr-designed brake disc to those events that had elicited high BOP strains on the spokes of the WABTEC/SAB-WABCO supplied brake disc, namely vertical impacts and cases in which sustained oscillations were observed in some brake applications.

Regarding the response to vertical impacts, it was immediately evident during testing, as well as in post-test data analysis, that for comparable vertical shocks on the two test axles, the BOP strains recorded on the spokes of the Knorr brake disc were substantially lower than the BOP strains recorded on the spokes of the WABTEC/SAB-WABCO supplied brake disc. This observation is exemplified by the comparison of Figures 3.48 and 3.49.

Figure 3.48 illustrates a severe vertical impact and the response of the WABTEC/SAB-WABCO supplied brake disc as characterized by the BOP strains measured on spoke 6. The data shown in Figure 3.48 was recorded on June 18 while the test train was traveling southbound in the vicinity of Lane Interlocking near MP AN 12 at 124 mph. As seen in the plots of vertical accelerations within the figure, the axle was subjected to an asymmetric vertical, or tilting, acceleration in which a positive acceleration of 147 g was measured on the left end axle box and a negative acceleration of -73 g was measured on the right end axle box. Figure 3.49 illustrates the corresponding response of the Knorr disc to the same disturbance, measured as a positive acceleration of 145 g on the left end axle box and a negative acceleration of 49 g on the right end axle box. Spoke 6 of each of the center brake discs at the time of the impacts illustrated in Figures 3.48 and 3.49 was approaching the straight up or 12:00 position. Spoke 6 of the Knorr disc was approximately 20º from the 12:00 position; spoke 6 of the WABTEC/SAB-WABCO supplied disc was approximately 60º from the 12:00 position.

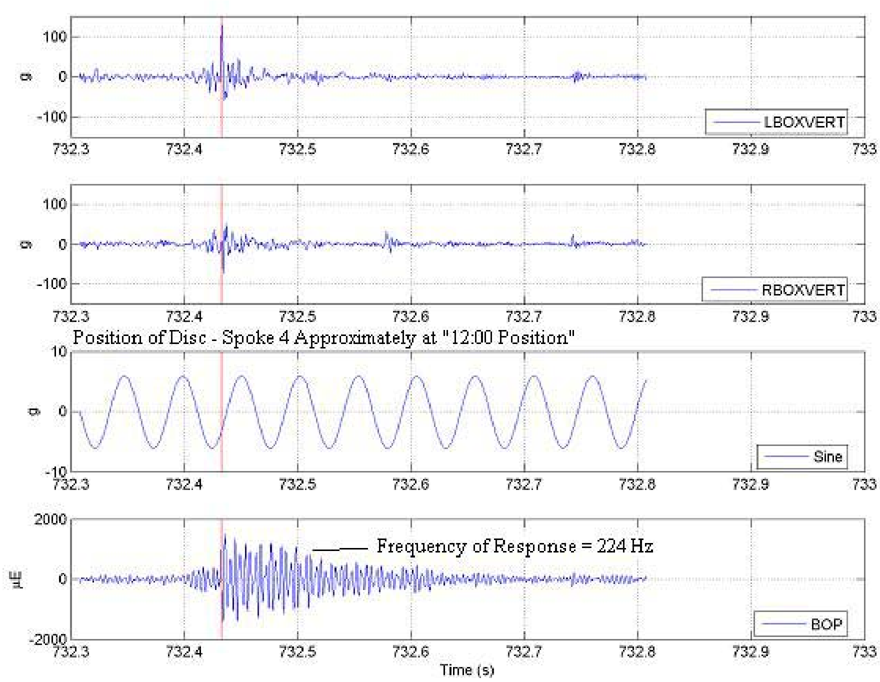


Figure 3.48. Vertical Shock and BOP Spoke Strain Response of WABTEC/SAB-WABCO Supplied Brake Disc Measured Near Lane Interlocking (File 061805_30.AB3)–June 18, 2005

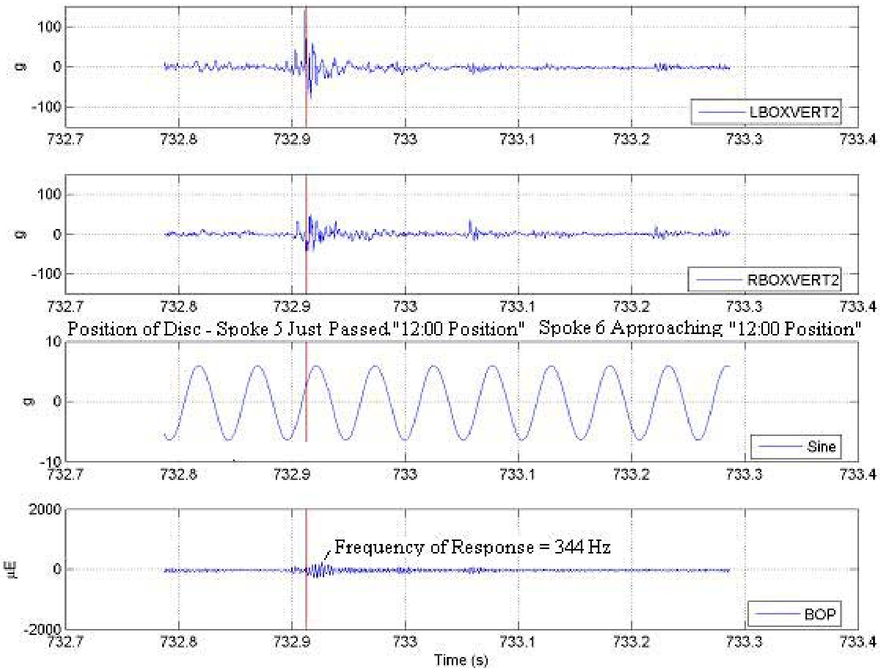


Figure 3.49. Vertical Shock and BOP Spoke Strain Response of Knorr Brake Disc Measured Near Lane Interlocking (File 061805_30.AB3)–June 18, 2005

As seen in the bottom of Figure 3.48, the shock produces a BOP spoke strain on the WABTEC/SAB-WABCO supplied brake disc with an amplitude of 1,487 microstrain, zero-to-peak, that requires almost 0.20 seconds to die out. The asymmetric vertical shock produces a BOP spoke strain with an amplitude of 290 microstrain, zero-to-peak, in the Knorr brake disc that requires approximately 0.03 seconds to die out. The frequency associated with this particular response of the WABTEC/SAB-WABCO supplied brake disc is 224 Hz while the frequency associated with the Knorr disc is 344 Hz. Both of these frequencies are close to those associated with the out-of-phase responses of the respective discs determined in the modal tests conducted during Phase 3 testing (see Table 3.4 for WABTEC/SAB-WABCO supplied disc and Table 3.5 for Knorr disc). Similar results with respect to the relative responses of the two discs to vertical shocks were observed throughout Phase 3 testing. The highest strains on the center brake disc resulting from a vertical impact only during Phase 3 testing was the event illustrated in Figure 3.48.

With regards to the sustained oscillations observed during selected brake applications, 33 cases were observed on the WABTEC/SAB-WABCO supplied brake disc during Phase 3 testing, 24 on the northbound test run conducted on June 17 and 9 during the southbound test run on June 18. In none of these cases was any oscillation of appreciable amplitude observed on the Knorr brake disc. Table 3.6 provides the number of events of sustained oscillations during braking for all testing on the trips between Washington and Boston. The test run conducted on June 17 included more brake applications than any of the other test runs.

Table 3.6. Summary of Observations of High BOP Strain Sustained Oscillations During Braking

Date	Direction	Position of Instrumented Axles	Number of Sustained Oscillation Events Observed on Center Disc During Braking		Number of Brake Applications
			W/S-W Brake Disc	Knorr Brake Disc	
May 16, 2005	Northbound	Trailing	0	N/A	103
May 17, 2005	Southbound	Leading	8	N/A	76
May 26, 2005	Northbound	Leading	11	N/A	82
May 27, 2005	Southbound	Trailing	0	N/A	98
June 17, 2005	Northbound	Leading	24	0	147
June 18, 2005	Southbound	Leading	9	0	95

Details associated with each of the significant events of sustained oscillations during braking are provided in Table 3.7 for testing conducted on June 17 and Table 3.8 for testing conducted on June 18. Appendix G provides additional details associated with these events. Figure 3.13 defines terminology used in Tables 3.7 and 3.8. A large number of the events observed on June 17 occurred on the north end of the corridor in relatively close proximity to one another. Many additional brake applications were made during June 17 testing in the New England Division to observe the sustained oscillations. This is reflected in the higher number of brake applications for this particular test shown in Table 3.6. The conditions of the brake pads on the WABTEC/SAB-WABCO supplied and Knorr brake discs were slightly different. The pads used with the WABTEC/SAB-WABCO supplied brake discs were installed before the commencement of the test program, while the pads used with the Knorr brake discs were installed at the same time that the Knorr discs were installed.

Table 3.7. Summary of Measurements Collected from Center WABTEC/SAB-WABCO Supplied Brake Disc During Brake Applications Exhibiting Signs of High BOP Strain–June 17, 2005

Geographic Location	Duration (s)	Measurements from Center Disc						Brake Cyl Press (psi)	Speed at Start of Braking (mph)
		Max Avg-to-Pk Amplitude (με)	Avg Strain @ Start (με)	Avg Strain @ End (με)	Disc Temp @ Start (ºF)	Disc Temp @ End (ºF)	Peak Disc Temp (ºF)		
2089 NE of MP AP 4	3.5	532	1282	1348	169.2	212.2	242.1	46	85
980 NE of MP MN 21	7	335	488	694	143.3	145.9	179.7	42	89
1627 NE of MP MN 25	14	327	528	766	152.5	158.6	181.0	32	73
772 E of MP MN 28	4	316	611	646	158.6	158.6	169.2	29	67
2599 E of MP MN 45	5	186	604	677	146.8	147.2	155.6	23	69
582 SW of MP MN 59	6	277	478	611	130.1	134.0	179.3	31	68
1163 W of MP MN 64	9	288	470	633	136.7	138.9	156.4	28	70
1530 SW of MP MN 68	9	314	528	704	144.6	145.9	157.8	30	74
49 E of MP MN 69	12	395	665	861	149.0	162.6	178.4	34	72
717 NE of MP MN 70	9	334	750	930	168.7	170.5	188.9	32	71
1022 E of MP AB 99	11	658	756	1035	144.6	148.5	170.1	44	120
1768 E of MP AB 102	6	290	770	922	164.8	163.0	180.6	35	85
1525 NE of MP AB 115	14	1010	580	1038	138.4	147.6	167.9	43	81
N/A (GPS Error)	6	526	984	1081	190.3	190.7	204.3	41	83
N/A (GPS Error)	6	403	1172	1280	203.9	203.9	221.9	31	78
821 SE of MP AB 125	4	256	938	1005	204.8	204.8	213.6	29	66
639 SE of MP AB 126	6	658	1004	1176	211.4	211.4	215.3	41	71
2129 SE of MP AB 128	6	899	1142	1486	214.9	232.0	266.3	44	94
29 NE of MP AB 131	20	379	1218	1520	224.5	236.4	250.5	37	95
2136 SW of MP AB 138	15	719	1015	1413	189.4	242.6	245.2	40	90
673 SW of MP AB 140	20	749	1272	1710	221.0	276.4	278.2	51	92
464 W of MP AB 143	13	1139	1170	1686	222.3	227.2	247.0	50	107
2455 NE of MP AB 158	47	1372	658	2202	144.1	310.7	330.0	55	148
2579 NE of MP AB 160	11	591	520	996	130.5	134.0	179.3	33	141

NOTE: No oscillations of appreciable amplitude observed on center Knorr brake disc.

Table 3.8. Summary of Measurements Collected from Center WABTEC/SAB-WABCO Supplied Brake Disc During Brake Applications Exhibiting Signs of High BOP Strain–June 18, 2005

Geographic Location	Duration (s)	Measurements from Center Disc						Brake Cyl Press (psi)	Speed at Start of Braking (mph)
		Max Avg-to-Pk Amplitude (με)	Avg Strain @ Start (με)	Avg Strain @ End (με)	Disc Temp @ Start (ºF)	Disc Temp @ End (ºF)	Peak Disc Temp (ºF)		
2396 NE of MP AB 202	22	948	1309	1918	100.6	253.5	252.7	56	116
2619 S of MP AB 178	21	1226	438	1483	115.6	244.3	243.4	52	130
691 SW of MP AB 170	16	559	971	1406	169.2	198.2	225.0	35	113
4 SW of MP AB 162	37	1200	650	2154	145.4	266.3	298.8	54	150
1222 SW of MP AB 159	24	1132	1491	2315	249.6	301.4	327.8	54	120
732 SW of MP AB 156	27	835	1719	2512	282.5	314.6	341.9	52	120
784 SW of MP AN 13	15	1129	285	925	107.2	156.0	199.9	55	110
1211 SW of MP AN 19	7	1172	643	938	143.3	148.5	179.3	51	120
1748 SW of MP AN 55	17	1455	1466	1974	226.7	261.9	325.6	56	133

NOTE: No oscillations of appreciable amplitude observed on center Knorr brake disc.

The highest amplitude of sustained BOP oscillations on the center WABTEC/SAB-WABCO supplied disc during a brake application during Phase 3 was observed on June 18 at 1748' southwest of MP AN 55 during braking from 133 mph. This event was subject to the effects of the sustained oscillations, the rise in mean strain due to heat buildup and a vertical impact experienced in the middle of the brake application. The highest BOP oscillations due solely to a brake application were observed near MP AB 158.5 on June 17 during a brake application from 148 mph. In this case, a BOP strain amplitude of ± 1,372 microstrain, average-to-peak, was observed during a prolonged application of the brakes in which the mean strain reached 2,202 microstrain and the temperature reached 330 °F. The strains presented are as measured and have not been corrected for pre-load strains in the spoke.

Figure 3.50 illustrates a comparison between the strains recorded on one side of spoke 6 of both the WABTEC/SAB-WABCO supplied and Knorr brake discs during a braking event. In this case, sustained BOP oscillations were observed on the WABTEC/SAB-WABCO supplied disc 2396' northeast of MP AB 202 during braking from 116 mph. The top portion of the figure illustrates the entire event while the middle portion of the figure illustrates the results during a period lasting corresponding to two cycles of vibration of the WABTEC/SAB-WABCO supplied disc. In this case, strain oscillations reached average-to-peak amplitudes of ± 948 microstrain, or peak-to-peak amplitudes of almost 1,900 microstrain. These oscillations were superimposed on a mean strain that reached 1,918 microstrain due to a large temperature rise from 100.6 °F to 253.5 °F. The response of the Knorr disc to this braking is similar to that of the WABTEC/SAB-WABCO supplied disc with respect to the average tensile strain in the spoke, but it is clear that no BOP strain oscillations were observed on the Knorr disc. Brake cylinder pressures associated with the WABTEC/SAB-WABCO supplied and Knorr discs reached 56.3 psi and 54.0 psi, respectively, and the temperatures measured on each of the discs were similar. The lower portion of Figure 3.50 illustrates the frequencies associated with the motion of the two discs. The frequency observed in the motion of the WABTEC/SAB-WABCO supplied disc near 185 Hz is prevalent in the PSD, as well as other frequencies resulting from modulation by the rotational speed of the wheel. Clearly, no particular frequency is associated with the vibration of the Knorr disc.

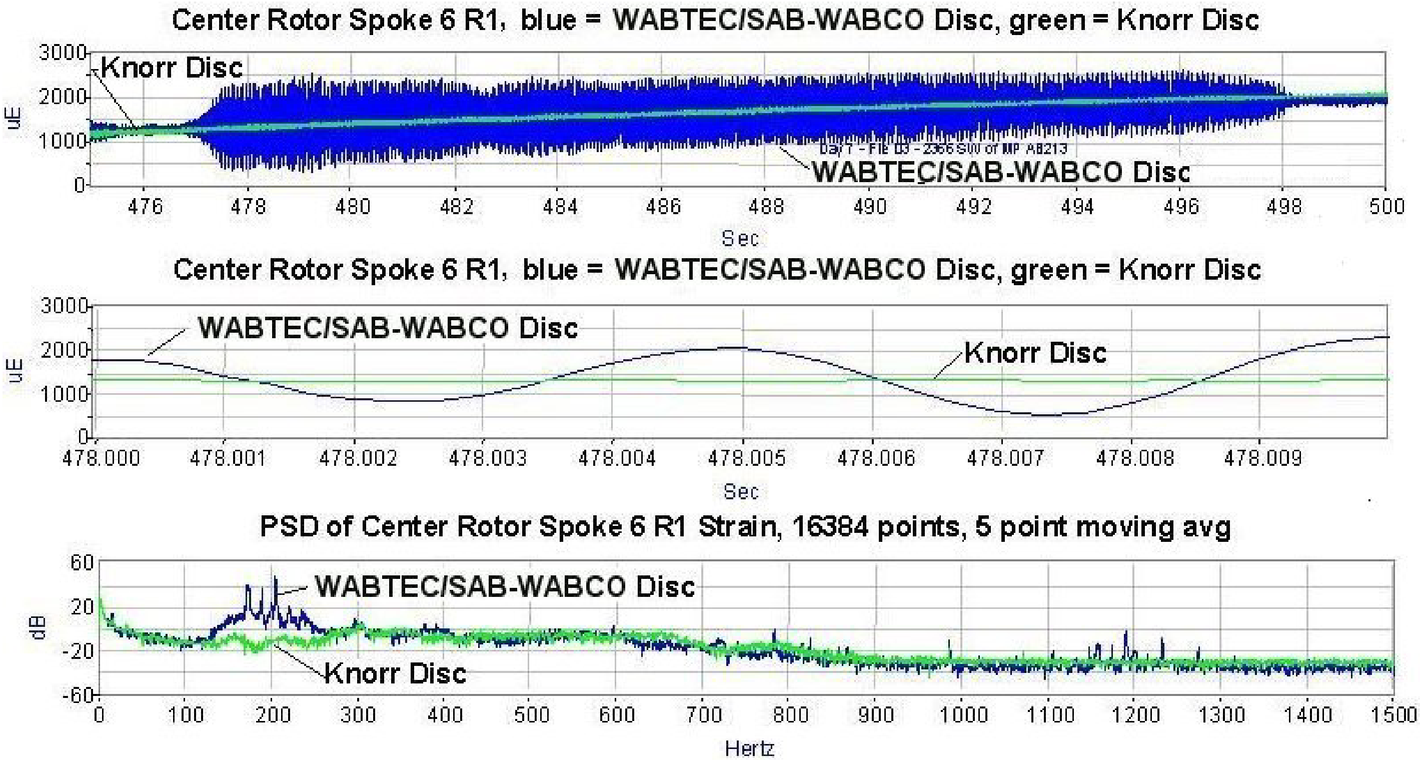


Figure 3.50. Comparison of WABTEC/SAB-WABCO Supplied Disc and Knorr Disc During a Brake Application From 116 MPH with Sustained Oscillations (File 061805_03.AB3)–June 18, 2005

One of the factors that affects the relative responses of the spokes of the two brake discs is the cross sectional geometry of the spokes. Figure 3.51 compares the geometry of the spokes for the different brake discs in the vicinity of the strain gages. The resistance of the spokes to bending depends on the cross-sectional moment of inertia. Table 3.9 provides a comparison of moment of inertia values for the cross sections of the WABTEC/SAB-WABCO supplied and Knorr brake disc spokes.

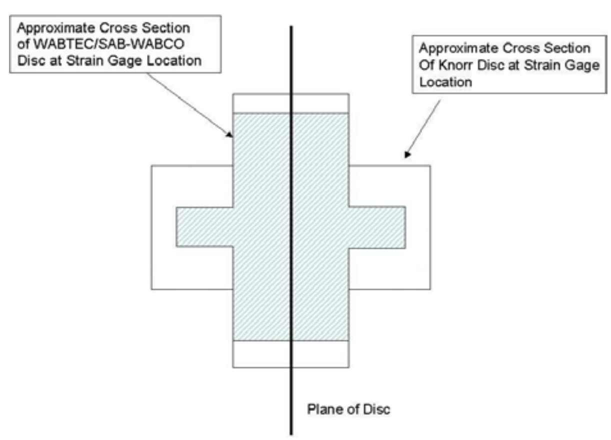


Figure 3.51. Comparison of Cross Sections of Spokes from WABTEC/SAB-WABCO Supplied and Knorr Brake Discs

Table 3.9. Properties of Cross Sections of Spokes of WABTEC/SAB-WABCO Supplied and Knorr Brake Discs

Property	WABTEC/SAB-WABCO Supplied Brake Disc Spoke	Knorr Brake Disc Spoke
Area	1.9 in^2	3.6 in^2
Moment of Inertia (BIP)	0.44 in^4	0.85 in^4
Moment of Inertia (BOP)	0.25 in^4	1.69 in^4

The moment of inertia for BOP of the Knorr disc is over six times that of the WABTEC/SAB-WABCO supplied disc, providing a higher resistance to BOP vibration at the location at which the strain gages were installed than can be provided by that of the WABTEC/SAB-WABCO supplied disc spoke. Due to its higher cross-sectional area, the spoke of the Knorr disc will experience a higher stress due to thermal expansion than the spoke of the WABTEC/SAB-WABCO supplied disc will for a given thermal load. Appendix M addresses this subject.

