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FINAL REPORT

TECHNICAL TASK NO. 9
CONTRACT NO. DTFR53-86-C-00006

on

RAIL GARRISON - VEHICLE STATIONARY VIBRATION TESTS

to

FEDERAL RAILROAD ADMINISTRATION
U.S. DEPARTMENT OF TRANSPORTATION

March 24, 1988

by

J. A. Hadden, D. R. Ahlbeck, M. Kurre and J. M. Tuten

BATTELLE
Columbus Division

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16. Abstract

The United States Air Force (USAF/BMO) requested support from the Federal Railroad Administration (FRA) to assist in technical issues related to the development of the Peacekeeper Rail Garrison Program. During operation of the Rail Garrison train, the consist will stop at various locations to calibrate the missile guidance system. Ground vibrations from the idling locomotive or from trains passing on an adjacent track pose a potential for interference with this operational process. It is critical therefore to characterize the operating and environmental vibration levels, so that conditions which might jeopardize the successful calibration of the missile guidance system are identified.

A series of tests were conducted at the Transportation Test Center (TTC) near Pueblo, Colorado to establish environmental vibration levels. These tests utilized a heavily-loaded 8-axle flat car to simulate the missile launch car, plus combinations of other loaded cars to approximate the weight and geometry of other Rail Garrison cars. Background vibration levels were established at the test site both with and without the a.c. power generator in operation. A variety of test conditions was run, including the locomotive coupled and uncoupled (at different separation distances), two-cycle and four-cycle locomotive engines, different engine idling speeds, and different positions in the consist of the test car. Orthogonal accelerations were measured on the test car over front and rear truck-pair centerplates, and at the track beneath the test car leading axle or beneath the locomotive trailing axle. Train pass-by vibration levels were also recorded.

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TABLE OF CONTENTS

DRAFT

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF FIGURES

DRAFT

TABLE OF CONTENTS

LIST OF FIGURES
(Continued)

DRAFT

TABLE OF CONTENTS

LIST OF FIGURES
(Continued)

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TABLE OF CONTENTS

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RAIL GARRISON - VEHICLE STATIONARY VIBRATION TESTS

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1.0 INTRODUCTION

1.1 Background

The United States Air Force (USAF/BMO) has requested support from the Federal Railroad Administration (FRA) to evaluate the railroad network and to assist in technical issues related to the development of Peacekeeper Rail Garrison Program. Peacekeeper Rail Garrison is a new basing mode for the fifty Peacekeeper missiles. In the Rail Garrison concept, the missiles are placed on specially-designed railcars in train consists which are placed at selected Air Force bases around the country. In time of national emergency, these trains are dispersed around the country on the existing railroad network.

During operation of a Rail Garrison train on the railroad network, the consist will stop at various locations to calibrate the missile guidance system. Ground vibrations from the idling locomotive or from trains passing on adjacent tracks pose a potential for interference with this operational process. This will have an effect on the requirements for identifying network segments where there may be considerable interference from traffic. This may also require some separation distance between the idling Rail Garrison locomotive and its consist.

It is critical that the vibration environment of the Rail Garrison train is characterized sufficiently so that operating and environmental conditions which jeopardize the successful calibration of the missile guidance system are identified. This Final Report describes in detail the field test program and subsequent data reduction and analysis conducted under Task 9 to characterize the missile car stationary vibration environment for a range of ambient conditions.

1.2 Task Objective

The objective of the test program was to establish the stationary vibration environment on a heavy railroad car with a locomotive idling and coupled in the proposed operational configuration, with the locomotive idling at various distances from the consist, and with train consists of several cars passing on an adjacent track.

1.3 General Test Description

Field tests were performed at the Transportation Test Center (TTC) near Pueblo, Colorado, where track, locomotives and rail cars were available under controlled conditions. Using a stationary train consist representative of a Rail Garrison train, multiaxis acceleration measurements were measured at selected locations on the simulated missile car (a heavily-loaded, 8-axle flatcar) and in the track ballast. Variations were made in consist and site parameters to investigate the influence on missile car vibration response of locomotive idle speed, distance of the uncoupled locomotive from the missile car, position of the missile car in the train, and speed of another train consist passing the simulated Rail Garrison consist on adjacent CWR and BJR (jointed) track. Background vibration levels also were measured with no locomotive or APU operating.

The tests were performed during the week of January 18, 1988 by Battelle-Columbus Division (BCD) with operational support provided by the Association of American Railroads (AAR/TTC). Tests were observed by Mr. Leonard Discenza, Ballistic Missiles Division, TRW, who provided technical suggestions and advice. Photographic and videotape recordings were made during the tests by a USAF photography team. Tests were immediately delayed several days by inclement weather as heavy snow and winds hit the Pueblo area. The Test Center was reopened on January 20, but low temperatures (down to zero Fahrenheit), high winds (gusts exceeding 50 mph) and drifting snow impeded test progress. Actual tests were begun on January 21, with winds of 20 to 30 mph, and gusts exceeding 50 mph. Wind effects dominated until 17:30 hours, when the wind died down. Several test conditions were then repeated so that a direct comparison of wind versus no-wind measurements could be made. Tests on January 22 were conducted with winds less than 3 mph; and the test matrix was completed, including post-test calibrations, by 22:00 hours of that day.