In summary, the Knorr disc exhibited smaller BOP strains in response to vertical shocks than those observed on the WABTEC/SAB-WABCO supplied brake disc. The BOP strains observed on the Knorr disc were not only smaller in amplitude, but they also died out in a much shorter time than the ones observed for the same shocks on the WABTEC/SAB-WABCO supplied disc. The BOP strains observed on both discs due to vertical impacts were found to have the same frequencies as those associated with out-of-phase vibrations on each of the brake discs observed during modal testing. The sustained oscillations of high BOP strains observed on the WABTEC/SAB-WABCO supplied brake disc during some brake applications were not observed on the Knorr disc during any brake applications.

A subsequent section will address the subject of the BOP strains resulting from vertical impacts and observed in sustained oscillations during brake applications and the impact of those strains on the fatigue of the spokes.

3.3.5 Axle Strains

Section 3.2.3 discussed the measurement of axle strains. The only change in approach during Phase 3 testing, in addition to installation of instrumentation on the Knorr test axle, was the addition of two strain gages on the Knorr axle near the center brake disc so that four gages were located around the circumference of the axle at 90° intervals.

During a review of axle strains measured during Phase 2 testing, it was observed that axle strains could be affected by modulation of the strain signals by the wheel rotational rate and the effects of the lateral acceleration imposed on the axle as it moves through curves. This became more evident in review of data collected in Phase 3 testing.

To more clearly illustrate the change in axle strains with movement through a curve, the lateral accelerations recorded on the truck frame over a short portion of track are compared to axle strains recorded from both test axles in Figure 3.52. When the test vehicle moves over curved track, an increase or decrease in lateral acceleration will usually be recorded on the truck. A strong correlation exists between the presence of curves and the change in the amplitude of the axle strains.

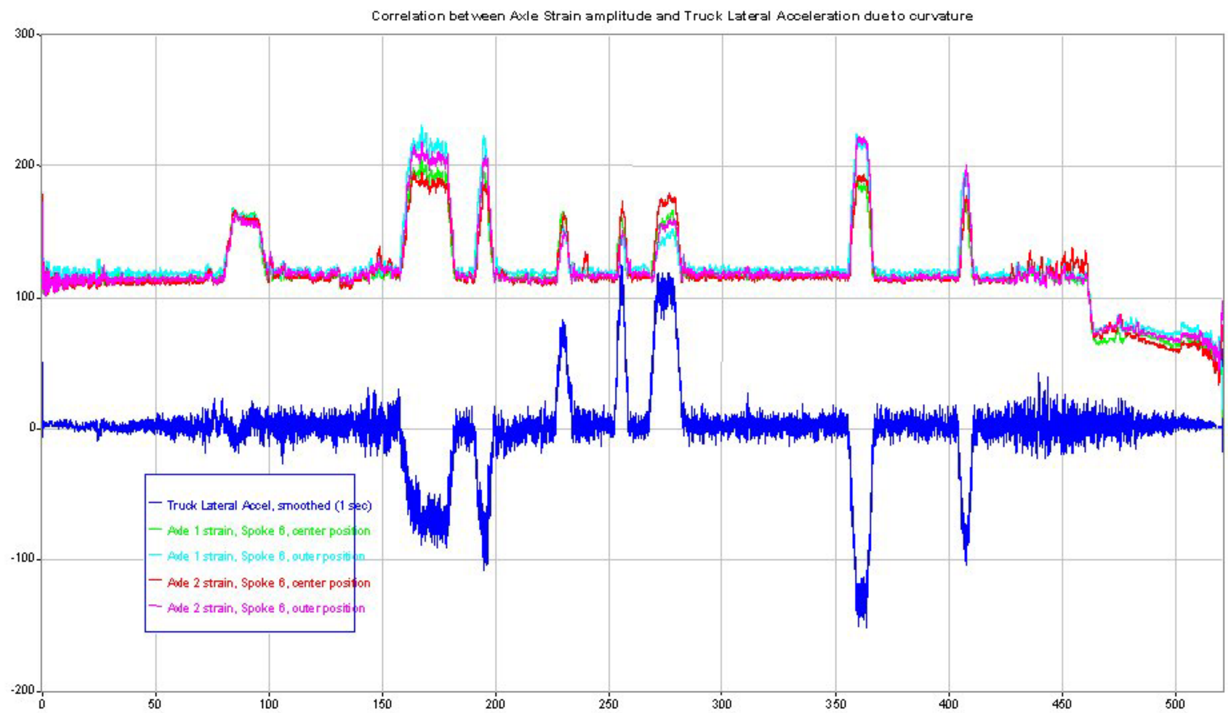


Figure 3.52. Comparison of Truck Frame Lateral Accelerations and Axle Strains (File 061805_03.AB3)–June 18, 2005

Figure 3.53 illustrates axle strains recorded on both test axles while traveling at speeds between 0 and 150 mph on June 18. The change in the overall amplitude of the axle strains can be seen to change as the speed increases; the effect of the rotational speed of the axle can be seen in the frequency spectra of both axles included in the lower portion of the figure. This frequency analysis was conducted for data collected on tangent track at relatively constant speed.

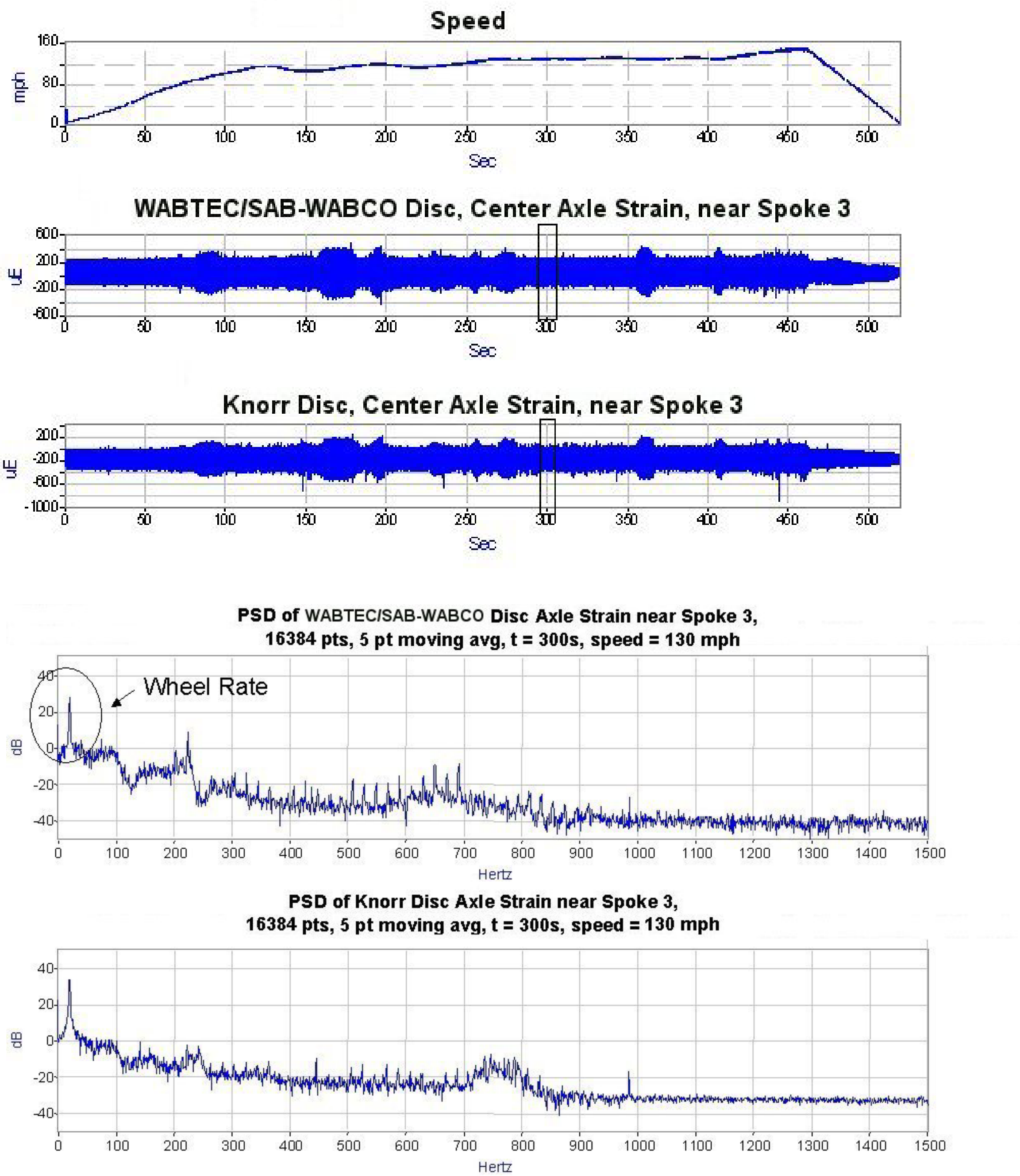


Figure 3.53. PSD of Axle Strains Collected Over Tangent Section of Track (File 061805_03.AB3)–June 18, 2005

Figure 3.54 provides the PSD of axle strains recorded on the test axles during the brake application illustrated in Figure 3.50. One can see the effect of the vibration of the WABTEC/SAB-WABCO supplied brake disc in the strains recorded on the WABTEC/SAB-WABCO axle. The dominant frequencies evident in the lower portion of Figure 3.50 can be seen in the consideration of the WABTEC/SAB-WABCO axle in Figure 3.54.

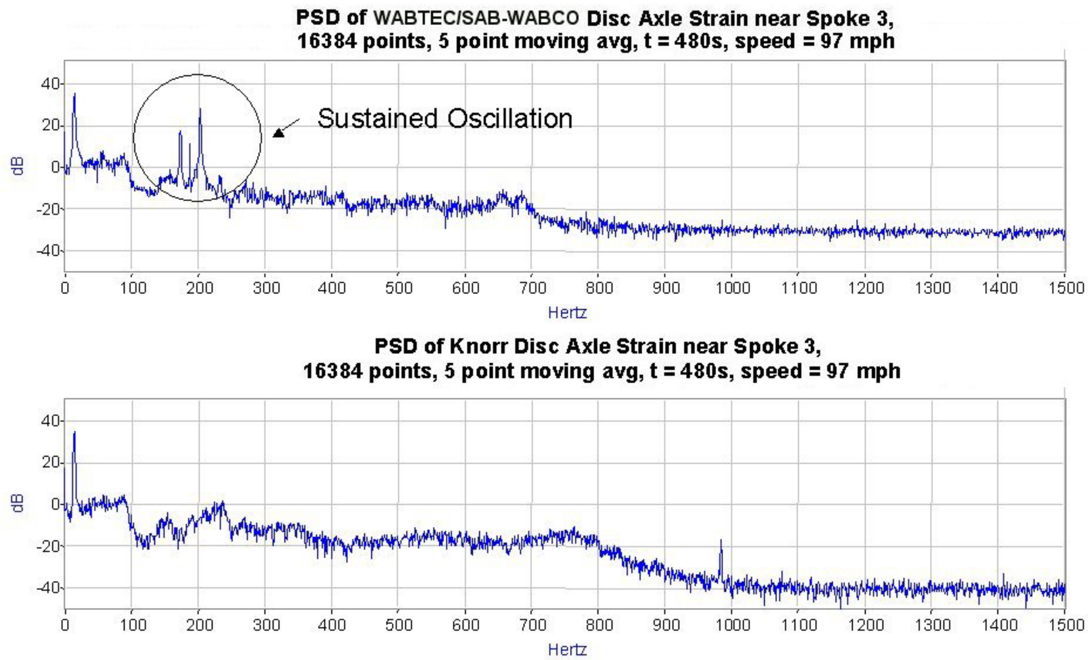


Figure 3.54. PSD of Axle Strains of WABTEC/SAB-WABCO Supplied Disc and Knorr Disc During a Brake Application from 116 MPH with Sustained Oscillations (File 061805_03.AB3)–June 18, 2005

As stated in Section 3.2.3, analysis of the axle strains requires one to be mindful of the effects of many factors. Appendix H discusses processing techniques to obtain more information from the modulated signals resulting from the axle-mounted strain gages.

3.3.6 Temperatures

During Phase 3 testing between Washington, DC, and Boston, MA, on June 17 and 18, the maximum temperature measured on the back of the friction ring of the center-mounted WABTEC/SAB-WABCO supplied brake disc was 342 °F. This was measured following a full-service brake application made near MP AB 155.5 on June 18 (File 061805_07.AB3). In a related topic, this was the incident that resulted in the highest mean spoke tensile strain of each of the discs, 2,668 microstrain for the WABTEC/SAB-WABCO supplied disc and 2,896 microstrain for the Knorr disc. The maximum temperature measured on the back of the friction ring of the center-mounted Knorr brake disc was 327 °F, measured following a suppression (i.e., less than 56 psi) brake application made near the Trenton, NJ, train station on June 18 (File 061805_24.AB3).

The highest brake disc temperature recorded occurred during the shakedown run made on June 16. In one case, the temperature on the WABTEC/SAB-WABCO supplied disc reached 361 °F and the Knorr disc reached 352 °F between MP 55 AN and Philadelphia, PA (File 061605_18.AB3). Figure 3.55 shows the temperature profiles recorded during this particular data file.

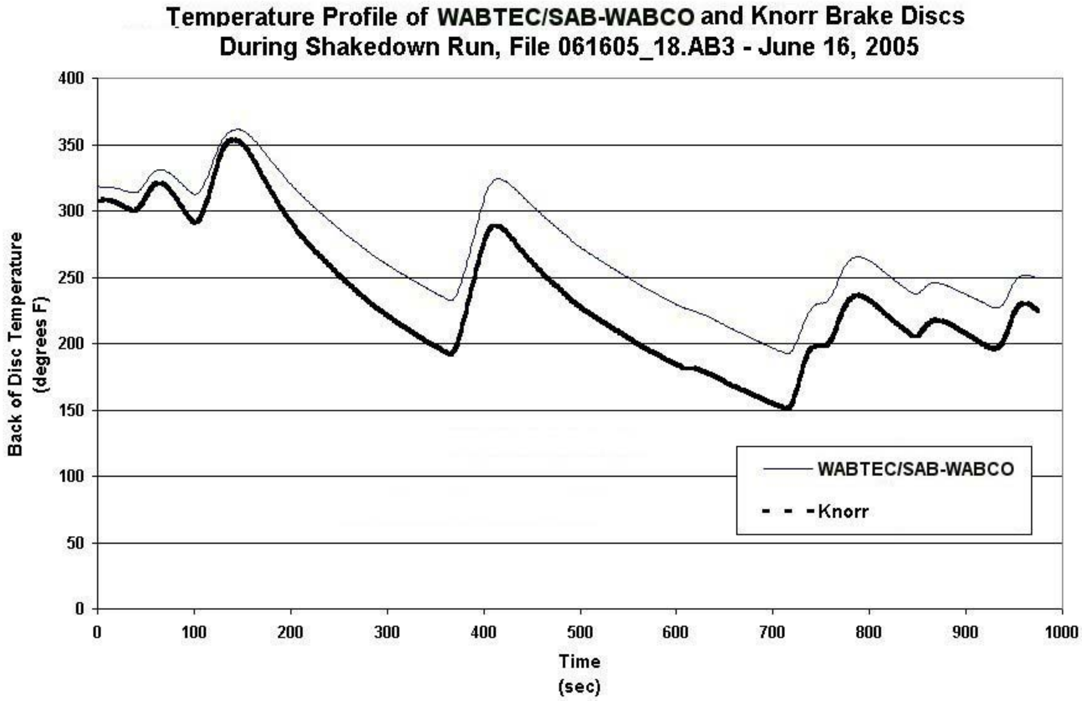
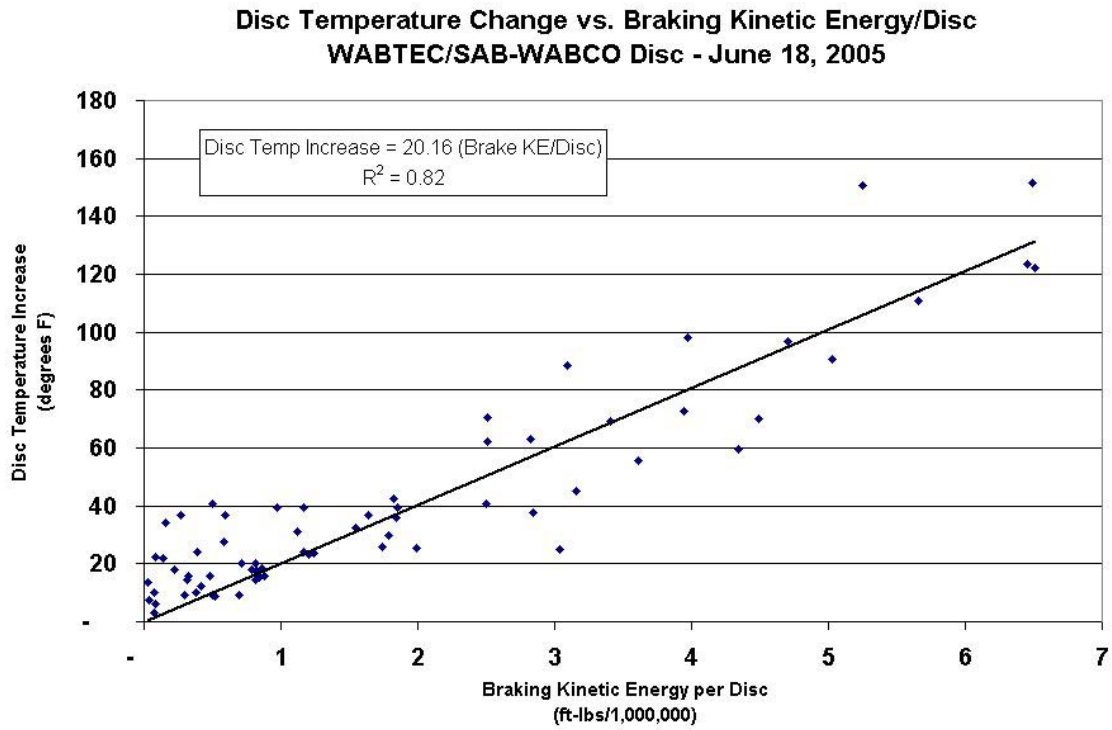


Figure 3.55. Temperature Profiles from Back of WABTEC/SAB-WABCO Supplied and Knorr Brake Discs During Shakedown Run (File 061605_18.AB3)–June 16, 2005

This illustration shows that the Knorr brake disc cools down faster than the WABTEC/SAB-WABCO supplied disc. The thermal time constant, a measure of how quickly the brake disc dissipates heat, was calculated for each brake disc using the temperatures shown above. Results of this analysis, details of which are provided in Appendix I, show that the thermal time constant for the Knorr brake disc is 4.6 while that for the WABTEC/SAB-WABCO supplied disc is 6.3, indicating that the Knorr disc will cool faster than the WABTEC/SAB-WABCO supplied disc.

An analysis of all the brake applications made during tests conducted on June 17 and 18 was performed to quantify the rate in which heat builds up within the discs. This was accomplished by identifying the temperature change of the Knorr and WABTEC/SAB-WABCO supplied brake discs due to the braking as a function of the kinetic energy dissipated. Details of this analysis are presented in Appendix I and the results of the analysis for testing conducted on June 18 are provided in Figure 3.56. In this analysis, it is presumed that each brake disc of a vehicle contributes an equal amount to the braking effort of the vehicle, a reasonable presumption to make in this analysis. Results from this graph, as well as those provided for the June 17 tests, indicate that on average, for a given change in dissipated kinetic energy, the Knorr disc experiences a slightly higher temperature change. This finding was consistent with observations made during the test.



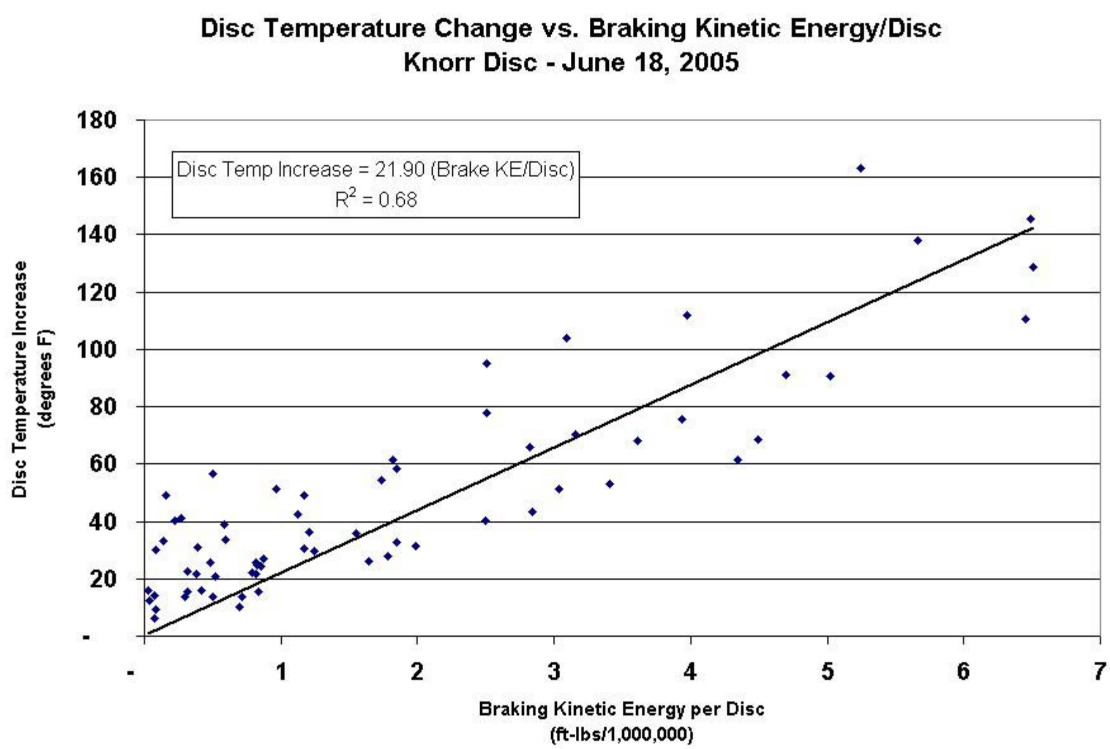


Figure 3.56. Comparison of Disc Temperature Changes versus Dissipated Kinetic Energy for Knorr and WABTEC/SAB-WABCO Supplied Brake Discs–June 18, 2005

As done with temperature measurements collected from the back of the WABTEC/SAB-WABCO supplied brake disc's friction ring during previous testing, friction ring temperatures were used to estimate the state of thermal stress in the spokes of each of the discs. Based on the analysis method described in Section 3.1.5, estimates of the thermal strains in the spoke were derived from data collected during testing on June 17 and 18. The results of this analysis are illustrated in Appendix I and summarized in Table 3.10; results from the analysis conducted using Phase 2 test data are also provided for the sake of comparison. The results for the WABTEC/SAB-WABCO supplied disc are similar to those arrived at in earlier testing. These estimated thermal strains would not account for any existing pre-load strains in the spokes.