Test data recorded on analog cassette tapes were brought back to Battelle's laboratories for data reduction and analysis. Transducers were recalibrated under laboratory conditions to verify that no changes in sensitivity had occurred during tests. Analog data were recorded as time histories on strip charts to verify data quality and to note any unusual transient events in the acceleration records. Quick-look analysis of selected records was then conducted with the HP 5420A and 5423A analyzers to examine typical power spectral density (PSD) and root-mean-square (rms) values. "Production" analysis of the test matrix was then conducted on the MASSCOMP MC-500 supermicrocomputer.

2.0 TEST PROCEDURES

Test procedures were designed to meet the overall objectives and specific requirements of the Rail Garrison stationary vibration tests. These included the measurement system design and calibration procedures, as well as the specific field test conditions to be investigated. Test procedures are described in the following sections.

2.1 Measurement System and Calibration Procedures

The Rail Garrison stationary vibration measurement system was based on high-resolution seismic-type accelerometers, plus signal conditioning and recording equipment to provide a high dynamic range in data acquisition. A schematic of the field measurement system for the this test program is shown in Figure 2.1. The system consisted of the elements described in the following sections.

2.1.1 Transducers and Signal Conditioning

Eight high-resolution piezoelectric accelerometers were the primary transducers for measuring the vibration environment. These accelerometers have built-in preamplifiers, and are described below:

- <u>5 PCB Model 393C Seismic Accelerometers</u>
  Full Scale: 2.5 g
  Resolution: 36 micro-g rms (broad-band electrical noise)
  Bandwidth: 0.025 to 800 Hz

- <u>3 B&K Model 8306 Low-g Accelerometers</u>
  Full Scale: 2.8 g
  Resolution: 2 micro-g (with narrow-band filter)
  Bandwidth: 0.3 to 1000 Hz

Three of the PCB accelerometers were mounted triaxially over the span bolster of the rearward pair of trucks, recording only one of the two horizontal transducers at any one time. The other two PCB accelerometers were mounted on a "ground rod", a steel rod driven about 3 ft into the ballast, to measure track (ballast) acceleration levels at different locations for different test series. Locations included beneath the leading axle of the test car, and beneath the trailing locomotive axle. A typical installation is shown in Figure 2.2, with its protective cover removed.

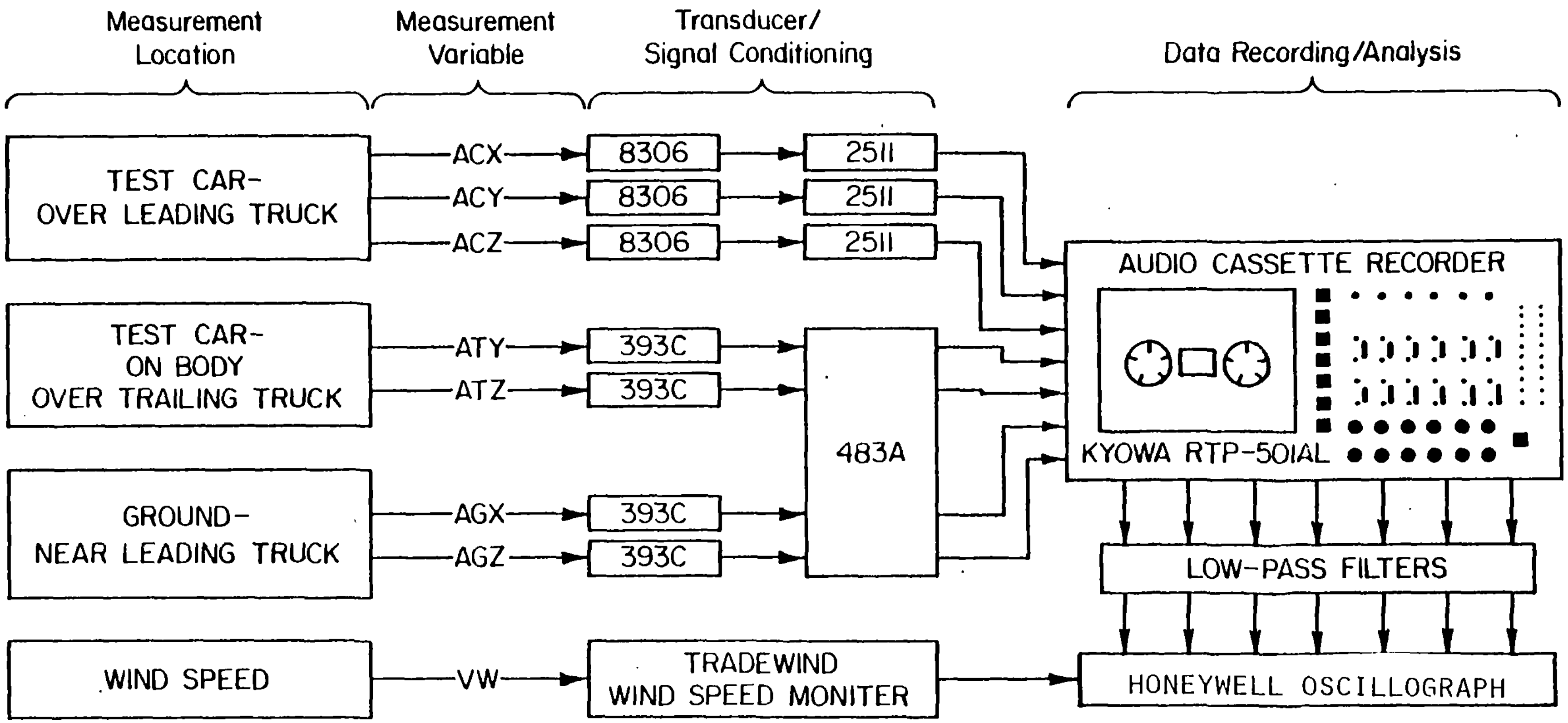

FIGURE 2.1 SCHEMATIC OF FIELD MEASUREMENT AND DATA ACQUISITION SYSTEM

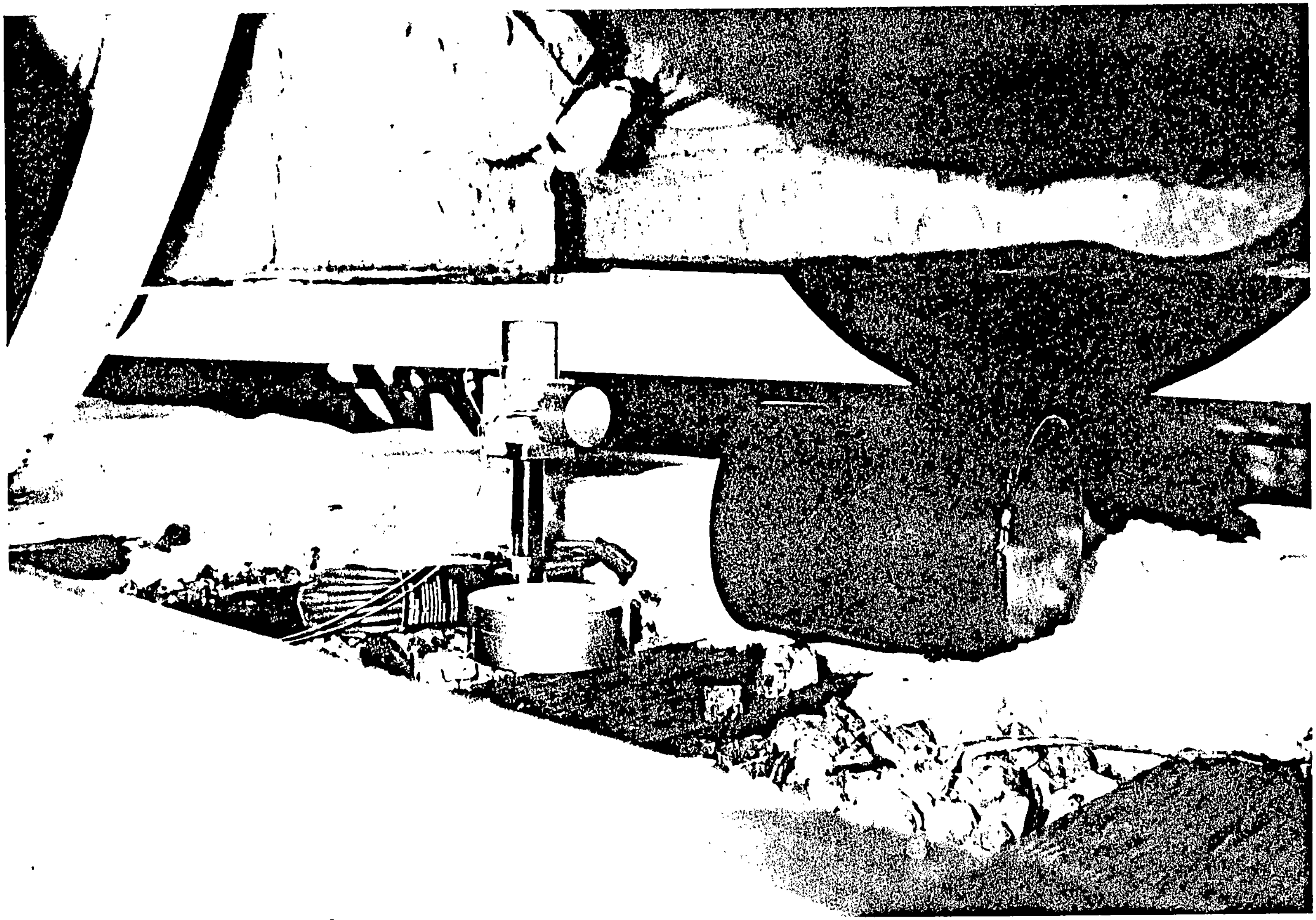

Figure 2.2 Installation of Ground Vibration Accelerometers (Photo: L. Discenza, BMD/TRW)

These units were powered and signal-conditioned by a PCB Model 483A 12-Channel Power Unit. Several PCB Model 480 single-channel power units also were provided as a backup.

The three B&K accelerometers were mounted triaxially over the span bolster centerplate of the forward pair of trucks. These units were powered and signal-conditioned by three B&K Model 2511 Vibration Monitors.

Accelerometers were mounted on the standard fiber mounting block, which was in turn cemented to the base of a heavy protective casing, made from an 8-inch diameter (1/4-inch wall) piece of steel pipe, 7-1/2 inches in length. The casing was attached to the flatcar deck with three magnetic bases, and covered with a thermal blanket to minimize temperature drift problems. This mounting arrangement is shown in Figure 2.3.