Table 3.10. Estimate of Change in Tension Per Unit Change in Temperature in Spoke 6 of WABTEC/SAB-WABCO Supplied and Knorr Brake Discs–June 17 and 18, 2005

Test	Estimate of Tension Change in Spoke 6 (microstrain/ °F)	
	WABTEC/SAB-WABCO Supplied Brake Disc	Knorr Brake Disc
May 17	7.11	-
May 26	7.34	-
May 27	7.23	-
June 17	8.14	8.86
June 18	7.29	8.06
Average Results	7.42	8.46

In summary, the key findings regarding temperatures associated with the WABTEC/SAB-WABCO supplied and Knorr brake discs that resulted from Phase 3 testing include the following:

- The highest temperature measured on either of the brake discs was 361 °F. This was on the order of what was expected by the brake suppliers.
- Based on observations made during testing and subsequent data analysis, the Knorr brake disc heats up faster and cools down faster than the WABTEC/SAB-WABCO supplied brake disc. This difference in heating and cooling rates is considered to be small.
- The average rise in spoke tension for the Knorr brake disc was estimated to be approximately 8.5 microstrain/°F. The same quantity for the WABTEC/SAB-WABCO supplied brake disc was estimated to be approximately 7.4 microstrain/°F.

3.3.7 Brake System Hardware–Mounting Tube, Links and Calipers

Appendix F provides information pertaining to the frequency content of acceleration data collected from the brake calipers, the brake mounting tube and the truck frame during periods in which sustained oscillations of high BOP strains during braking was observed, periods in which braking was occurring without sustained oscillations, and periods in which an impact resulted in high BOP strains for a short period of time. This section will highlight these results.

During sustained oscillations within brake applications, accelerations measured on the brake mounting tube associated with the WABTEC/SAB-WABCO supplied brake disc test axle show a very strong harmonic characteristic. This same characteristic is not observed on the brake mounting tube above the Knorr brake disc test axle. Figure 3.57 provides an illustration of the time history and frequency content of the vertical accelerations measured on both brake mounting tubes during the period of sustained oscillations near MP AN 55 on June 18. Figure 3.58 shows the corresponding information for the lateral accelerations measured at the same locations. In both figures, a fundamental frequency of 187 Hz along with a number of harmonics are observed in the accelerations measured on the tube above the WABTEC/SAB-WABCO test axle. The amplitude of the vertical acceleration is approximately twice that of the lateral acceleration.

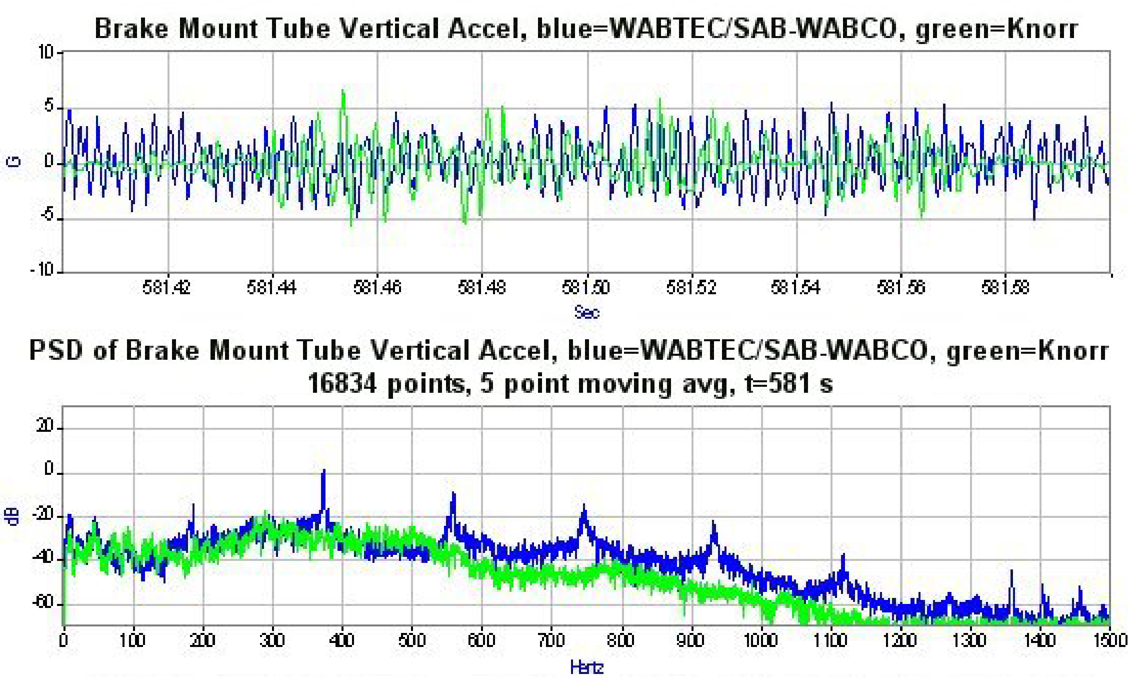


Figure 3.57. Time History and PSD of Brake Mounting Tube Vertical Accelerations During Sustained Oscillations While Braking (File 061805_24.AB3)–June 18, 2005

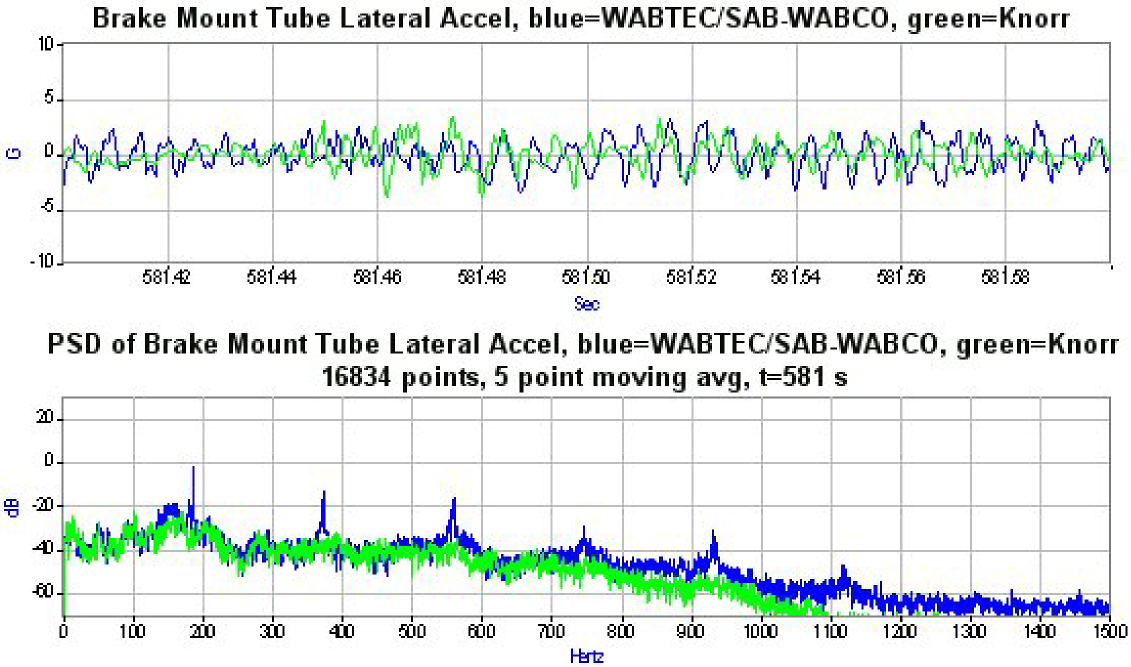


Figure 3.58. Time History and PSD of Brake Mounting Tube Lateral Accelerations During Sustained Oscillations While Braking (File 061805_24.AB3)–June 18, 2005

Figures 3.59 and 3.60 provide the same type of information shown in the previous figures for the vertical and lateral accelerations measured near the center caliper pads over the two test axles. As seen in the previous figures, the same fundamental frequency of 187 Hz, along with a number of harmonics, are observed in the frequency distribution. On the brake pad, the lateral accelerations associated with the WABTEC/SAB-WABCO supplied disc reach levels as high as 30 g, while the vertical accelerations on the same pad are only as high as 20 g. The accelerations measured on the pad are characterized by a saw-tooth shaped pattern.

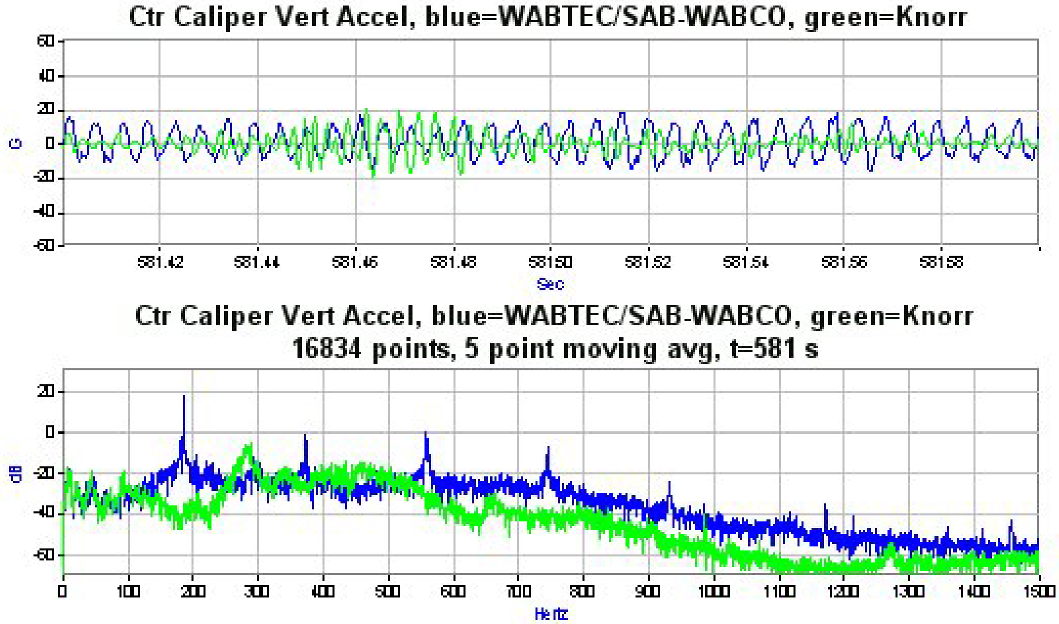


Figure 3.59. Time History and PSD of Brake Caliper Pad Vertical Accelerations During Sustained Oscillations While Braking (File 061805_24.AB3)–June 18, 2005

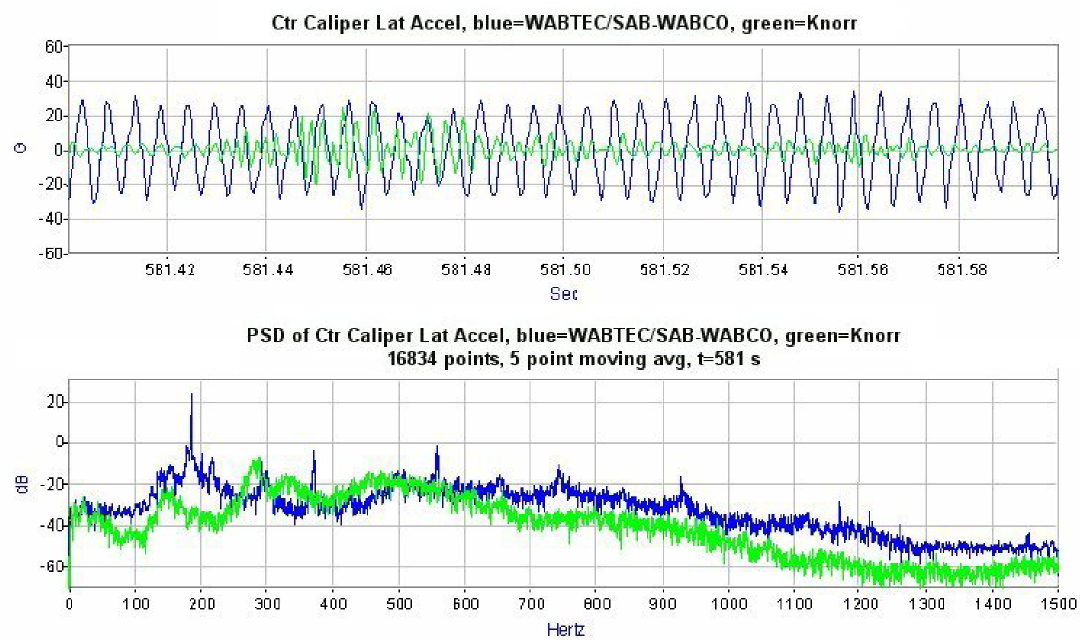


Figure 3.60. Time History and PSD of Brake Caliper Pad Lateral Accelerations During Sustained Oscillations While Braking (File 061805_24.AB3)–June 18, 2005

The brake support links transfer the loads generated during braking from the caliper assembly to the brake mounting tube. Before Phase 3 testing, two spare caliper assembly support links were instrumented with single-axis strain gages as indicated in the top of Figure 3.61. The existing links employed by the center caliper assembly used with the WABTEC/SAB-WABCO test axle were removed and replaced with the instrumented links.

This may be related to a slip-stick behavior at the interface of the brake pad and friction ring. Appendix K examines this behavior.

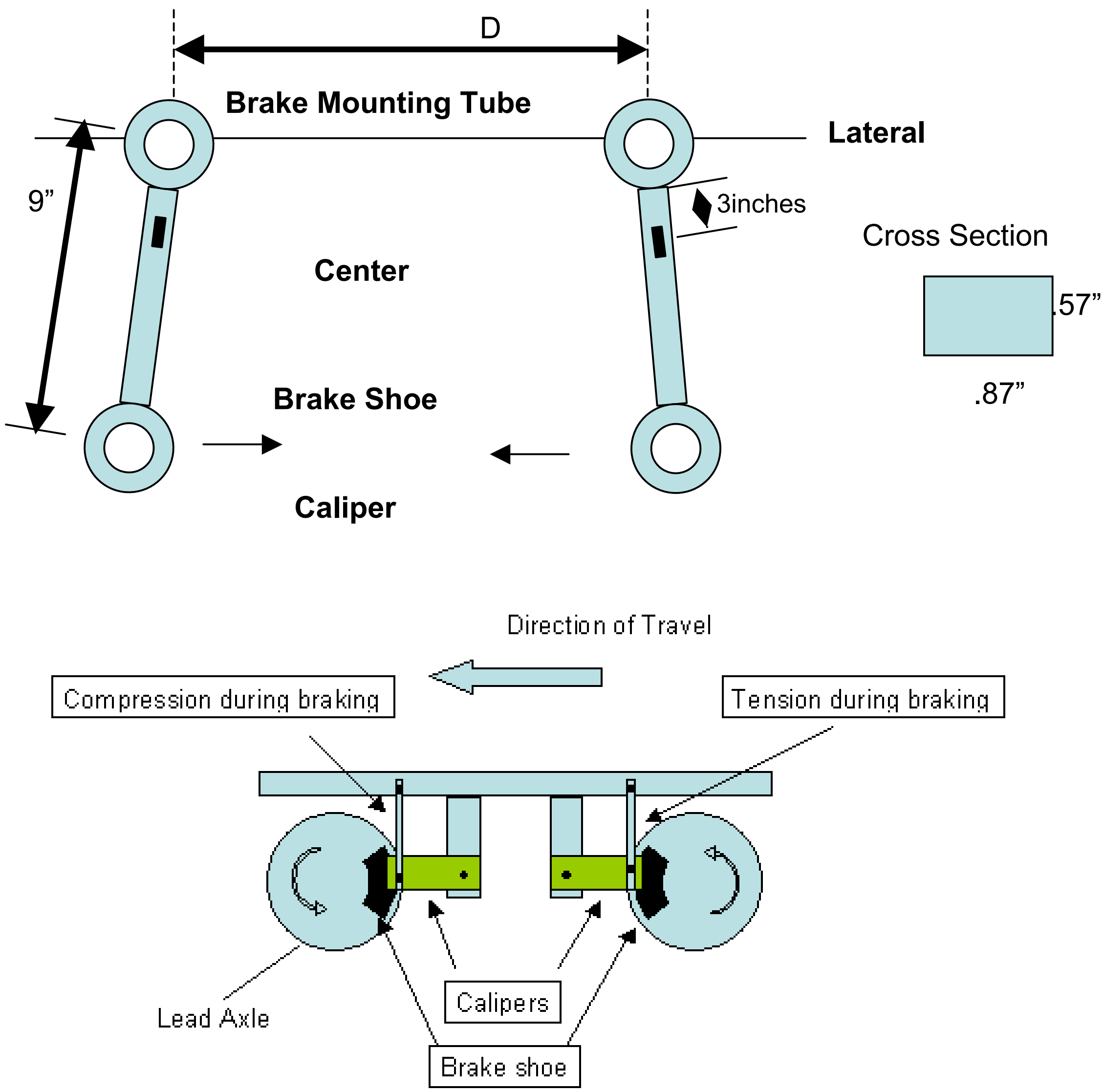


Figure 3.61. Illustration of Instrumented Brake Links and Locations within Truck

Consideration of Figure 3.61 shows that the caliper support links associated with the lead axle of the truck will be in compression during a brake application while the links associated with the trailing axle will be in tension. This is likely one of the aspects of the braking process that has influenced the observation that sustained oscillations during selected brake applications are only observed when the test axle was in the lead position. The fact that the links are in compression during periods of sustained oscillations during braking is important.

For the analysis of the caliper links that follows, it is assumed that the strains measured by the single gage on each link are a measure of the tension or compression in the link. This is a reasonable assumption because the links are pinned at each end. Based on a 0.5 square inch cross-sectional area, the relationship between strain and force carried by the link is that shown in Figure 3.62.

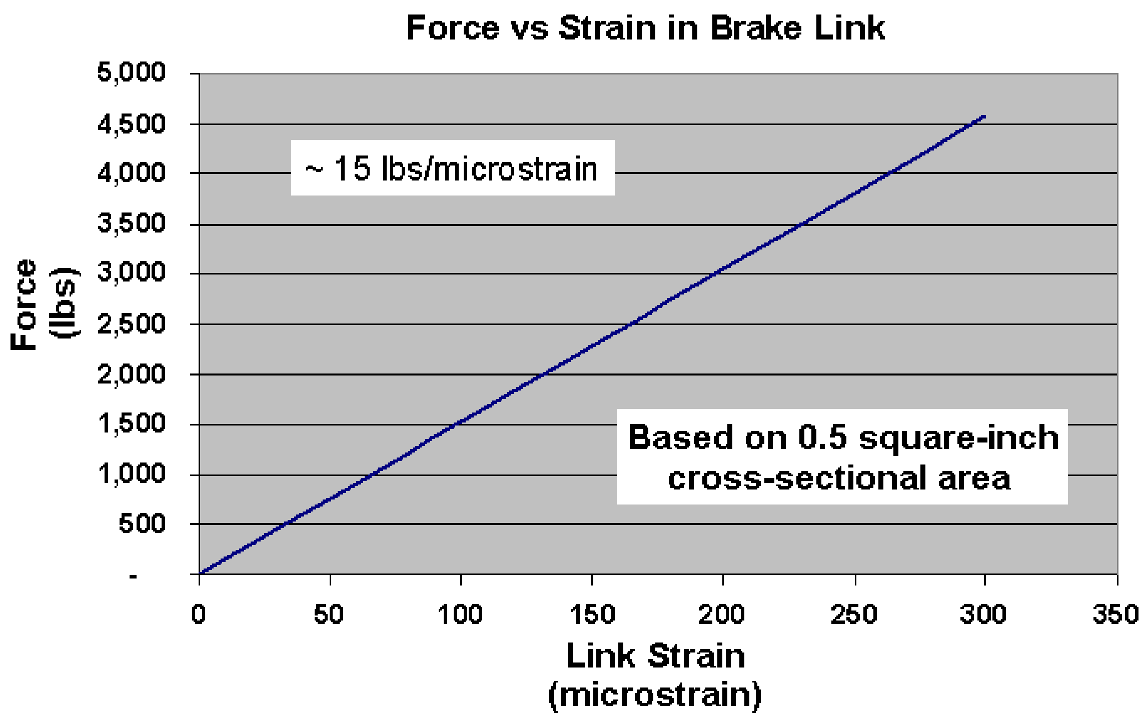


Figure 3.62. Brake Link Strain Level–Force Relationship

Four braking events were selected for analysis, which Table 3.11 details. During the first two events, no sustained oscillations of the WABTEC/SAB-WABCO supplied brake disc were observed. One of these segments was with the instrumented axle in the lead position and one with the instrumented axle in a trailing position. The other two events were selected because sustained oscillations of the WABTEC/SAB-WABCO supplied brake disc were observed. Appendix K provides the details of the analysis.