A Tradewind Model A-1 tachometer-type wind speed monitor was used to monitor wind speed at the test site. Its electrical signal was amplified by one of the Ectron amplifiers, then recorded on the Honeywell oscillograph.

2.1.2 Data Recording

A Kyowa RTP-501AL 7-channel Data Recorder was used to record accelerations on standard cassette tapes during the field tests, in place of the malfunctioning 14-channel FM recorder. Signals from the signal conditioning amplifiers were recorded at a tape speed of 4.76 cm/sec (1-7/8 in/sec), with a recording bandwidth of 1250 Hz. In addition to the tape recorder, a Honeywell Viscicorder (18-channel high-speed oscillograph recorder) was used to examine signal time-histories. An oscilloscope also was used to monitor the quality of the acceleration signals. A bank of Frequency Devices 4-pole Butterworth filters was used ahead of the oscillograph to adjust channel gains, but were set to a 4-kHz break frequency.

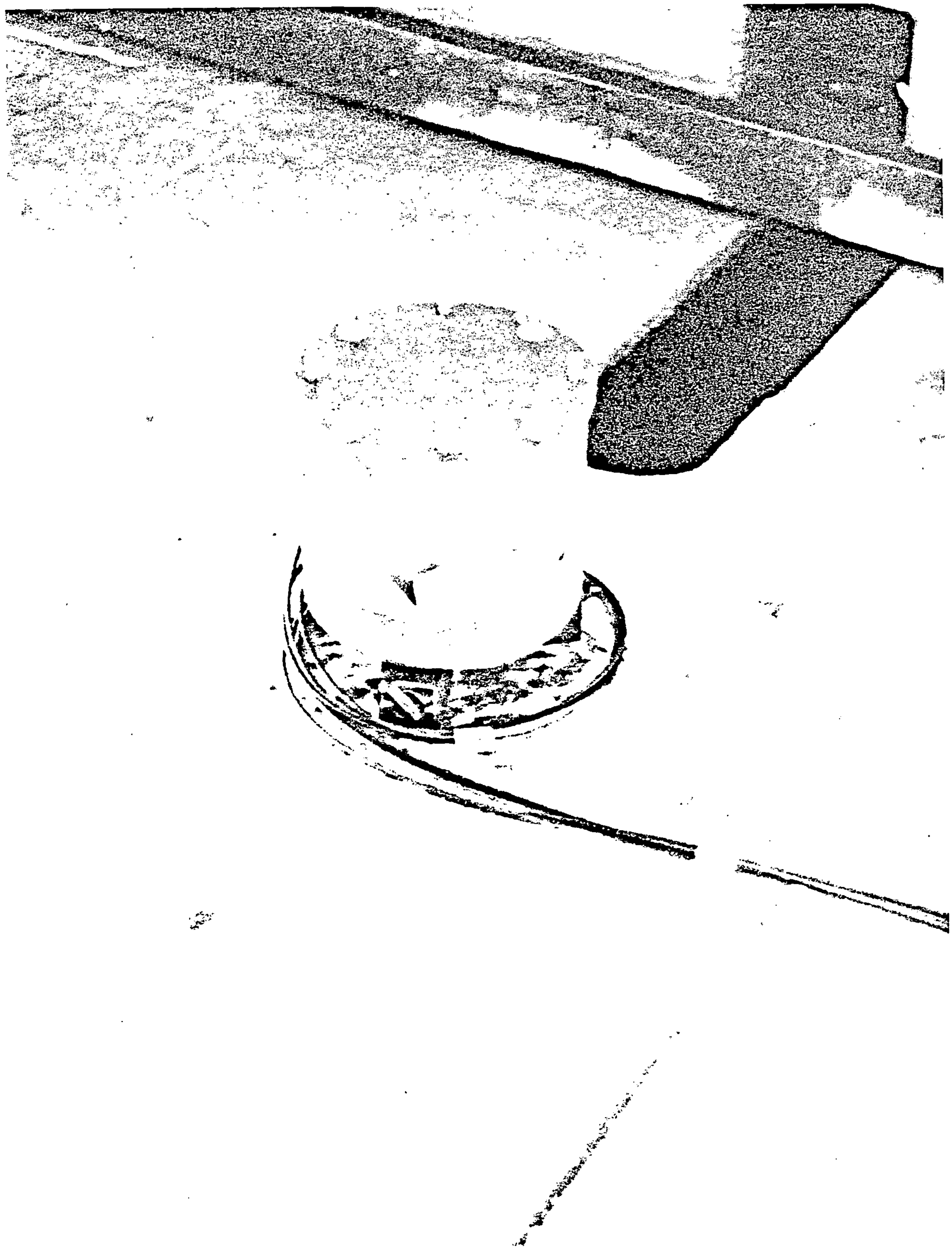

Figure 2.3 Mounting Configuration for Car Body Accelerometers (In Protective Cover)

A test log sheet was used to record set up and test conditions for each separate test in the matrix. An example log sheet is shown in Figure 2.4.

2.1.3 Support Equipment

A Kohler 1750 watt portable generator was used to provide 110 volt, 60-Hz power to the measurement system on site. The signal conditioning for the accelerometers was located in closed cases within a few feet of the transducers in order to minimize line losses. The accelerometer arrays were housed in thick-walled, thermally-insulated steel casings (described in Section 2.1.1) to minimize thermal-, wind- and acoustic- induced response of the accelerometers.

The recorders and other equipment were located in a truck camper, which was parked along the track, adjacent to the test car.

2.1.4 Calibration Procedures

The pre-test activities included the calibration of transducers and the checkout in the laboratory of the complete field data recording system. The transducer calibration procedure consisted of first calibrating a PCB Model 303A02 accelerometer (2.7 grams in weight) to 1 g rms at 100 Hz on a General Radio 1557A Calibration Shaker. The heavier seismic accelerometers were then mounted on an Unholtz-Dickie Model I Shaker, with the calibrated PCB 303A02 accelerometer mounted on the seismic accelerometer base. Both accelerometer signals were then monitored with the U-D shaker run with a low-level 100-Hz signal, and the seismic accelerometer sensitivity was then determined by comparing its output with the PCB 303A02 output.

An HP 3312A Precision Function Generator was used to provide a 100-Hz voltage signal for end-to-end field calibration of the system, from transducer/signal conditioner output to tape recorder output. This provided a field verification of cable integrity and the gains of amplifiers, filter box and tape recorder channels.

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x = Long.
y = Lat
z = Vert.

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RAIL GARRISON
VEHICLE STATIONARY VIBRATION TESTS
TTC, PUEBLO, CO - JAN 18-22, 1988
TEST LOG

Date: 1/20/88

Time: 1:30 - 2:00 Temp: ______ F Wind: 0-6 mph (calm)

TEST CATEGORY

___ 1 Background Vibration
___ 2 Coupled Locomotive
___ 3 Uncoupled Locomotive
___ 4 Test Car Position
___ 5 Passing Train
___ 6 Locomotive Type

100 Hz, ±5 V end-to-end cals on Accels

MEASUREMENT STATE

KYOWA ±DV in = ±5 V out ±2 ... f.s.

Meas. Var.		Xducer	Ampl./Gain	Tape Ch.	OGraph Ch.
ACX	OVER	8306-A	2511-A / 1a	1	1
ACY	LEADING	8306-C	2511-C / 1c	2	2
ACZ	TRUCKS	8306-B	2511-B / 1a	3	3
ATX	OVER	393C-1	PCB 483 / 10	4	4
ATY	TRAILING	393C-23	" / 10	4	4
ATZ	TRUCKS	393C-6	" / 10	5	5
AGX	GROUND	393C-4	" / 10	6	6
AGY		"	" / 10	6	6
AGZ		393C-5	" / 10	7	7
VW		TRADEWIND A-1	ECTRON / VAR.	NOT REC.	8

ECTRON - 22 mV in = 5.03 V out = 50.3 mph

DATA RECORDS

RG-1

Tape Reel No.: 1 2 Tape Speed: 1-7/8 3-3/4 7-1/2 15 30 (4.76 cm/s)

Tape Count: 000 to 100 [Calibrations]

OGraph Record No.: 1 Plot Nos.: X

TEST CONDITIONS

Locomotive Type: __________ Idle Speed: ______ rpm

Coupled: ______ Uncoupled/Sep.Dist.: ______ / ________

Coupler Slack: __________ Test Car Posn: ______

Passing Train Speed: ______ mph

(Comments on Back of this Page)

FIGURE 2.4 EXAMPLES OF TEST LOG SHEET

RAIL GARRISON
VEHICLE STATIONARY VIBRATION TESTS
TTC, PUEBLO, CO - JAN 18-22, 1988
TEST LOG

Date: 1/21/88 NE

Time: 1:29 -1:34 Temp: 30 F Wind: 30-40 mph Gusts to 50+

TEST CATEGORY

	1	Background Vibration		4	Test Car Position
X	2	Coupled Locomotive		5	Passing Train
	3	Uncoupled Locomotive		6	Locomotive Type

MEASUREMENT STATE

Meas. Var.	Xducer	Ampl./Gain	Tape Ch.	Ograph Ch.
ACX		/		
ACY		/		
ACZ		/		
ATX		/ 100		
ATY		/ 100		
ATZ		/ 100		
AGX		/ 100		
AGY		/ 100		
AGZ		/ 100		
VW		/		

105) Set
170)

DATA RECORDS

Tape Reel No.: RG-1 1 2 Tape Speed: 1-7/8 3-3/4 7-1/2 15 30

Tape Count: 100 to 197

OGraph Record No.: 2 Plot Nos.:

TEST CONDITIONS

Locomotive Type: DOT-4 Idle Speed: ~~[illegible]~~ Idle rpm

Coupled: X Uncoupled/Sep.Dist.: /

Coupler Slack: Loose (Frontially - otherwise tight) Test Car Posn: Nominal

Passing Train Speed: N/A mph
(Comments on Back of this Page)

FIGURE 2.4 (CONTINUED)

Upon return to Battelle from the field tests, transducers were again calibrated to verify that no changes in sensitivity had occurred during the tests. The Kyowa tape recorder was shipped to Battelle on loan from TTC to assure that the same recorder was used during data reduction and processing.