Although data collected on June 16 was not analyzed in great detail because the test on this day was conducted for shakedown purposes, data recorded with the instrumented links on June 16 was considered in this analysis. This was because June 16 was the only day of testing that the instrumented links were in place with the test axle in the trail position.

Table 3.11. Details of Braking Events Selected for Further Analysis of Instrumented Caliper Links

Date/File	Time in File (Sec)	Sustained Oscillation	Axle Position	Speed (mph)
June 16 061605_18.AB3	375	No	Trail	94
June 18 061805_24.AB3	310	No	Lead	117
June 18 061805_24.AB3	580	Yes	Lead	110
June 17 061705_25.AB3	559	Yes	Lead	69

The nominal brake cylinder pressure during all four events was 50 psi.

The links did not evenly share the braking forces in any of the four cases considered. Table 3.12 shows the results for the change in strain levels in the right and left links each of the brake applications. When the instrumented axle is in the trailing position, the left link shows the largest change in strain. When the instrumented axle is in the lead position, the right link shows the largest change in strain.

Table 3.12. Strain Changes in Right and Left Links During Selected Brake Applications

Date/File/Time	Sustained Oscillation	Axle Position	Left Link Microstrain	Right Link Microstrain
June 16 061605_18.AB3; t=375	No	Trail	+130	+21
June 18 061805_24.AB3; t=310	No	Lead	-32	-231
June 18 061805_24.AB3; t=580	Yes	Lead	-32	-221
June 17 061705_25.AB3; t=559	Yes	Lead	-17	-189

A major difference was observed between the strains when sustained oscillations were observed and those when no sustained oscillations were observed. When sustained oscillations were observed, the frequency spectrum of the strains recorded in the links exhibited a strong harmonic content. Figure 3.63 shows the frequency content of the strains recorded during the sustained oscillation of the WABTEC/SAB-WABCO supplied disc recorded near MP AN55 on June 18.

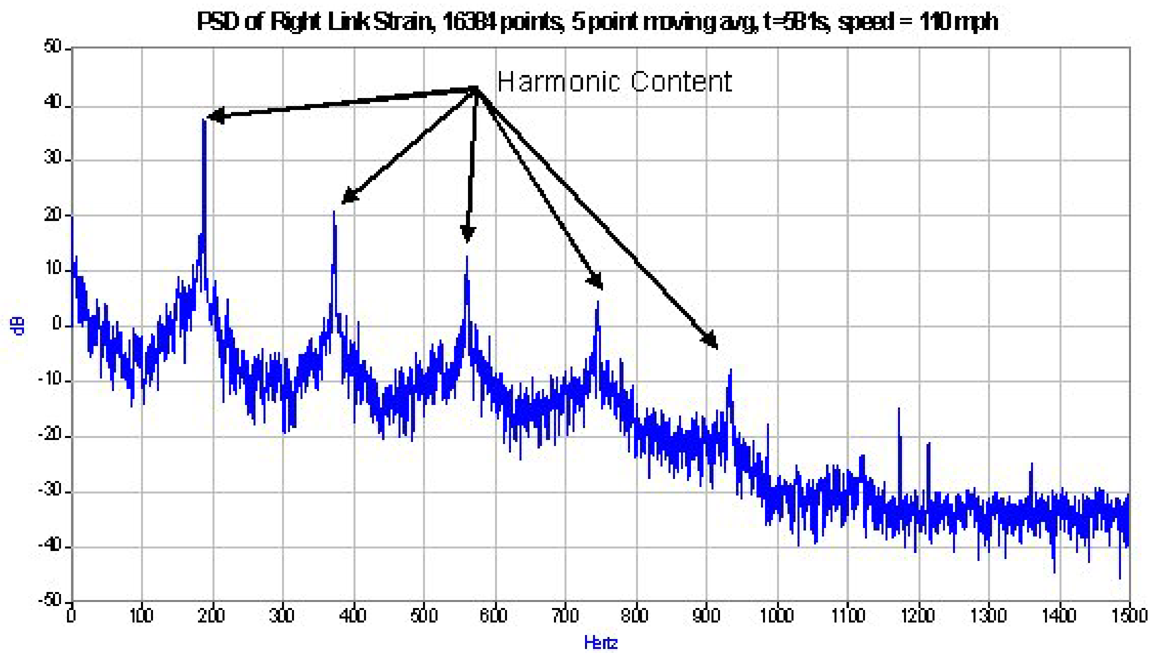


Figure 3.63. Frequency Spectrum of Strains Recorded on Caliper Link During Sustained Oscillations While Braking (File 061805_24.AB3)–June 18, 2005

The fundamental frequency of this oscillation is 187 Hz. This frequency was observed at vehicle speeds of 69 and 110 mph. Four harmonic frequencies are clearly observed in the PSD. Based on the 750 Hz, anti-aliasing filters used during Phase 3 testing, the amplitude of the fourth harmonic is attenuated, and additional harmonics would be significantly attenuated. Figure 3.64 shows the time history of the strains recorded on the right and left links during this event.

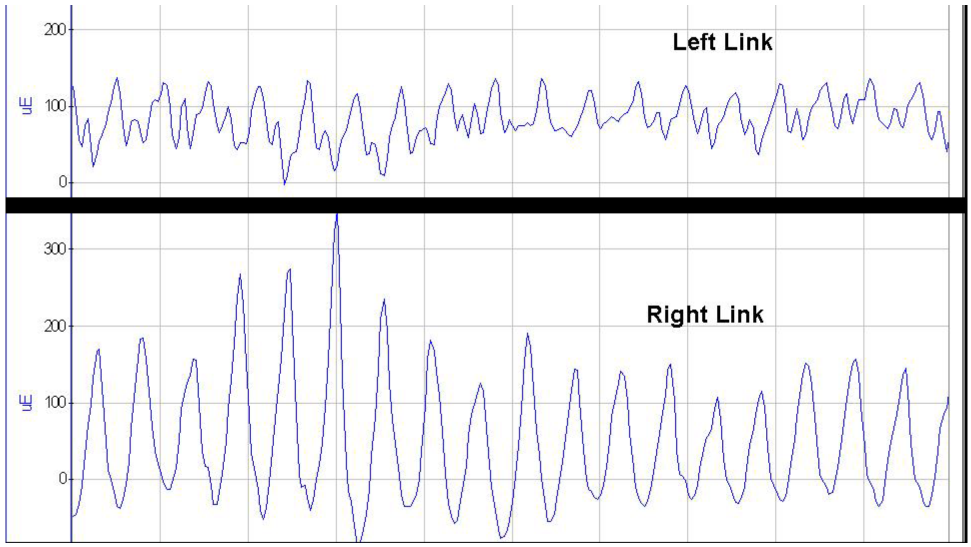


Figure 3.64. Strains Recorded on Caliper Links During Sustained Oscillations of WABTEC/SAB-WABCO Supplied Brake Disc While Braking (File 061805_24.AB3)–June 18, 2005

The 187 Hz frequency observed in the strains on the links is a characteristic of the sustained oscillation events. The right link strains exhibit the same distinctive saw-tooth pattern observed in the caliper pad accelerations in Figures 3.59 and 3.60. The strains in the left link exhibit reversals. These patterns may be indicative of a slip-stick behavior at the interface of the brake pad and the friction ring. Appendix K examines this phenomenon, but no firm conclusions are reached.

What determines the frequency observed in the oscillations of the various components within the system remains unknown.

3.3.8 Brake Pressures

As illustrated in Section 3.1.6, brake cylinder pressure has a direct effect on the amplitude of the sustained oscillations of BOP strains in the brake applications in which they are observed. This trend was evident in data collected during the third phase of testing as well. Figure 3.65 illustrates the brake cylinder pressure variation and the strains on the sides of spoke 6 from each brake disc recorded on June 17 near MP AB 154 during a short exhibition of oscillations.

In general, testing on June 17 and 18 provided the largest peak-to-peak sustained oscillations observed during testing. Figure 3.66 shows the distribution of the maximum peak-to-peak sustained oscillations observed during Phase 3 testing as a function of the highest brake cylinder pressure realized during the brake application. Figure 3.66 also provides corresponding information from results collected during the first two phases of testing.

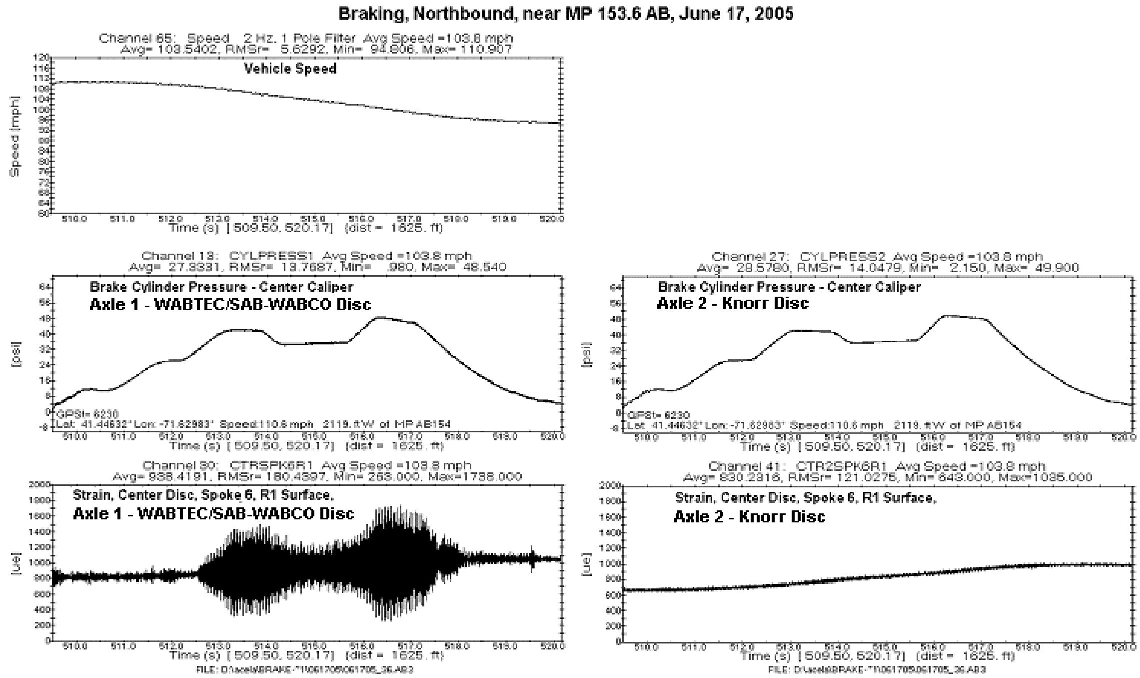


Figure 3.65. Brake Cylinder Pressure and Strains Recorded on Side of WABTEC/SAB-WABCO Supplied and Knorr Brake Disc Spokes During Short Case of Sustained Oscillations (File 061705_36.AB3)–June 17, 2005

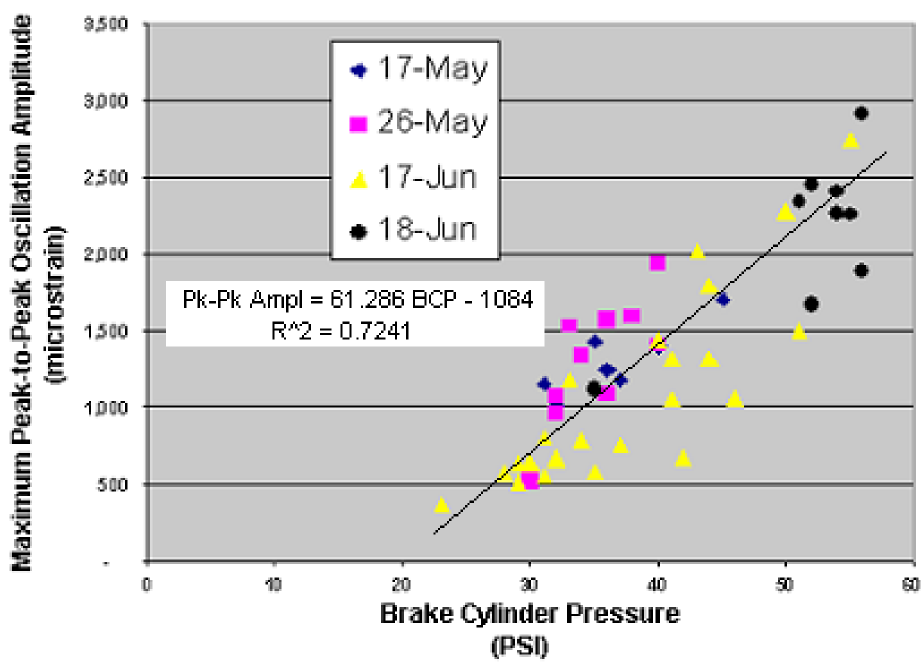


Figure 3.66. Relationship of Peak-to-Peak Sustained Oscillations to Brake Cylinder Pressure, Data Collected Throughout Test Effort

3.3.9 Sound Tests

Figure 3.67 illustrates the frequency analysis of sound measurements collected while the center WABTEC/SAB-WABCO supplied brake disc was exhibiting mild BOP strains during a brake application near MP AB 179 on June 17. Recordings were made over both the WABTEC/SAB-WABCO and Knorr test axles. As was the case with data presented in Section 3.2.6, the sound level expressed in decibels is plotted as a function of the frequency associated the particular component of the sound.

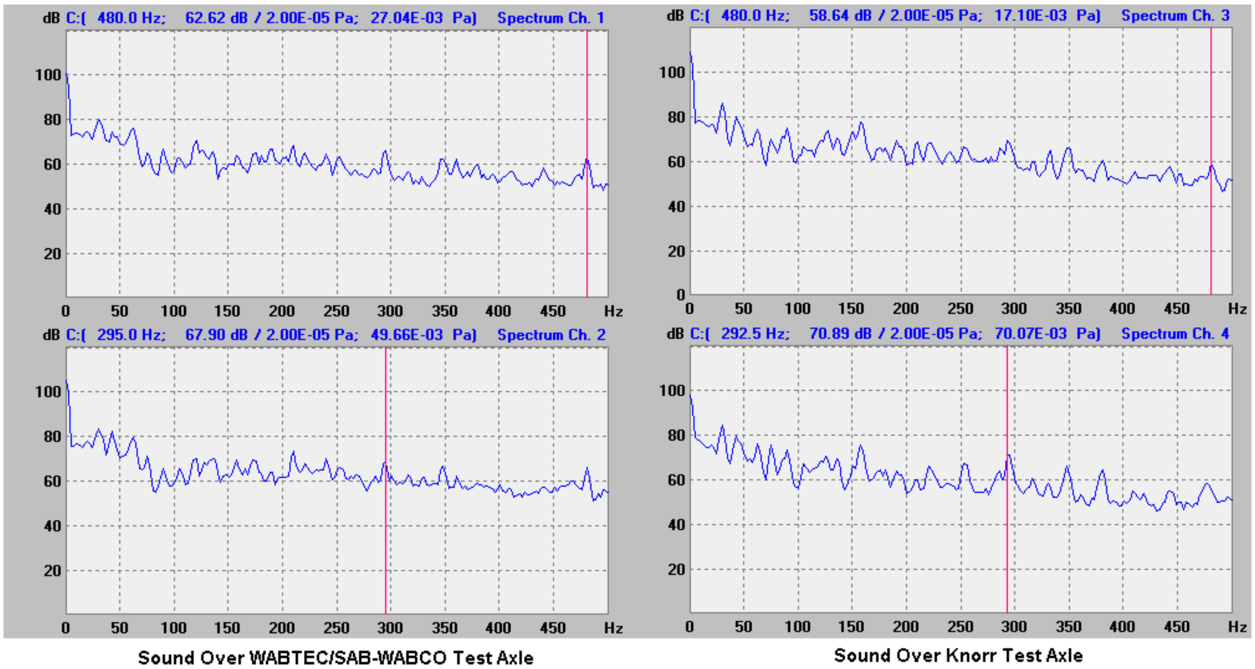


Figure 3.67. Analysis of Sound Recorded Over Both Test Axles During Mild Case of Sustained Oscillations on WABTEC/SAB-WABCO Supplied Disc During Braking Near MP AB 179–June 17, 2005

Within this recording, it was difficult to identify any particular dominant component of sound in any of the channels. No frequencies that present themselves are consistent with other frequencies that have become evident throughout the test effort. Analysis of sound measurements collected during Phase 3 testing did not provide any useful information.

3.3.10 Concluding Comments

Results of Phase 3 testing provided critical information for this study. In summary:

- Tests were conducted with a WABTEC/SAB-WABCO supplied brake disc being removed from an axle and a Knorr brake disc being installed on the same axle to determine pre-load stresses. Results from these single-sample tests indicate that an average pre-stress equivalent of approximately 1,000 microstrain may be present as a residual strain in a spoke of a WABTEC/SAB-WABCO supplied brake disc, comprised of an average compressive strain of 390 microstrain attributed to the pressing operation and an average compressive strain of 600 microstrain in a spokes attributed to the manufacturing process. The installation of the Knorr disc results in an average compressive strain of 533 microstrain on the spokes. Appendix M provides more information related to the nature of these existing stresses.

- During modal testing conducted on brake discs in the early stages of Phase 3 testing, a BOP mode was identified on the WABTEC/SAB-WABCO supplied brake disc with a frequency of 220 Hz. Results from tests involving the Knorr brake disc identified an out-of-phase vibration of the disc with a frequency of 351 Hz. These results were determined for discs installed on axles that had been removed from under the coach cars.

- The load environment as characterized by high lateral and vertical impacts was similar for each of the test axles. This observation is important because it established that each test axle is subjected to similar loads, allowing for straightforward comparisons of the response of the respective discs for given load conditions.

  The highest vertical shock observed throughout the program was recorded during Phase 3 testing. An impact of 189 g was measured on the left end of the WABTEC/SAB-WABCO test axle on June 17 near MP 56 of the Metro-North Rail Road while the test train was traveling at 48 mph. At this same location, the Knorr test axle experienced a vertical impact of 172 g.

  The highest lateral acceleration observed on the WABTEC/SAB-WABCO test axle during Phase 3 testing, 58.5 g, was measured on June 17 in the vicinity of Union Interlocking near MP AN 20 while traveling at 113 mph. The Knorr test axle also experienced its highest lateral impact of the test on the June 17 northbound test run, a 58.4 g impact recorded near the Bowie Interlocking near MP AP 120.8 while traveling at 125 mph.

- The Knorr disc exhibited smaller BOP strains in response to vertical shocks than those observed on the WABTEC/SAB-WABCO supplied brake disc. The BOP strains observed on the Knorr disc were not only smaller in amplitude, but they also died out in a much shorter time than the ones observed for the same shocks on the WABTEC/SAB-WABCO supplied disc. The BOP strains observed on both discs due to vertical impacts were found to have the same frequencies as those associated with out-of-phase vibrations on each of the brake discs observed during modal testing. The sustained oscillations of high BOP strains observed on the WABTEC/SAB-WABCO supplied brake disc during some brake applications were not observed on the Knorr disc during any brake applications.

  The highest amplitude of sustained BOP oscillations on the center WABTEC/SAB-WABCO supplied disc due solely to a brake application was ± 1,372 microstrain, average-to-peak, and was observed during a prolonged application of the brakes in which the mean tensile strain reached 2,202 microstrain and a temperature of 330 °F. An event was also identified in which the WABTEC/SAB-WABCO supplied disc was subjected to a vertical impact during a sustained oscillation resulting from a brake application.

  The highest BOP spoke strain on the WABTEC/SAB-WABCO supplied disc resulting from an asymmetric vertical impact had an amplitude of ± 1,487 microstrain, zero-to-peak, that required almost 0.20 seconds to die out. The same shock produced a BOP spoke strain with an amplitude of ± 290 microstrain, zero-to-peak, in the Knorr brake disc that required approximately 0.03 seconds to die out. The frequencies associated with the responses of each of the two brake discs were close to those associated with the out-of-phase responses of the discs determined in the modal tests.

  Strains in the preceding paragraphs are as measured and have not been corrected for pre-load strains in the spoke.

  The cross-sectional geometry of the spoke found on the Knorr disc offers a higher resistance to BOP vibration at the location at which the strain gages were installed than can be provided by that of the WABTEC/SAB-WABCO supplied disc spoke. Due to its higher cross-sectional area, the spoke of the Knorr disc will experience a higher stress because of thermal expansion than the spoke of the WABTEC/SAB-WABCO supplied disc will for a given thermal load. Appendix M addresses this subject.