2.2 Test Conditions

2.2.1 Simulated Rail Garrison Consist

A 86-ft straight-deck, 8-axle span-bolster flatcar, ATSF 90022, was used to simulate the missile launch car during the stationary vibration tests. The car was ballasted to its maximum capacity by placing a large concrete and steel block (about 300,000 lb) at the center of the car, two heavy flywheel assemblies (about 20,000 lb each) at each end, and an additional flywheel assembly on top of the block. This is shown in the outline drawing of Figure 2.5 and (along with the instrumentation van) in the photograph in Figure 2.6.

The simulated consist was assembled from other cars available at TTC to approximate the adjacent launch control, maintenance and security cars in weight and number of axles. Two locomotives were used during the vibration tests: the DOT-4, a 4-axle EMD GP9 locomotive (1750-hp 2-cycle diesel engine), and DOT-1, a 6-axle GE U30C locomotive (3000-hp, 4-cycle engine). Vibration levels from these older locomotives should be equal to or greater than the newer F40PH or B39-8 4-axle units which are being considered for the actual Rail Garrison train. Sketches with descriptions of the train consists used during the tests are given in Figures 2.7 and 2.8. A view of Train Consist I is shown in Figure 2.9.

2.2.2 Test Facilities

The Rail Garrison Stationary Vibration Tests were conducted at the Transportation Test Center (TTC) near Pueblo, Colorado, a U.S. Department

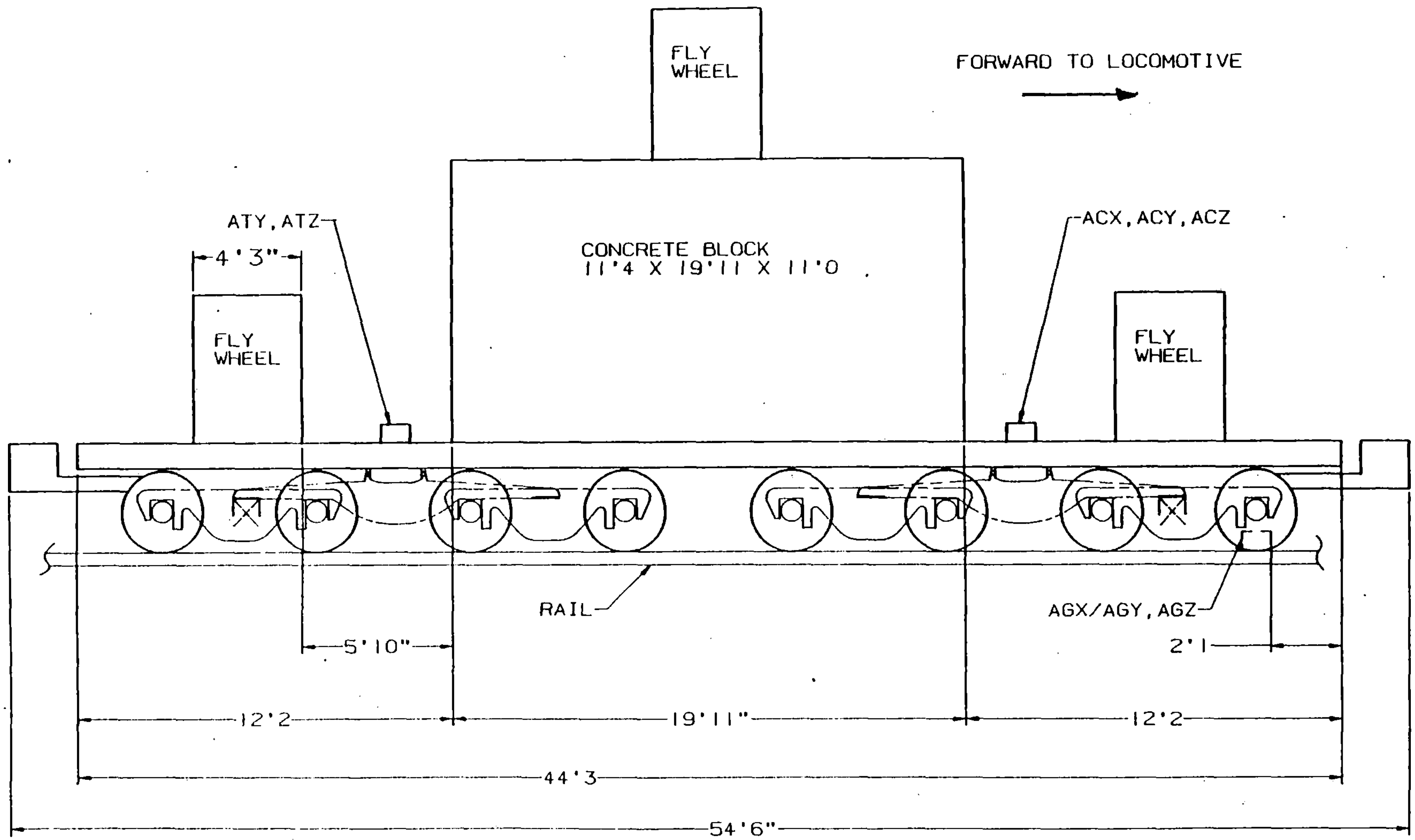


FIGURE 2.5 SKETCH OF SIMULATED MISSILE LAUNCH CAR
WITH LOAD AND TRANSDUCER LOCATIONS

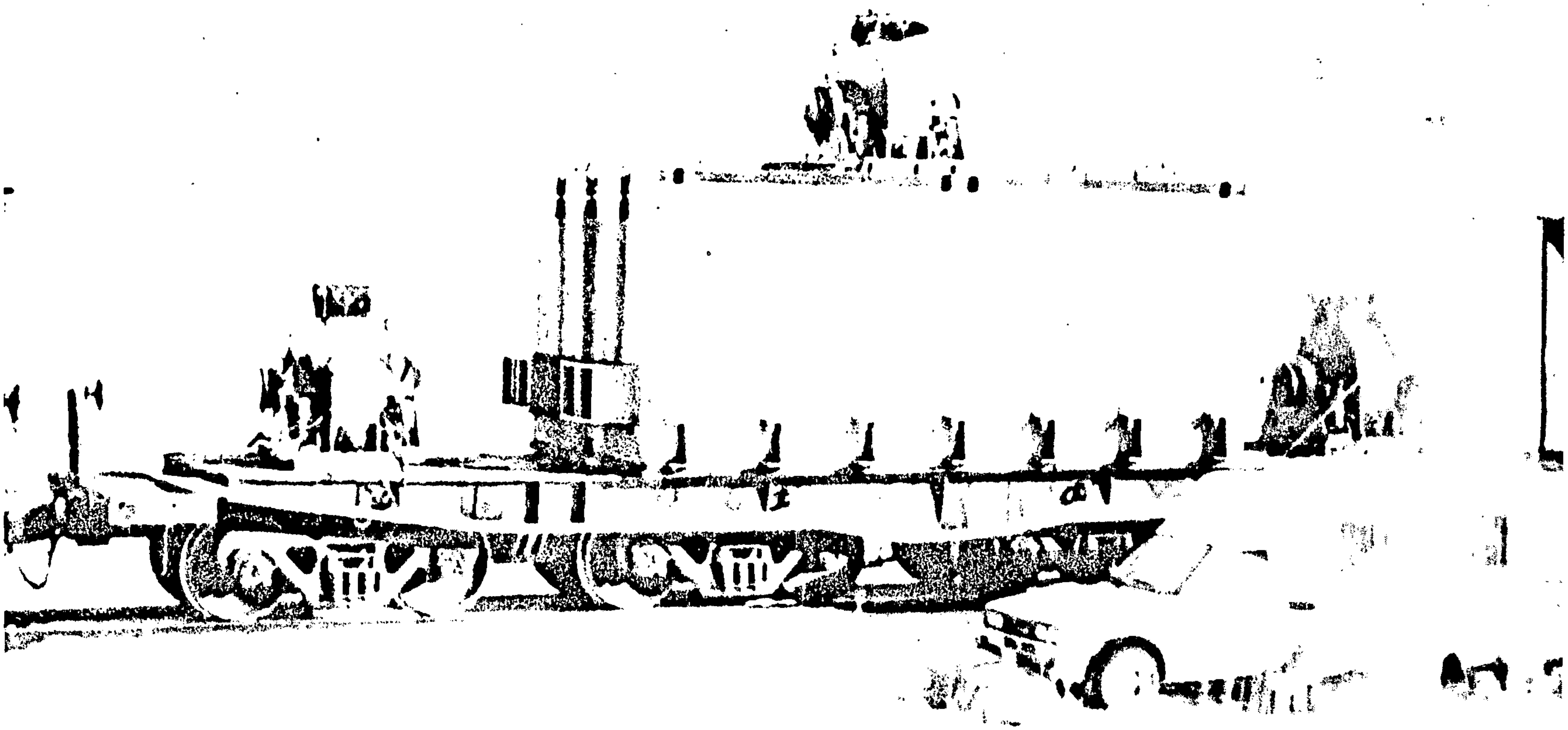
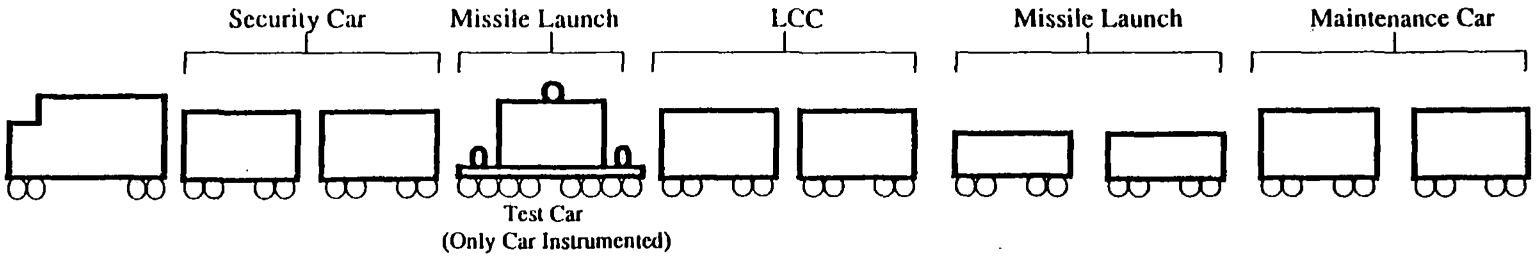