- The highest temperature measured on either of the brake discs was 361 °F. This was on the order of what was expected by the brake suppliers.

  The Knorr brake disc heats up faster and cools down faster than the WABTEC/SAB-WABCO supplied brake disc. This difference in heating and cooling rates is considered small.

- The 187 Hz frequency associated with the sustained oscillation of the WABTEC/SAB-WABCO supplied disc during selected brake applications was observed in the accelerations and strains measured on the brake hardware during these periods of oscillation.

  During a given brake application, the caliper support links associated with the lead axle of the truck are in compression, and the links associated with the trailing axle are in tension. This is likely one of the aspects of the braking process that has influenced the observation that sustained oscillations during selected brake applications are only observed when the test axle was in the lead position. The fact that the links are in compression during periods of sustained oscillations during braking is important.

3.4 Further Consideration of Test Results

This section will address four topics that span across the various phases of the test effort:

- The impact of the strains measured on the brake discs to the fatigue life of the material.
- The sequence of events that led up to the sustained oscillations observed under certain braking conditions.
- A review of the frequencies identified throughout the report.
- The effect of cold weather on shock amplitudes.

3.4.1 Consideration of Strains and the Impact on Fatigue

As evidenced by the test results presented to this point, it is clear that the spokes of the WABTEC/SAB-WABCO supplied brake discs are subjected to tensile stresses due to heat buildup during braking and to oscillating stresses resulting largely from vertical shocks and dynamics during braking. The oscillating stresses can die out quickly, as is the case with those resulting from vertical shocks, or can last for an extended period of time, as observed in several of the brake applications highlighted in this report. The combination of mean stresses and oscillating stresses could have an impact on the fatigue life of the material. A consideration of the data from a fatigue point-of-view is warranted. ENSCO employed an exercise based on the Goodman criteria to determine where in the data significant combinations of mean and alternating strains, and consequently stresses, occur.

The Goodman criteria is traditionally conducted in a graphical fashion in which the mean strain that the part in question is subjected to is represented on the horizontal axis and the amplitude of the oscillating strain is represented along the vertical axis. The ultimate strain of the material is marked on the horizontal axis, and the endurance limit strain is marked on the vertical axis; the Goodman line connects these two points. Combinations of average and oscillating strains are plotted on this diagram. Points on this diagram that fall near the Goodman line merit further consideration in a rigorous fatigue analysis.[4]

This exercise does *not* represent a rigorous fatigue analysis. Among the factors that this treatment does not take into account are surface conditions, the presence of stress risers, and environmental conditions. This analysis was used merely as a way to identify situations of concern.

Table 3.13 shows the mechanical properties of the WABTEC/SAB-WABCO supplied brake disc used for this analysis. The table also provides the sources for this information. For the purpose of reference, Table 3.14 provides the material properties associated with the Knorr brake disc.

The ultimate strain and the endurance limit, equal to 30 percent of the ultimate strain shown in this table, were used to generate a Goodman fatigue curve for alternating and mean strains measured on the WABTEC/SAB-WABCO supplied brake disc. An automated routine was developed to identify the number of spoke strains, in either braking or non-braking situations, that were near or above the Goodman line. Appendix G explains this method. Both the number of cycles near the Goodman line and the number of events near the Goodman line were identified, where an event may include many cycles. Table 3.15 reports the results of the analysis in terms of cycles. In all the results determined for the WABTEC/SAB-WABCO supplied brake disc, a pre-strain of 1,000 microstrain was used, or 1,000 microstrain was subtracted from the measured tensile strain.

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[4] H. O. Fuchs and R. I. Stephens, Metal Fatigue in Engineering, (New York, NY: John Wiley & Sons, 1980) 72.

Table 3.13. Key Stress and Strain Values for WABTEC/SAB-WABCO Supplied Brake Disc

Value	Stress (MPa)	Stress (psi)	Comparison to Ultimate	Stress/E	Source
Young's Modulus (E)	210,345	30,500,000	-	-	Properties of Steel
Ultimate Strength	752	109,000	100%	3,574	SHTL
Yield Strength	550	79,750	73%	2,615	SHTL
Endurance Limit	226	32,700	30%	1,072	30% Ultimate
Pre-Strain (Press On)	84	12,200	11%	400	see Appendix J
Pre-Strain (As Built)	126	18,300	17%	600	see Appendix J
Pre-Strain (Total New)	210	30,500	28%	1,000	see Appendix J
True Fracture Stress (European)	1,232	178,689	164%	5,859	SHTL
True Fracture Stress (USA)	1,059	153,521	141%	5,033	SHTL

Table 3.14. Key Stress and Strain Values for Knorr Brake Disc

Value	Stress (MPa)	Stress (psi)	Comparison to Ultimate	Stress/E	Source
Young's Modulus (E)	210,000	30,450,000	-	-	SWL
Ultimate Strength	1,050	152,250	100%	5,000	N10193
Yield Strength	900	130,500	86%	4,286	N10193
Endurance Limit	300	43,500	29%	1,429	SWL
Pre-Strain (Press On)	112	16,230	11%	533	see Appendix J

Table 3.15. Number of Cycles Identified in Goodman Analysis of Mean/Oscillating Spoke Strains

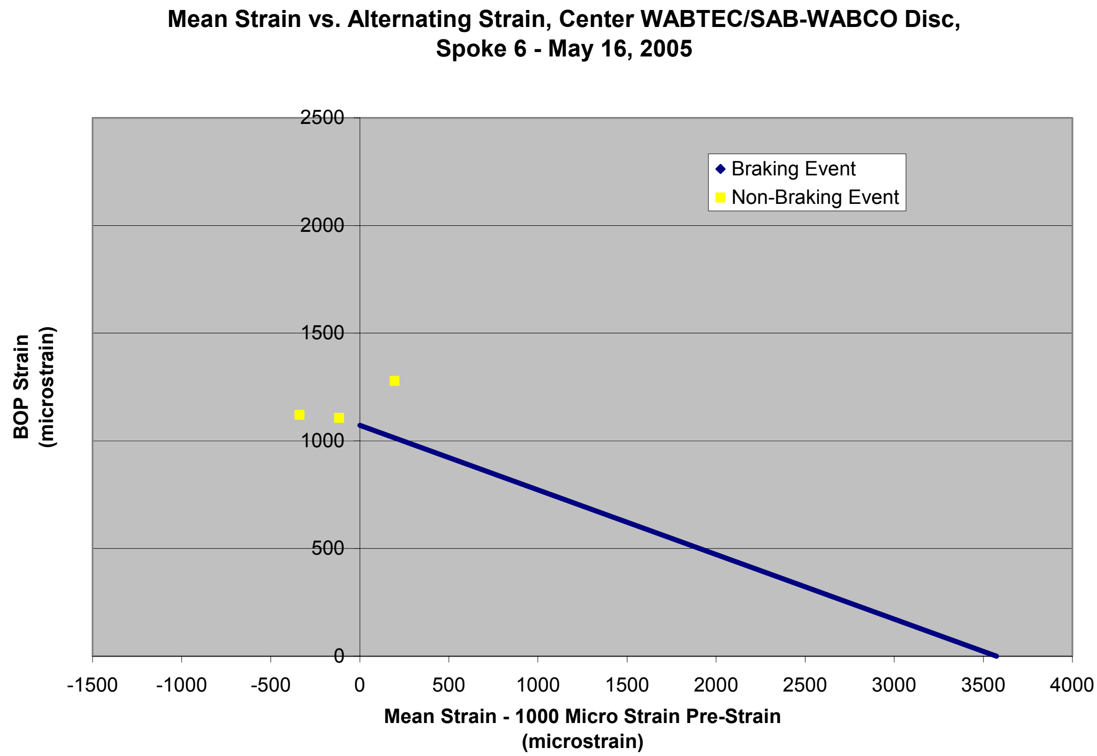
<table>
<tr><th></th><th></th><th colspan="8">WABTEC/SAB-WABCO Supplied Disc Axle 1</th><th colspan="2">Knorr Disc Axle 2</th></tr>
<tr><th></th><th></th><th colspan="4">Center Disc</th><th colspan="4">Outer Disc</th><th colspan="2">Center Disc</th></tr>
<tr><th></th><th></th><th colspan="2">Spoke 3</th><th colspan="2">Spoke 6</th><th colspan="2">Spoke 3</th><th colspan="2">Spoke 6</th><th colspan="2">Spoke 6</th></tr>
<tr><th></th><th>Date</th><th>NB</th><th>B</th><th>NB</th><th>B</th><th>NB</th><th>B</th><th>NB</th><th>B</th><th>NB</th><th>B</th></tr>
<tr><td rowspan="2">Phase 1</td><td>16-May</td><td>n/a</td><td>n/a</td><td>4.5</td><td>0</td><td>n/a</td><td>n/a</td><td>5.5</td><td>0</td><td>n/a</td><td>n/a</td></tr>
<tr><td>17-May</td><td>n/a</td><td>n/a</td><td>11.5</td><td>55</td><td>n/a</td><td>n/a</td><td>1</td><td>0</td><td>n/a</td><td>n/a</td></tr>
<tr><td rowspan="2">Phase 2</td><td>26-May</td><td>12</td><td>14</td><td>9</td><td>20</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td></tr>
<tr><td>27-May</td><td>6.5</td><td>0</td><td>10.5</td><td>0</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td></tr>
<tr><td rowspan="2">Phase 3</td><td>17-Jun</td><td>2</td><td>2,754</td><td>5</td><td>3,156.5</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>0</td><td>0</td></tr>
<tr><td>18-Jun</td><td>5</td><td>7,074</td><td>6</td><td>6,947</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>0</td><td>0</td></tr>
</table>

n/a – Test plan did not include this measurement.
B – Braking
NB – Not Braking

The table shows a very large increase in occurrences on June 17 and 18, especially those associated with braking. This increase was most likely due to a larger number of brake applications in rapid succession that were made on the last 2 days of testing than is typical in a revenue service run. No occurrences of mean strain/alternating strain were identified that would come close to a Goodman line observed on the outer disc in braking or for the Knorr disc in either braking or non-braking conditions.

Figures 3.68 through 3.73 illustrate the occurrences identified in the analysis. Each figure contains two plots, one for the strains recorded on each spoke considered during a particular test. The results from a given test are contained within the same figure. Each plot is comprised of the alternating (BOP) strains plotted against the mean (tensile) strains. No plots are provided for strains recorded on the Knorr disc. Only those points approaching the Goodman line are provided on the graph in order to focus on the cases that have an implication of fatigue life of the material. Although plots provided in Figures 3.68 through 3.73 are typically presented in terms of stress, the illustrations provided here are in terms of strain because strains have been referenced throughout this report. Appendix G further addresses the presentation of this data in terms of strain, and not stress.

It is important to remember that the peak strain levels recorded during the test do not necessarily occur when either the BOP strains or mean strains are at a maximum. The peak stress level occurs when the sum of the BOP and mean strain is a maximum. For instance, a BOP strain of 1,700 microstrain and a mean strain of -500 microstrain produce a strain level of 1,200 microstrain. A similar strain can occur with a BOP strain level of only 1,000 microstrain but with a mean strain level of 200 microstrain.



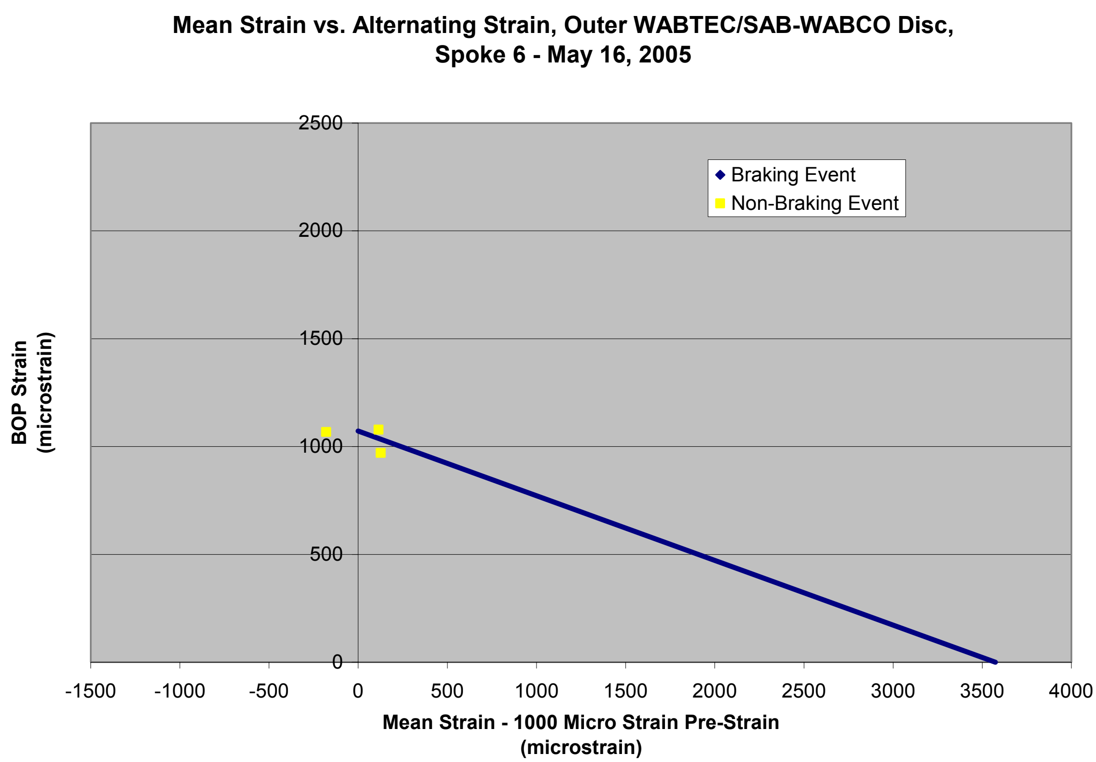
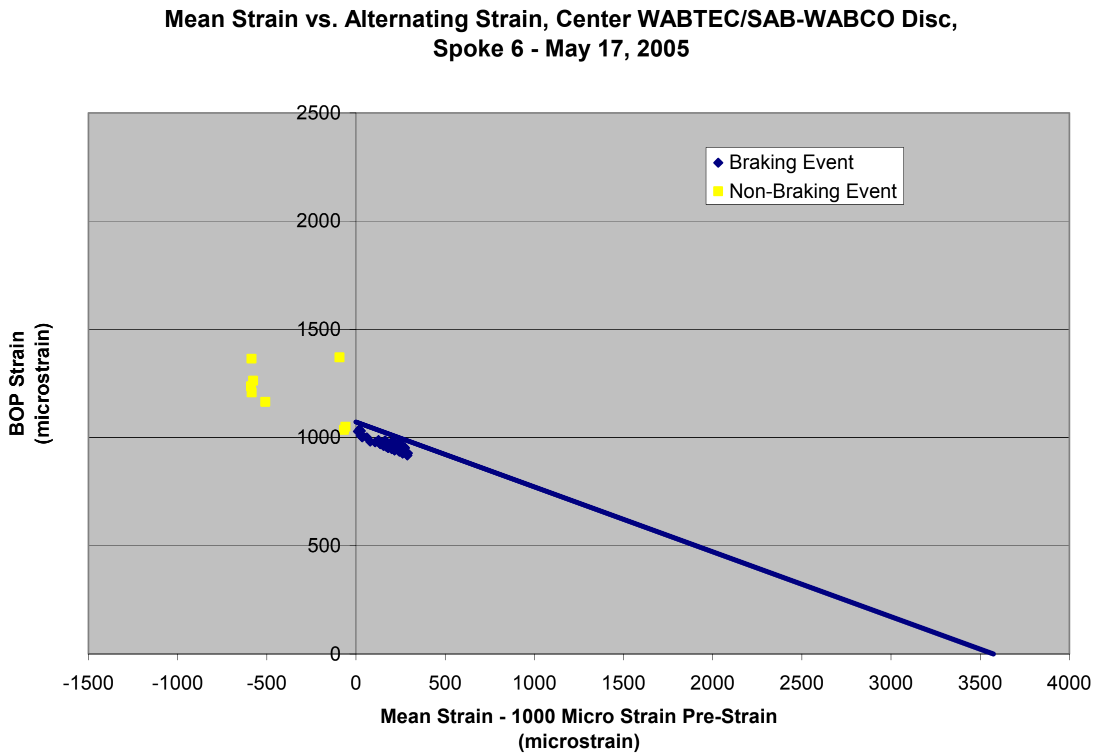


Figure 3.68. Mean Strain versus Alternating Strain, Center and Outer WABTEC/SAB-WABCO Supplied Brake Discs, Spoke 6–May 16, 2005



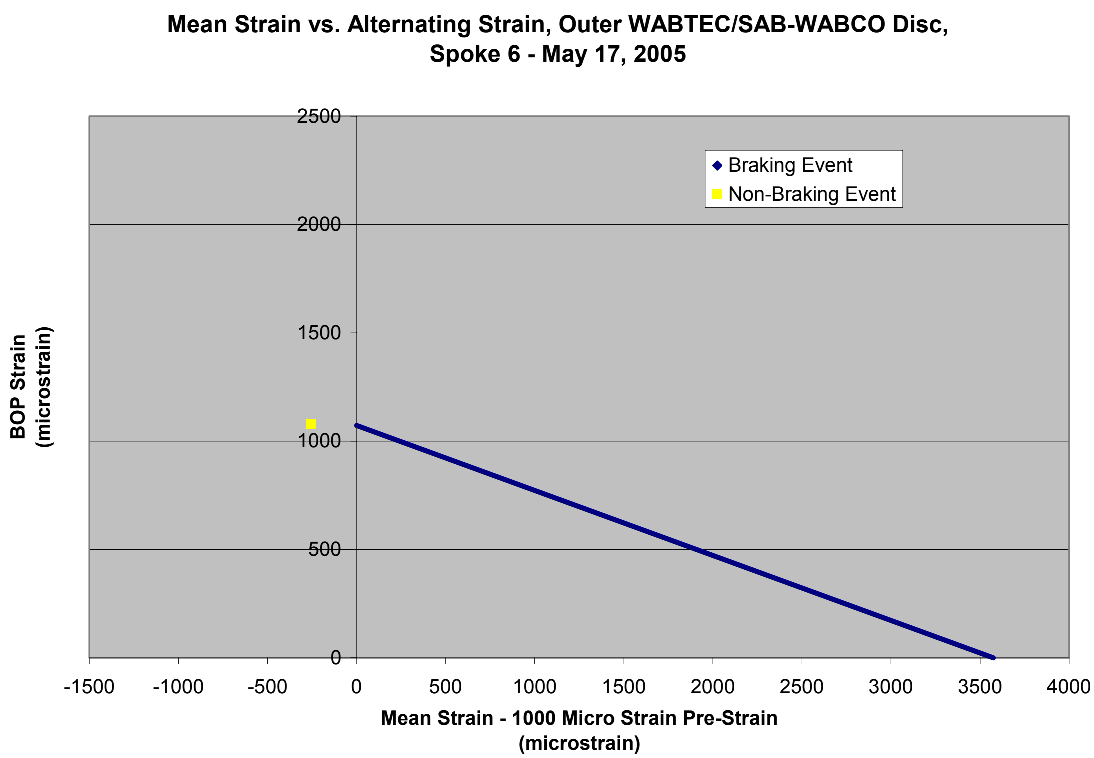
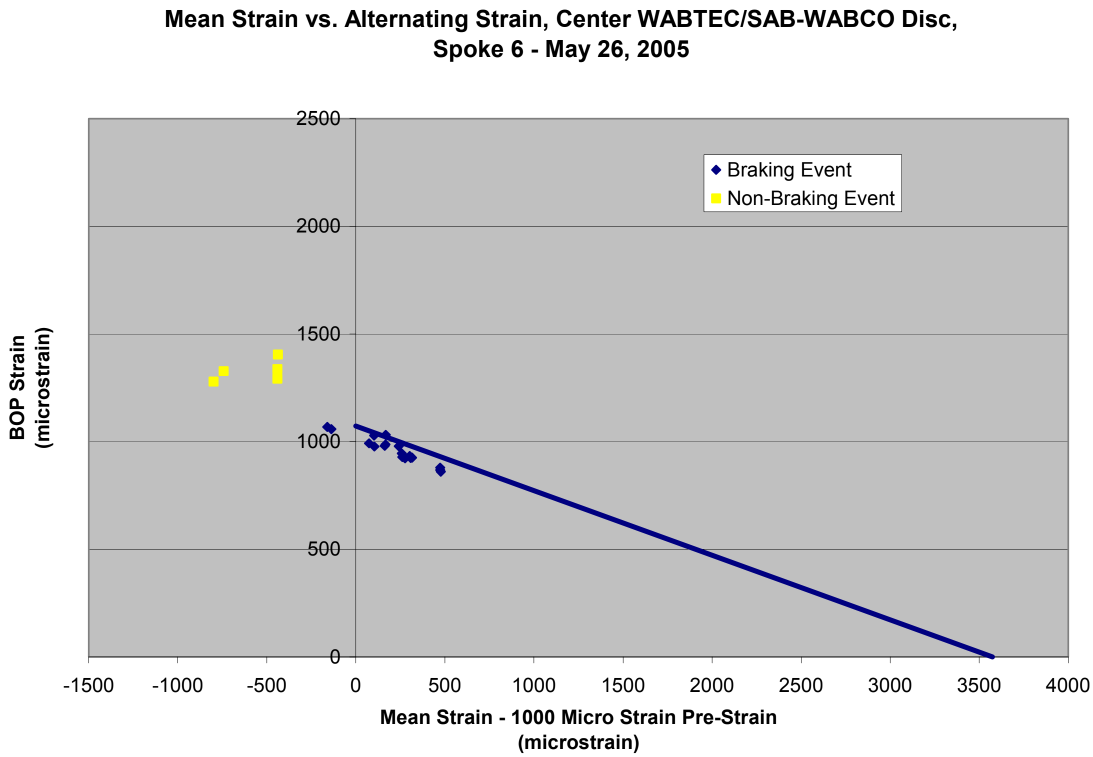


Figure 3.69. Mean Strain versus Alternating Strain, Center and Outer WABTEC/SAB-WABCO Supplied Brake Discs, Spoke 6–May 17, 2005



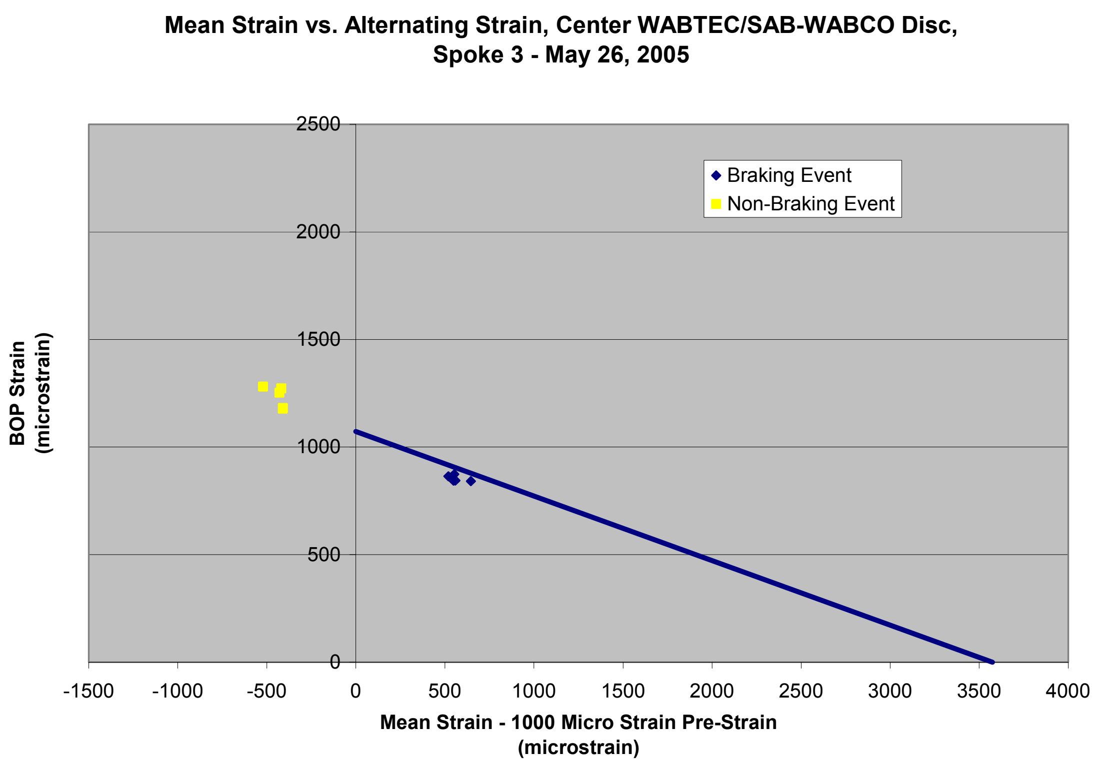
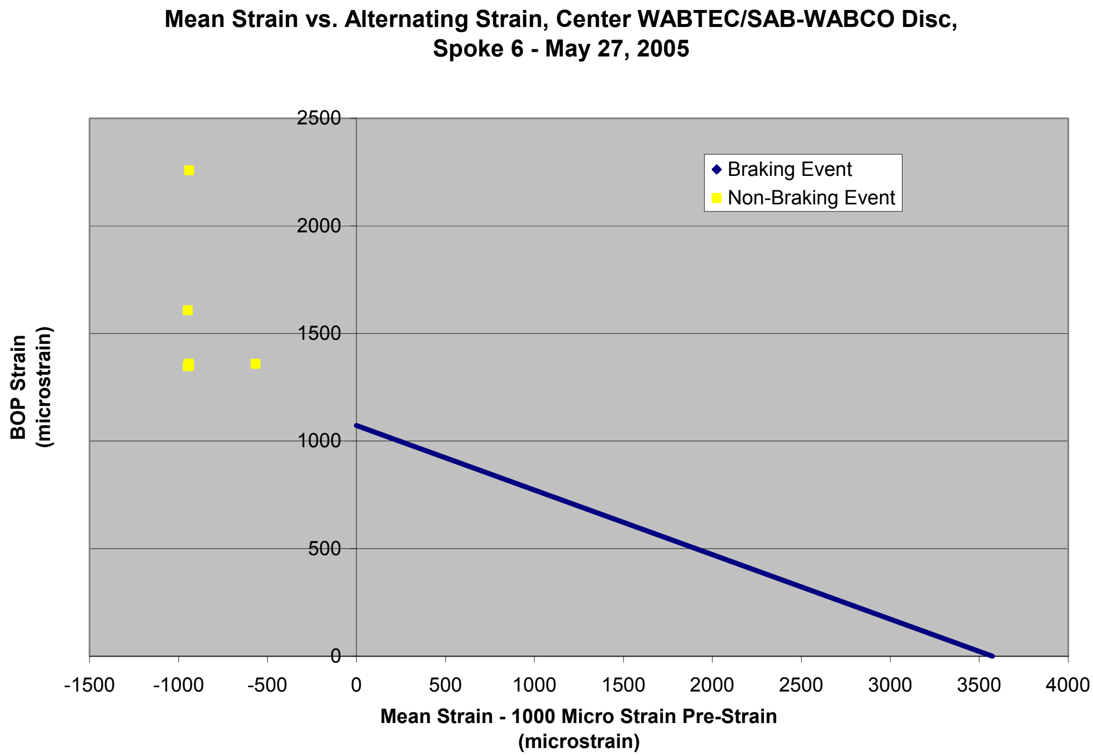


Figure 3.70. Mean Strain versus Alternating Strain, Center WABTEC/SAB-WABCO Supplied Brake Disc, Spokes 6 and 3–May 26, 2005



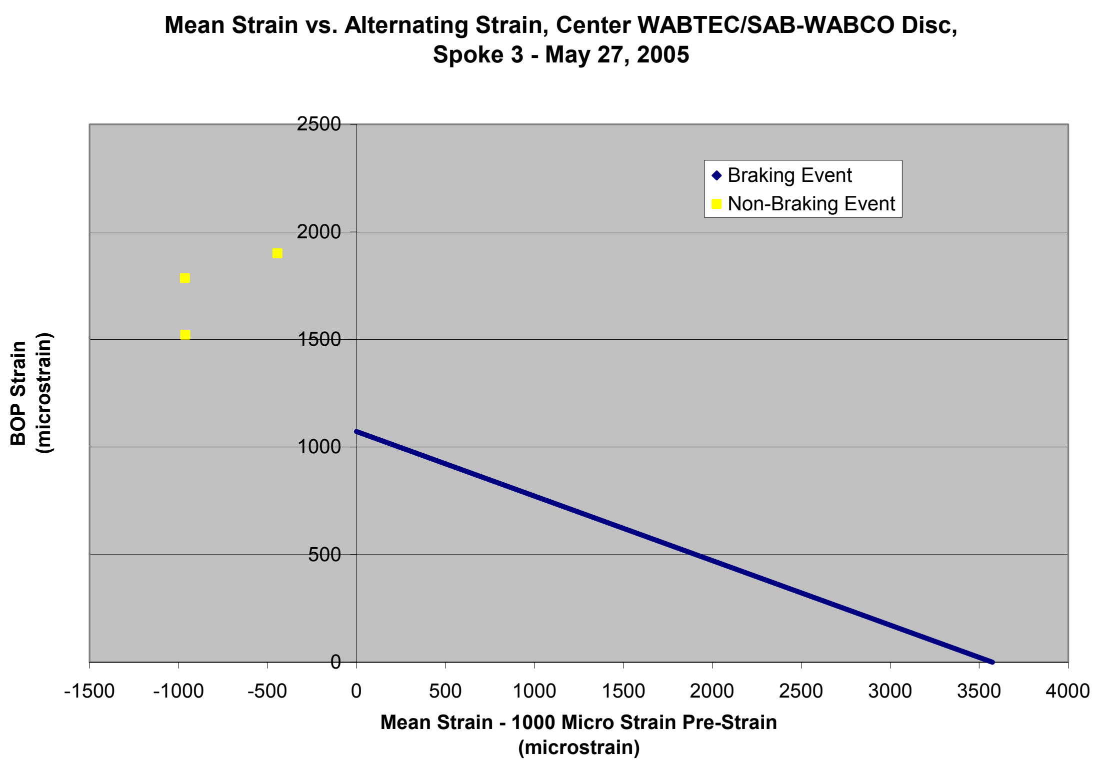
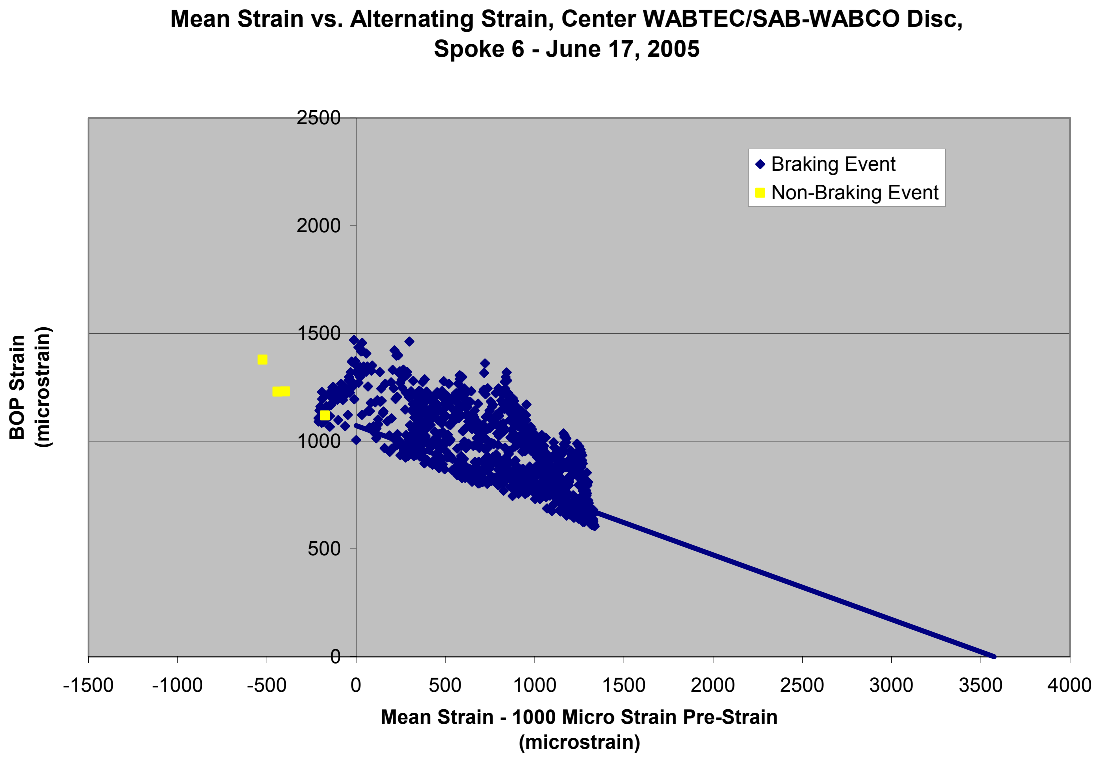


Figure 3.71. Mean Strain versus Alternating Strain, Center WABTEC/SAB-WABCO Supplied Brake Disc, Spokes 6 and 3–May 27, 2005



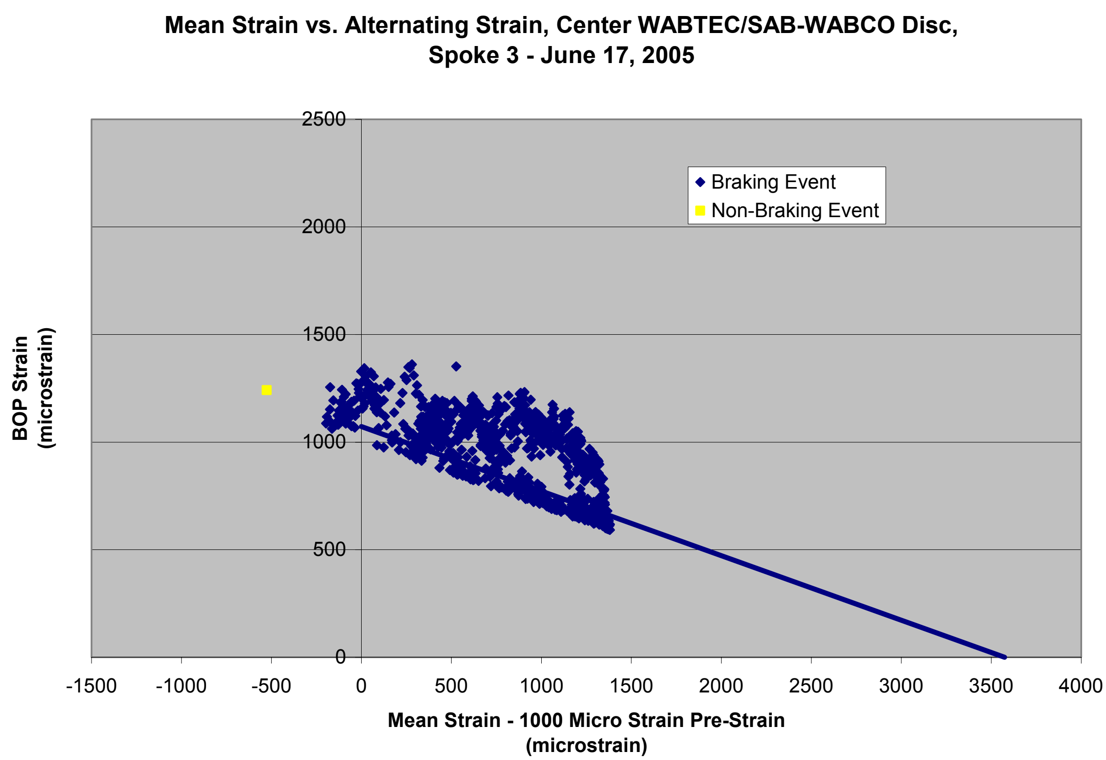
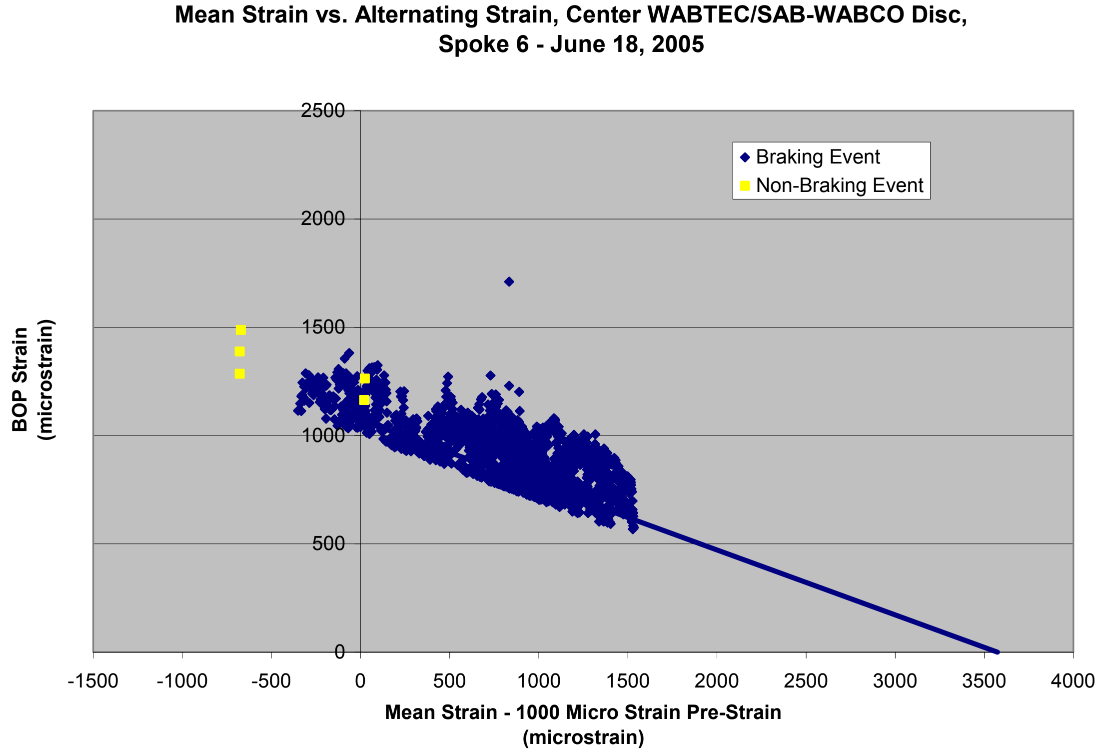


Figure 3.72. Mean Strain versus Alternating Strain, Center WABTEC/SAB-WABCO Supplied Brake Disc, Spokes 6 and 3–June 17, 2005



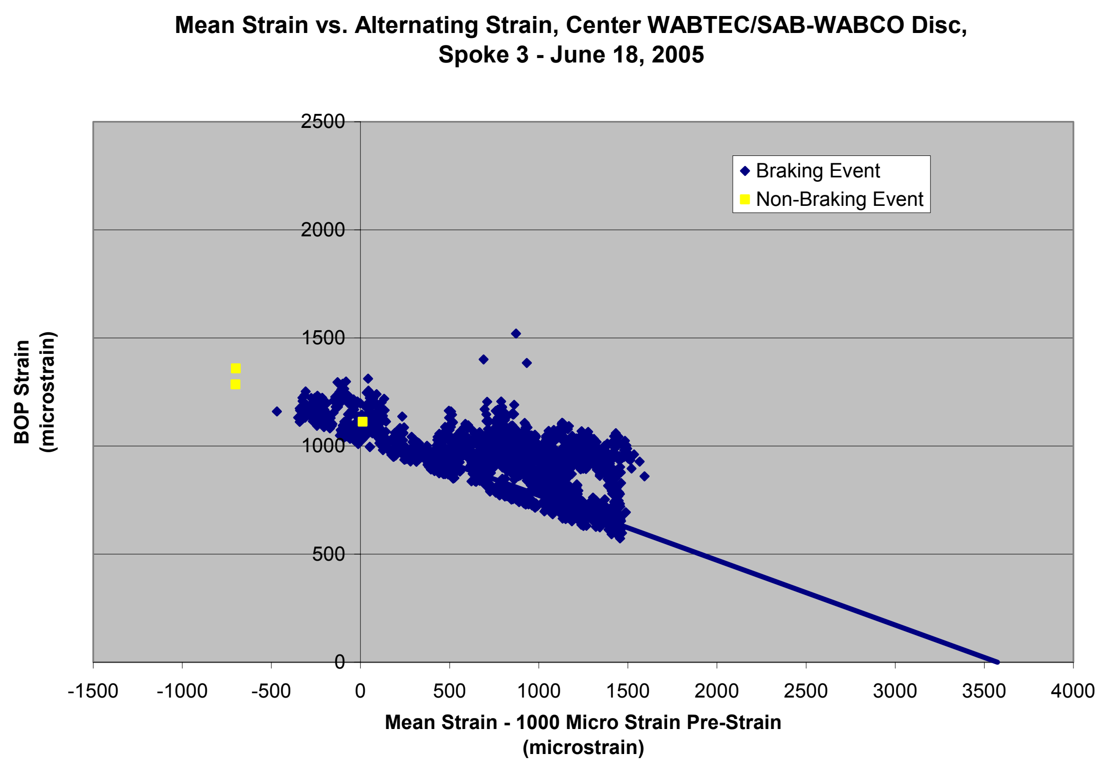


Figure 3.73. Mean Strain versus Alternating Strain, Center WABTEC/SAB-WABCO Supplied Brake Disc, Spokes 6 and 3–June 18, 2005

The most activity is observed to have taken place during Phase 3 testing. Again, the high number of points on the Goodman diagrams are likely due to the number of brake applications in rapid succession that were made on the last 2 days of testing. Brake applications made in rapid succession resulted in the heating of the discs, therefore creating higher mean, or tensile, strains. Alternating strains due to sustained oscillations or impacts will be plotted towards the right within the Goodman diagrams, thus creating more points plotted on the diagrams.

Comparison of the material properties of the two discs reveals that the Knorr brake disc has a higher ultimate strength and yield strength than the WABTEC/SAB-WABCO supplied brake disc does. Figure 3.74 provides an illustration of what the Goodman line for the Knorr disc would look like compared to the Goodman line prepared for the WABTEC/SAB-WABCO supplied disc. This illustration indicates that the material comprising the Knorr disc would provide a higher degree of protection against the effects of fatigue than the material comprising the WABTEC/SAB-WABCO supplied disc. The materials used for the different brake discs were selected using a variety of considerations. Appendix M provides information regarding the selection of material for the WABTEC/SAB-WABCO supplied brake disc.

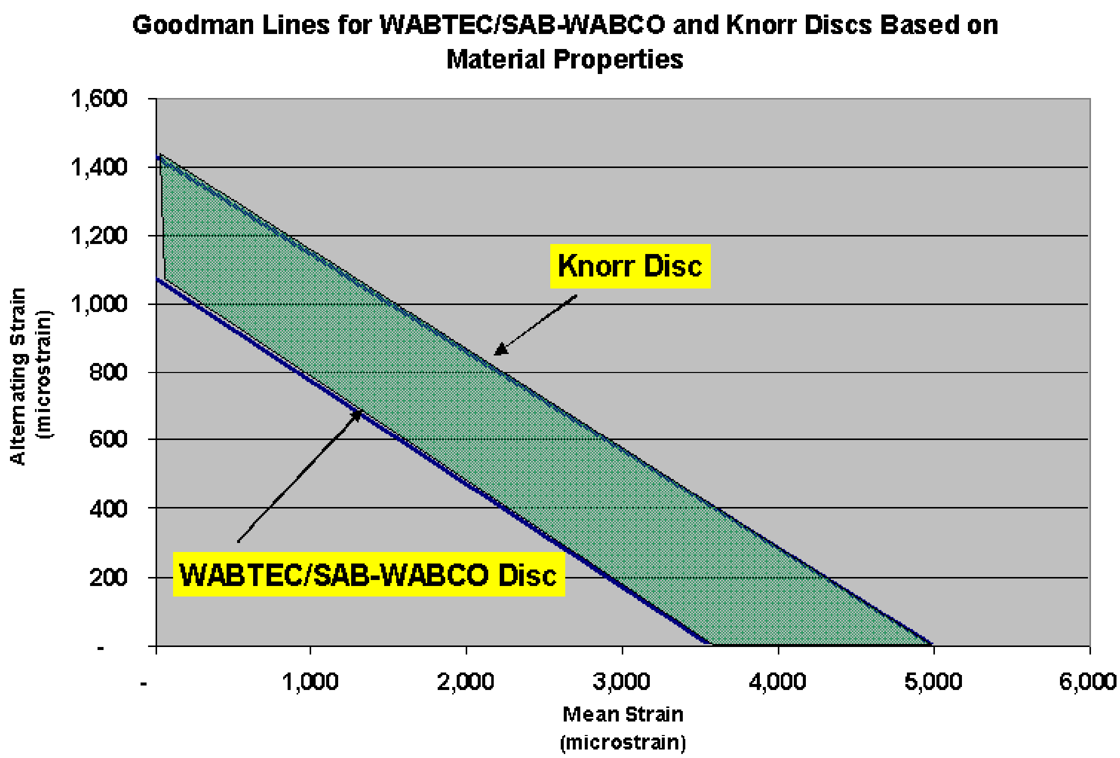


Figure 3.74. Comparison of Goodman Lines for WABTEC/SAB-WABCO Supplied and Knorr Brake Discs

3.4.2 Sequence of Events During Sustained Oscillations While Braking

The observations made regarding the sustained oscillations during some brake applications have characterized the event, but the cause and inception of the vibrations of the WABTEC/SAB-WABCO supplied brake disc have not been identified. To address this subject, the initial stages of four cases of sustained oscillations during braking recorded in Phase 3 testing were scrutinized in an attempt to identify the mechanism under which this motion manifests itself.

Table 3.16 identifies the four cases considered in this section.

Table 3.16. List of Cases of Sustained Oscillations During Braking Considered in Detail

Figure No.	Geographic Location	Measurements from Center Disc						Brake Cyl Press (psi)	Speed at Start of Braking (mph)
		Max Avg-to-Pk Amplitude (με)	Avg Strain @ Start (με)	Avg Strain @ End (με)	Disc Temp @ Start (°F)	Disc Temp @ End (°F)	Peak Disc Temp (°F)		
3.75	2089 NE of MP AP 4	532	1282	1348	169.2	212.2	242.1	46	85
3.76	464 W of MP AB 143	1139	1170	1686	222.3	227.2	247.0	50	107
3.77	1222 SW of MP AB 159	1132	1491	2315	249.6	301.4	327.8	54	120
3.78	1748 SW of MP AN 55	1455	1466	1974	226.7	261.9	325.6	56	133

Strains specified in Table 3.16 are as measured and have not been corrected for pre-load strains in the spoke. Figure 3.13 defines terminology used in Table 3.16.

The following parameters recorded on or near the WABTEC/SAB-WABCO test axle are illustrated in each of the figures:

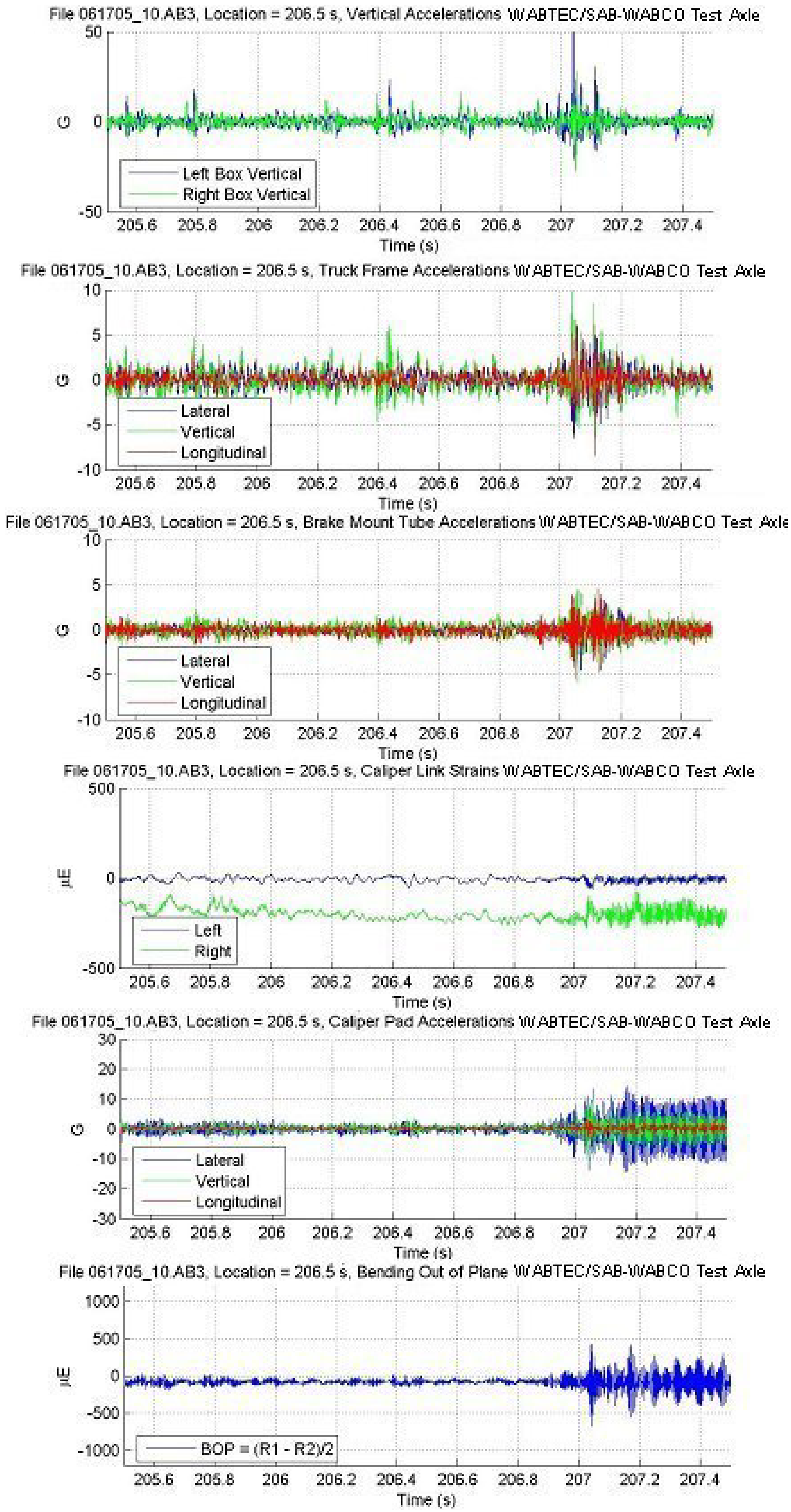
- The vertical accelerations recorded on the test axle
- The truck frame accelerations
- The accelerations recorded on the brake mounting tube
- The strains recorded on the caliper links
- The accelerations recorded on the caliper assembly near the pad
- BOP strain recorded on spoke 6

The arrangement of the illustrations allows one to follow the progression of the events from the rail, through the truck, and down to the brake disc. Based upon inspection of these figures, the following statements can be made:

- It appears that vertical shocks from the track can play a role in the development of the sustained oscillations during braking. Considering the event in Figure 3.75, clearly BOP strains and caliper pad motion have started before t~207 seconds, but the vertical shock measured at t~207.05 seconds appears to coincide with an increase in the amplitude of the BOP strain oscillation that continues to grow. The event that is depicted in Figure 3.78 shows that the BOP strain oscillations, the caliper pad motion, the strains in the caliper links, and the accelerations measured on the brake mounting tube all begin to show increased activity at the time that a vertical shock is measured on the test axle. The shocks in both of these particular examples are higher in amplitude on one end of the axle than on the other.

- It does not appear, however, that vertical excitation from the track is necessary to start the oscillations of the brake disc. In Figure 3.76, one can see the effects of a disturbance in the track at t~131 seconds on the brake disc, but this behavior appears to die out by t~131.2 seconds. The disc begins to display signs of increasing BOP strains at t~131.3 seconds, after the original activity has subsided. Inspection of Figure 3.77 shows that very little vertical activity is measured on the test axle, but the BOP strains in the brake disc have been initiated at t~32.2 seconds and continue to grow.

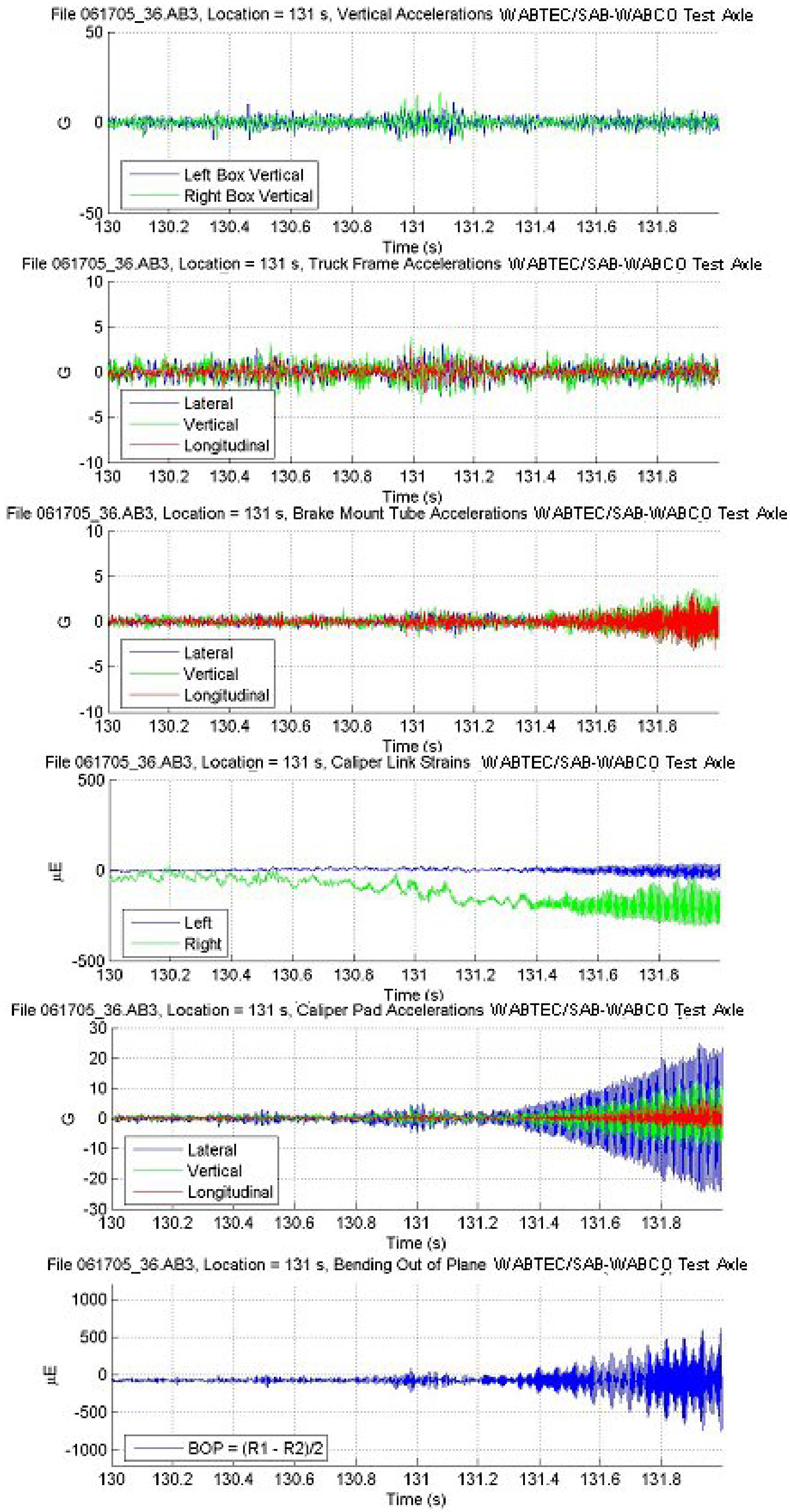
Ultimately, this document does not offer a definitive answer on the cause for the inception of the sustained oscillations of the WABTEC/SAB-WABCO supplied brake disc during some brake applications. The effects of brake cylinder pressure, initial temperature of the disc at the start of a braking event, speed, and the effects of previous braking events have been examined, but no clear pattern has been identified.



Notes:
Speed=85 MPH
Initial Temp=169.2 ºF

BOP Activity Starts t~206.9 s
Vertical Shock t~207.4 s

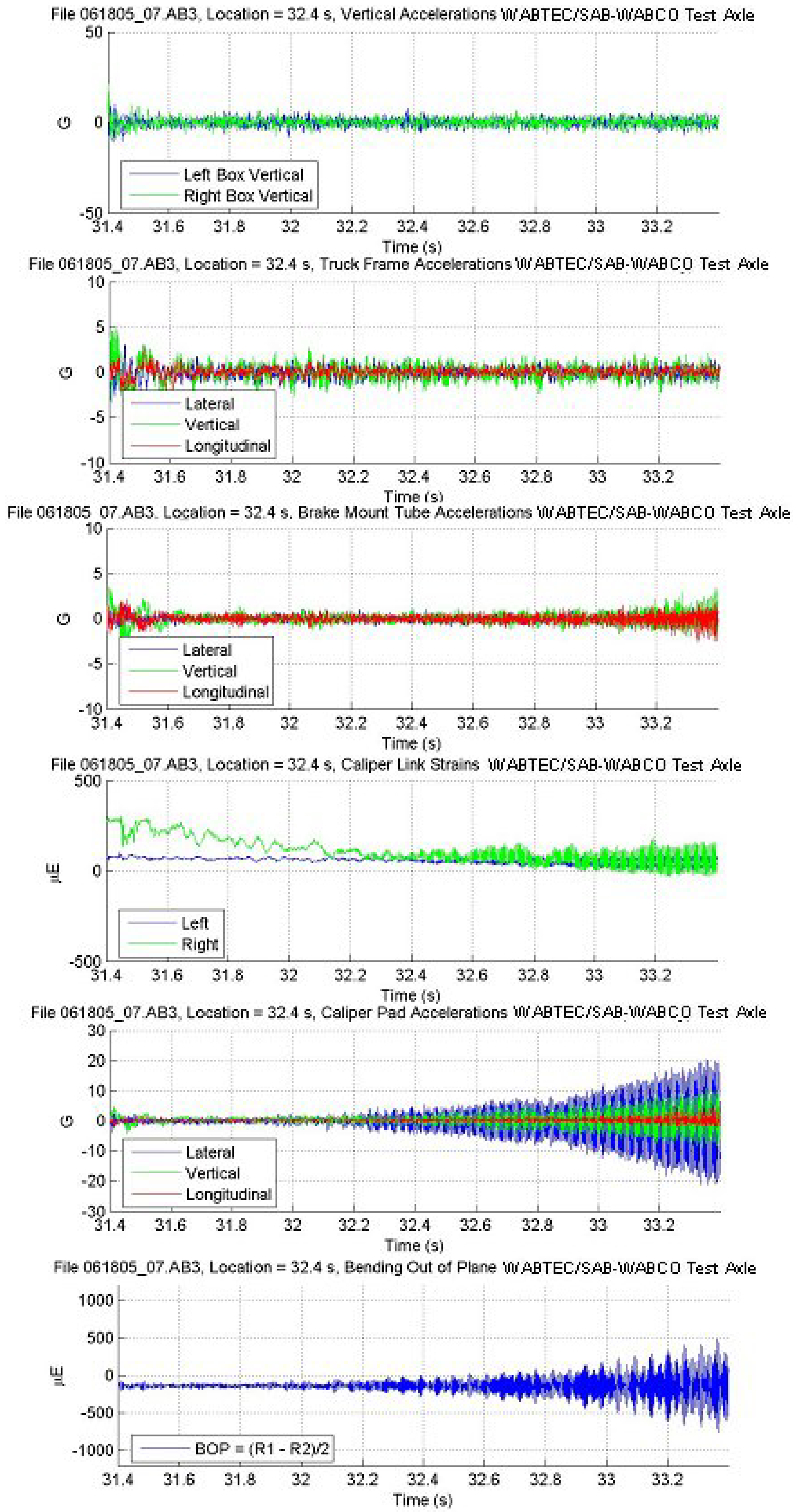
Figure 3.75. Inception of Sustained Oscillations During Braking, Near MP AP 3.5 (File 061705_10.AB3)– June 17, 2005



Notes:
Speed=107 MPH
Initial Temp=222.3 ºF

BOP Activity Starts t~131.2 s
Small Vertical Shock t~131 s, but effects appear to die out before t~131.2 s

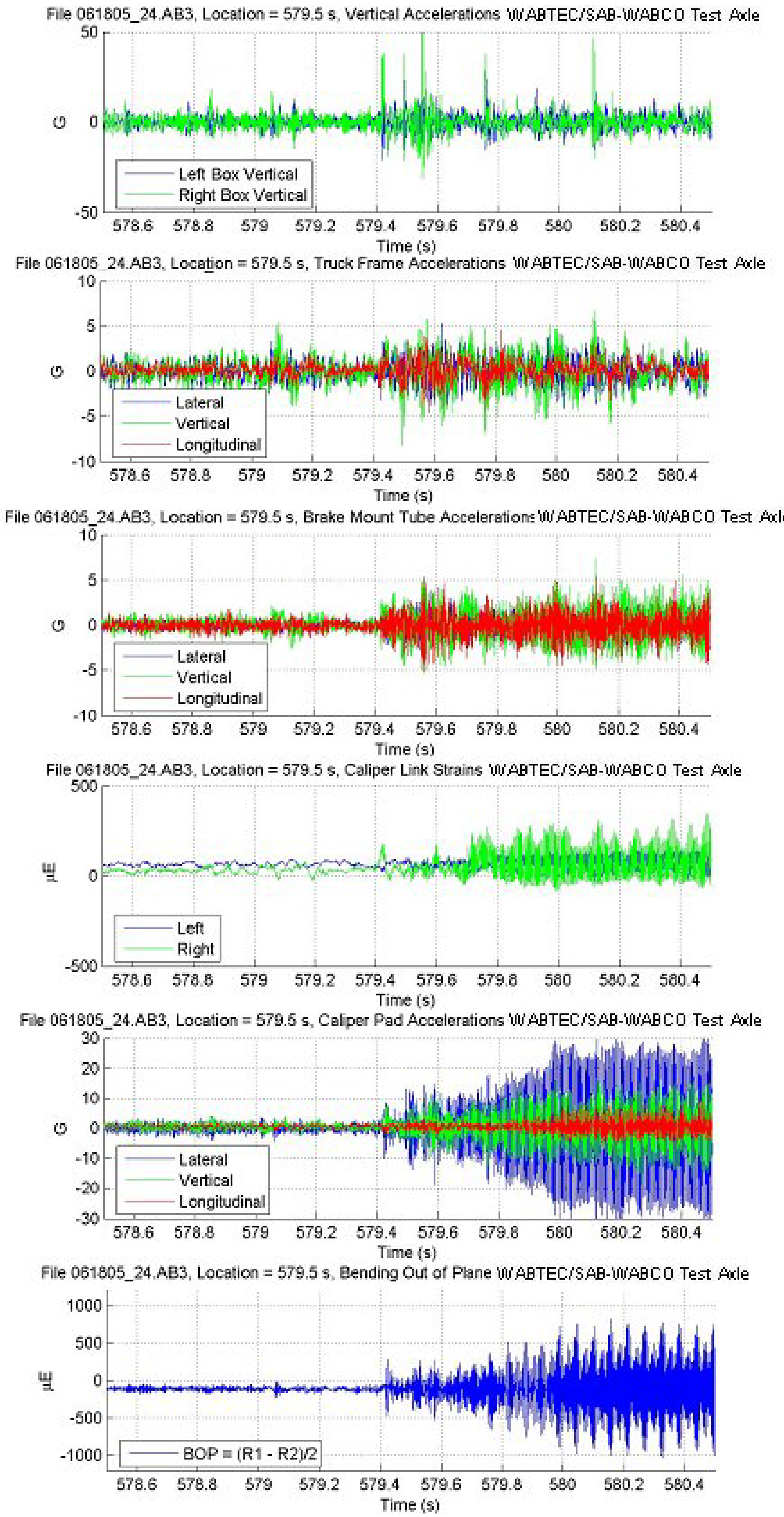
Figure 3.76. Inception of Sustained Oscillations During Braking, Near MP AB 143 (File 061705_36.AB3)– June 17, 2005



Notes:
Speed=120MPH
Initial Temp=249.6 ºF

BOP Activity Starts t~32.1 s
No Excitation from Track

Figure 3.77. Inception of Sustained Oscillations During Braking, Near MP AB 159 (File 061805_07.AB3)– June 18, 2005



Notes:
Speed=133 MPH
Initial Temp=226.7 ºF

BOP Activity Appears to Start at Same Time as Vertical Shock

Figure 3.78. Inception of Sustained Oscillations During Braking, Near MP AN 55 (File 061805_24.AB3)– June 18, 2005

3.4.3 Review of Frequencies

A number of different frequencies have been associated with the response of the WABTEC/SAB-WABCO supplied and Knorr brake discs under various conditions identified in this report. Table 3.17 provides a compilation of these frequencies and the conditions associated with them.

Table 3.17. Summary of Frequencies Determined During Acela Brake Disc Test Program

Method	Details	W/S-W Brake Disc	Knorr Brake Disc
First BOP Mode			
FEA	Only Brake Disc with Fixed Interior Hub Considered; Eigenvalue Analysis Conducted.	206 Hz	Not Measured
Hammer/Accelerometer Test	Conducted on Assembled Wheelset Supported by Jack Stands at Bearings; Frequency Analysis Conducted on Response to Hammer Blow.	220 Hz	Not Measured
Hammer/Strain Test	Conducted on Wheelset Installed in Truck Supported by Track; Frequency Analysis Conducted on Response to Hammer Blow.	Not Measured	351 Hz
Response to Vertical Impacts During Over-the-Road Test	Frequency Analysis Conducted on Response to Impacts.	224 Hz-227 Hz	344 Hz
Sustained Oscillations During Braking			
Behavior During Over-the-Road Test	Frequency Analysis Conducted on Response of Discs.	185 Hz-187 Hz	Not Observed

3.4.4 The Effect of Cold Weather on Shock Amplitudes

The magnitudes and the natures of shocks measured on the test axles have been discussed in great detail throughout this document. Previous studies conducted for Amtrak have shown that cold weather, along with its effect on the track structure, affects the loading experienced by brake discs.

During the winter months of 1977, 1978, and 1979, the pins employed in the Knorr brake disc used on the Amfleet and Turboliner passenger vehicles operating on the NEC and in the Midwest to secure the friction ring to the hub of brake disc were found to loosen. These pins loosened to such a degree that they were often bad ordered, requiring repair. Amtrak observed a significant increase in the failure rate around the beginning of February. Amtrak and FRA developed a test program to investigate the high failure rates and evaluate alternate designs. ENSCO conducted over-the-road and laboratory testing to support the test program.

The objective of the over-the-road tests was to gain an understanding of the effects of the environment (winter/summer) on the disc brakes by measuring the dynamics of a wheelset. Over-the-road tests featured two accelerometers mounted to the bearing housing of an axle, one mounted in the vertical direction and the other in the lateral direction, and additional test instrumentation mounted to non-rotating components of the truck. The accelerometers signals were processed using a root mean squared technique based on selected time segments chosen to represent different consist speeds and track locations. Accelerometer data was processed to determine the percent of the time that the acceleration exceeded a given level. The effect of the bandwidth of the acceleration data was also investigated.

Results from over-the-road testing demonstrated that the axle and discs are subject to higher acceleration levels (RMS) when the temperature is below 32 ºF. In the Executive Summary of the final report, the investigators stated:

> The tests showed that the accelerations were more than two to one higher on 26 February when the roadbed was partially frozen than on the 8 March test after the temperature had been above freezing for a week. Even higher accelerations were observed during the shakedown run which was made in the middle of a severe cold weather period of the 1979 winter. [5]

Amtrak maintenance records corroborated the results cited above. Records showed a sharp failure rate increase as the average daily temperature fell below 32 ºF. This pattern was apparent in 1978 and 1979 and was similar in 1977. The failure rate was significantly reduced 5 weeks after the average daily temperature exceeded 32 ºF.

Findings from the investigation cited above suggest that the shocks reported in this document, based on measurements made in May and June, may be lower than shocks that would be measured if the study were conducted in the winter due to stiffening of the ballast as a consequence of cold weather.

[5] R. Scofield & R. "Avant, Amtrak/Knorr Brake Disc Study," DOT Report No. FRA/ORD-80/62, September 1980.

4.0 OBSERVATIONS

The following observations are made based on the test data, laboratory tests, and analysis provided in the appendices. Following each statement will be a reference to the material within the report where supporting information can be found.

4.1 Accelerations

1) The magnitude of measured acceleration levels was influenced by the location and orientation of the accelerometer, rate at which the data is recorded, and speed of the train.
   - Accelerations measured on the test axles generally increase with speed [Section 3.2.2, Figure 3.27].
   - Lateral accelerations measured on the axle boxes at the end of the axle are generally higher than lateral accelerations measured on the axle [Section 3.1.2; Section 3.2.2, Figure 3.25; Section 3.3.3, Figure 3.47].
   - A maximum vertical acceleration of 189 g was measured on the end of the WABTEC/SAB-WABCO test axle [Section 3.3.3].
   - Vertical accelerations measured on axle bearing boxes are 2 to 3.7 times that of the lateral accelerations measured at the same location [Section 3.2.2, Figure 3.27, Figure 3.28].

2) The load environment does not change significantly when the direction of the train changes for a given configuration [Section 3.1.2; Section 3.2.2].

3) Vertical accelerations measured on axle bearing boxes exceed 50 g approximately 80-160 times per day [Section 3.1.2, Figure 3.6; Section 3.2.2, Figure 3.25; Section 3.3.3, Figure 3.46].

4) Vertical accelerations measured on axle bearing boxes exceed 100 g between 5 and 21 times per day [Section 3.1.2, Figure 3.6; Section 3.2.2, Figure 3.25; Section 3.3.3, Figure 3.46].

5) The number of high acceleration events on each test axle remains similar from day to day [Section 3.1.2; Section 3.2.2; Section 3.3.3].

6) The events where vertical accelerations exceeded 100 g were generally observed at switches, bridge approaches, and other special track work [Appendix F].

7) Vertical accelerations measured on the test axles above 100 g are observed at speeds as low as 42 mph [Appendix F].

8) High-amplitude vertical shocks can cause the WABTEC/SAB-WABCO supplied brake disc to exhibit high out-of-plane, first-mode bending strains with a frequency of 224 Hz to 227 Hz [Section 3.1.3; Section 3.2.3].

9) Vertical shocks during episodes of sustained oscillations during some brake applications can increase the severity of the BOP strains for a short duration [Section 3.3.4; Section 3.4.1].

4.2 Spoke Strains

1) For both the WABTEC/SAB-WABCO supplied and the Knorr brake discs, the spokes of the disc are pre-stressed (compressed) when the disc is pressed onto the axle. Based on testing conducted on one Knorr brake disc and two WABTEC/SAB-WABCO supplied brake discs:

   - For the WABTEC/SAB-WABCO supplied disc, the press-off operation relieved an average of 390 microstrain per spoke [Section 3.3.1; Appendix J, Part B].
   - Cutting all six spokes of a WABTEC/SAB-WABCO supplied brake disc relieved an average strain of 600 microstrain per spoke [Section 3.3.1; Appendix J, Part B].
   - Measurements made on a retired WABTEC/SAB-WABCO supplied disc with two cracked spokes showed no pre-strain in the two cracked spokes and retained strain levels of 680-800 microstrain on two of the remaining spokes [Section 3.3.1; Appendix J, Part B].
   - For the Knorr brake disc, the pressing operating used for installation produced an average compressive strain of 533 microstrain per spoke; data was not taken to confirm the residual strain in the spoke of the Knorr disc [Section 3.3.1; Appendix J, Part B].

   Appendix M discusses the nature of the residual compressive stresses.

2) For Knorr brake discs and WABTEC/SAB-WABCO supplied brake discs mounted in the center and outer position of the axle, the observed strains in the spokes were principally due to tension resulting from heating during braking, BOP of the spoke and, to a lesser degree, BIP of the spoke [Section 3.1.3].

3) Spoke tensile strains were mainly due to the heating of the friction rings during braking and reached levels near 2,700 microstrain for the WABTEC/SAB-WABCO supplied disc and 2,900 microstrain for the Knorr disc [Section 3.3.6].

4) An estimate of the average change in tensile strain as a function of temperature measured on the back of the friction was arrived at by determining the temperature on the back of the friction ring before brake application and correlating it with the corresponding tensile strain in spoke 6. Choosing to consider the temperatures prior to the brake applications allows for equalization of temperatures throughout the disc. These estimated thermal strains would not account for any existing pre-load strains in the spoke.

   On the WABTEC/SAB-WABCO supplied disc, the average tensile strain in the spokes increases by approximately 7.4 microstrain/ ºF. For the Knorr disc, the average tensile strain in the spokes increases by approximately 8.5 microstrain/ ºF [Section 3.1.5; Section 3.2.4; Section 3.3.6; Appendix I].

5) For the WABTEC/SAB-WABCO supplied disc, an out-of-phase BOP mode at a damped natural frequency near 227 Hz is observed in response to vertical impacts [Section 3.1.3; Section 3.2.2; Section 3.3.4].

   - BOP strains resulting from vertical impacts reached an amplitude of ± 2,260 microstrain, zero-to-peak [Section 3.2.2].
   - Extreme responses to vertical impacts commonly reached values close to ± 1,500 microstrain, zero-to-peak [Section 3.1.3; Section 3.3.4].
   - The WABTEC/SAB-WABCO supplied disc's response to asymmetric vertical impacts was more severe than that resulting from impacts of similar magnitude being inflicted upon the ends of the axle [Section 3.2.2].

- The responses of the center and outer WABTEC/SAB-WABCO supplied brake discs to vertical impacts are similar to each other [Section 3.1.3].

6) During some braking applications, sustained oscillations of the WABTEC/SAB-WABCO supplied brake disc in the BOP mode were observed.
   - This behavior was observed on the center and outer brake disc, but the amplitudes of the oscillations were higher on the center disc typically by a factor of 2.9 to 3.4 [Section 3.1.3; Appendix G].
   - The frequency associated with this oscillation was typically 186 Hz [Section 3.1.3; Section 3.3.4].
   - The magnitude of the sustained oscillations increased with increasing brake cylinder pressure [Section 3.1.6; Section 3.3.8].
   - Sustained BOP oscillations during braking were only observed when the test axle was in the lead position or when the brake caliper links were in compression during braking [Section 3.1.3; Section 3.2.3; Section 3.3.4; Section 3.3.7].
   - The duration of this sustained BOP oscillation of the WABTEC/SAB-WABCO supplied disc during braking was as long as 44 seconds (8,800 cycles) [Section 3.2.2, Table 3.2].
   - Excitation from a vertical shock appears to be able to start the sustained oscillation, but it is not necessary for the oscillations to start [Section 3.4.2].

7) For the Knorr brake disc, an out-of-phase BOP mode at a damped natural frequency of 344 Hz is observed in response to vertical impacts [Section 3.3.4].
   - BOP strains resulting from vertical impacts reached an amplitude of ± 290 microstrain, zero-to-peak and died out much sooner than those on the WABTEC/SAB-WABCO supplied brake disc [Section 3.3.4].

8) For the Knorr disc, no sustained oscillations during braking were observed [Section 3.3.4; Section 3.4.1].

9) For the WABTEC/SAB-WABCO supplied disc, BIP strains are small compared to BOP strains [Section 3.1.3].

4.3 Axle Strains

1) Axle strains were modulated by the wheel rotational rate [Section 3.2.4].

2) The amplitude of the axle strains is significantly affected by the lateral acceleration imposed on the test axle as it is operating through a curve. Large axle strains were observed during high cant deficiency operations [Section 3.3.5].

4.4 Temperature of Friction Ring

1) For both the WABTEC/SAB-WABCO supplied and Knorr brake discs, the temperature measured on the back of the friction ring surface can reach a level of 360 °F [Section 3.3.6, Figure 3.55].

2) The Knorr brake disc heats up faster and cools down faster than the WABTEC/SAB-WABCO supplied brake disc. This difference in heating and cooling rates is considered to be small [Section 3.3.6].

4.5 FEA Model

1) The finite element model of the WABTEC/SAB-WABCO supplied brake disc showed good agreement with test results.
   - The BOP mode frequency was calculated to be 206 Hz; a value of 227 Hz was observed during over-the-road testing [Section 3.1.1].
   - The model indicated that the area of highest stress in the spoke were located approximately where the cracks were observed [Section 3.1.1].

4.6 Brake Caliper Links

The following observations are based on the Phase 3 testing of two instrumented brake links used with the center disc of WABTEC/SAB-WABCO test axle:

1) The links show a tensile strain change when the axle was in the trailing position and a compressive strain change when the axle was in the lead position [Section 3.3.7].

2) The right and left links did not show equal changes in the braking loads for a given brake application.
3) The left link produced the largest strain change (by a factor of 6) when the axle was in a trailing position [Section 3.3.7].
4) The right link produced the largest strain change (by a factor of 7 to 10) when the axle was in the lead position [Section 3.3.7].

5) Instances of sustained BOP oscillations during braking of the WABTEC/SAB-WABCO supplied brake disc were only observed when the test axle was in the lead position or when the links were in compression during braking [Section 3.1.3; Section 3.2.3; Section 3.3.4; Section 3.3.7].

6) During episodes of braking with sustained oscillations, the links exhibited oscillations of strain at a frequency of 187 Hz with strong harmonic content [Section 3.3.7, Figure 3.63].

5.0 CONCLUSIONS

The original goals of this evaluation were to gather data from which the causes and contributing factors associated with the observed cracking of the original (WABTEC/SAB-WABCO supplied) disc could be determined. Following initial tests an axle equipped with brake discs of a different design (Knorr) was included in a second series of tests. The goals of the latter portion of the evaluation were to determine whether the Knorr disc demonstrated acceptable thermal and mechanical response of the spokes under the conditions tested for service with the Acela Express vehicles.

The following key observations and conclusions are drawn from testing and analysis:

1) A detailed metallurgical analysis of a section of a cracked brake disc conducted at the onset of the investigation revealed that cracks developed due to a progression of bending fatigue that originated along a decarburized surface layer. The report states: "Although the decarburized surface provided a site for fatigue initiation, the root cause of the cracking is the level of bending stresses at the crack sites."

   The inspection revealed that, with the exception of the thin decarburized surface layer, the brake disc casting met mechanical and chemical specifications.

2) Sustained out-of-plane bending oscillations were observed on the WABTEC/SAB-WABCO supplied disc during some brake applications. The oscillating strains associated with this activity were found to be up to ± 1,370 microstrain on a disc mounted in the center position of the axle. The magnitude of the sustained oscillations on the center disc was 2.9 to 3.4 times that observed on the outboard disc. The magnitude of the oscillating strain was observed to grow proportionally with higher brake pressure. During braking events, these oscillating strains were added to the mean (tension inducing) strains associated with the heating of the disc friction surface. Braking-induced oscillations were sustained through the duration of brake application, typically lasting on the order of 10 seconds, but lasting up to 47 seconds. The frequency of these braking related oscillations was 187 Hz. This activity was only observed on the WABTEC/SAB-WABCO supplied disc when the test axle was in the leading position of the truck. This activity was not observed at any time for the Knorr disc.

   These responses are relevant to the fatigue life evaluation. The absence of this activity in the Knorr disc is expected to provide a beneficial effect on the fatigue life and a reduction in the likelihood of crack formation.

   The sustained out-of-plane bending did not occur during all brake applications for the WABTEC/SAB-WABCO supplied disc. Once it was observed, it was not always repeatable during a given test run.

3) Accelerations at the journal box were observed at several track locations with most peaks in the range of 50 to 100 g vertical and 30 to 50 g lateral. Up to 21 peaks were measured in the vertical direction in excess of 100 g per one-way trip between Washington and Boston, with the maximum vertical acceleration reaching 189 g. These were generally observed at switches, bridge approaches, and other special track work. Because these measurements were made in May and June, further stiffening of the ballast as a consequence of cold weather may result in higher loads.

   For center and outer WABTEC/SAB-WABCO supplied discs, when an asymmetric vertical shock occurred independent of braking, it frequently induced large out-of-plane bending oscillations of the spokes. These oscillations were observed to be of similar amplitudes on the center and outer discs. For an asymmetric vertical shock of 102 g, oscillation-amplitudes were observed up to ± 2,260 microstrain and damped out in a short time. These oscillations were observed at a frequency of 227 Hz. Laboratory tests on a wheel-axle assembly have indicated a natural out-of-plane bending frequency of 220 Hz for the brake disc. Since shocks of this nature are independent of braking, these oscillations did occur about a wide range of mean strain levels.

A similar response to vertical shocks was observed for the Knorr disc, but the amplitudes of these strains were typically 40 percent of the strains observed on the WABTEC/SAB-WABCO supplied disc, and these strains damped quicker.

Lateral shocks did not appear to induce similar oscillations in either of the disc designs tested.

These responses are relevant to the fatigue life evaluation of the two disc designs.

The reduced level of strains observed in the Knorr disc is expected to provide a beneficial effect on the fatigue life and a reduction in the likelihood of crack formation.

4) Temperatures of the brake disc friction ring and strains associated with this thermal heating under test braking conditions were within normal ranges and on the order of what was expected by the brake suppliers.

5) The installed WABTEC/SAB-WABCO supplied disc retains a compressive preload in the spokes. Laboratory tests on a disc that was removed from service showed compressive strain measurements in the range of 800-1135 microstrain. This compares with the 333-618 microstrain values determined by the suppliers due solely to the pressing of the brake discs on to the axle.

6) Finite Element Analysis indicated the highest strains associated with out-of-plane bending at the location of the observed cracking. Discontinuities found on the surface of some spokes arising from a mold parting line also appeared in this location.

In summary the following conclusion is drawn:

The mechanical and thermal responses of the spokes of the Knorr designed disc measured during testing with the Acela Express vehicles were within predicted and acceptable values. Although experiencing slightly lower thermal strains, the WABTEC/SAB-WABCO supplied disc experienced significantly higher mechanical strains at times. The lower mechanical strains observed in the Knorr design disc, in comparison with those observed in the WABTEC/SAB-WABCO supplied disc, associated with the absence of sustained oscillations during braking and the response to vertical shocks are expected to provide a beneficial effect on the fatigue life associated with the Knorr disc design, as well as a reduction in the likelihood of crack formation.

The findings discussed in this report permitted Amtrak to arrive at an acceptable alternative that allowed the Acela equipment to return to service.

TECHNICAL DEFINITIONS

	Definition
Cant Deficiency	For a train traveling through curved track at a given speed, the cant deficiency is the additional height that the elevated rail would have to be raised in order to produce a condition in which there is no net lateral force exerted on the rail.
Decibels	A unit for expressing the ratio of two amounts of electric or acoustic signal power equal to 10 times the common logarithm of this ratio
Truck/Bogie	Swiveling carriage consisting of a frame, two pairs of wheels and a collection of springs used to carry and guide one end of a railroad car during navigating over railroad tracks

ACRONYMS AND ABBREVIATIONS

	Acronym and Abbreviation
Amtrak	National Passenger Railroad Administration
Axle 1	Test axle with the WABTEC/SAB-WABCO supplied discs on Coach 3413; Axle 1 on A-end truck adjacent to Power Car 2038
Axle 2	Test axle with the Knorr discs on Coach 3534; Axle 4 on B-end truck adjacent to Coach 3413
BIP	Bending of spokes in-the-plane of the disc
BOP	Bending of spokes out-of-the-plane of the disc
DB	Decibels
°F	Temperature measured in degrees Fahrenheit
F_1	Strain Gage in plane face of spoke facing Spoke 1
F_2	Strain Gage in plane face of spoke facing Spoke 5
Faiveley	Faiveley Transport
FEA	Finite element analysis
FRA	Federal Railroad Administration
g	Acceleration of gravity
GPS	Global Positioning System
IR	Infrared
Knorr	Knorr Brake Corporation
MP&E	Motive power and equipment
MPH, mph	Miles per hour
MTI	Metallurgical Technologies, Inc., P.A.
NEC	Northeast Corridor
NECMSC	Northeast Corridor Maintenance Services Company
PSD	Power Spectral Density; describes how the variance, or power, of a time series is distributed as a function of the different frequencies that form the signal
PSI, psi	Pounds per square inch
R_1	Strain Gage on out of plane face of spoke 6 (nut side)
R_2	Strain Gage on out of plane face of spoke 6 (opposite nut side)
SO	Sustained Oscillation
Spoke Number	Spoke naming convention
E	Strain
W/S-W	WABTEC/SAB-WABCO Supplied
Wabtec	Wabtec Corporation
μE, με	Microstrain - Strain times 10^6