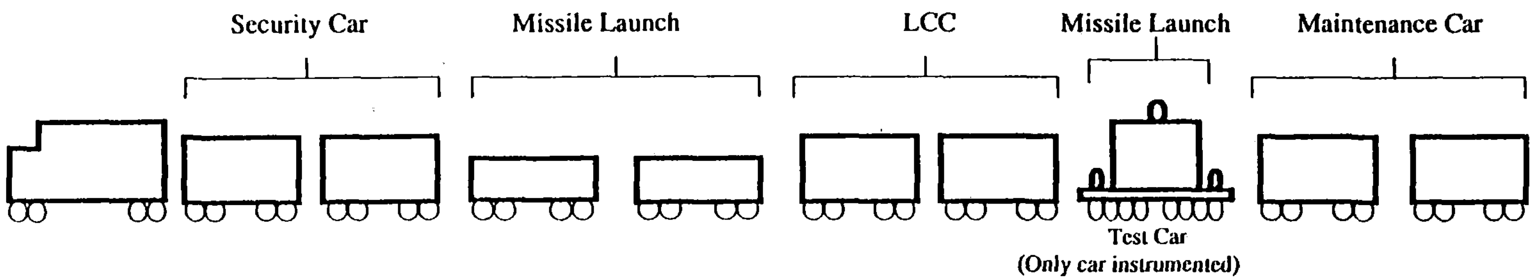
Figure 2.6 View of Simulated Missile Launch Car and Instrumentation Van

CONSIST #1 - Configuration I



Type	Loco. **	Hopper	Hopper	Flatcar	Hopper	Hopper	Hopper	Hopper	Hopper	Hopper
Car	DOT	UP	UP	ATSF	UP	UP	AMTK	AMTK	UP	UP
I.D.	004	41331	41318	90022	41306	41345	11809	11818	41350	41327
Wt.	237,700	164,350	163,800	499,450	161,250	162,800	264,800	262,200	159,450	224,400
L.	56'- 2"	54'-10"	54'-10"	54'- 6"	54'- 10"	54' -10"	43'- 2"	43'- 2"	54'-10"	54'-10"
Ht.	15'- 6"	12'- 6"	12'- 6"	*	12'- 6"	12'- 6"	10'- 6"	10 '- 6"	12'- 6"	12'- 6"

CONSIST # 1- Configuration II



Type	Loco. **	Hopper	Hopper	Hopper	Hopper	Hopper	Hopper	Flatcar	Hopper	Hopper
Car	DOT	UP	UP	AMTK	AMTK	UP	UP	ATSF	UP	UP
I.D.	004	41331	41318	11809	11818	41306	41345	90022	41350	41327

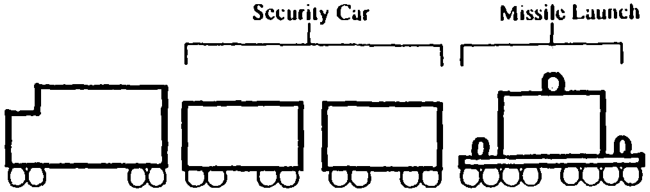
* See Test Car Drawing

** Locomotive Type EMD, 1800 Horsepower, GP-9 or GE, 3000 Horsepower, U30C

Note: Consist positioned at Train Dynamics Track Station 166.1.

FIGURE 2.7 CONFIGURATIONS OF TEST CONSIST #1
(Courtesy: L. Discenza, BMD/TRW)

CONSIST # 2 -

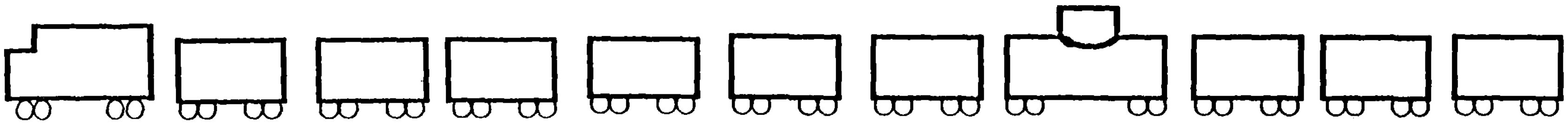


Type	Loco. *	Hopper	Hopper	Flatcar
Car I.D.	DOT 001	UP 41331	UP 41318	ATSF 90022
Wt.	371,250	Same as Consist # 1		
L.	67' - 3"	"		"
Ht.	15' - 5'	"		"

* Locomotive Type GE, 3000 Horsepower, U30C

Note: Consist # 2 positioned on the TDT track at station 172.8 for the Train Pass-By test.

CONSIST #3



Type	Hopper	Hopper	Hopper	Hopper	Hopper	Hopper	Tankcar	Hopper	Hopper	Hopper
Wt.	262,760	271,350	263,250	277,900	262,700	262,400	262,350	270,300	222,600	272,400
L.	54'-10"	54'-10"	48'- 8"	48'- 8"	43' -2"	53'- 1"	70'-3"	54'-10"	54'-10"	54'-10"
Ht.	12'- 6"	12'- 6"	12'- 6"	12'- 6"	10'- 6"	12'- 6"	15 '- 6"	12'- 6"	12'- 6"	12'- 6"

** Locomotive Type EMD, 3000 Horsepower, GP40-2

Note: Consist # 3 used on the RTT track as Pass-By Train.

FIGURE 2.8 CONFIGURATIONS OF TEST CONSIST #2 AND PASSING TRAIN (CONSIST #3) (Courtesy: L. Discenza, BMD/TRW)

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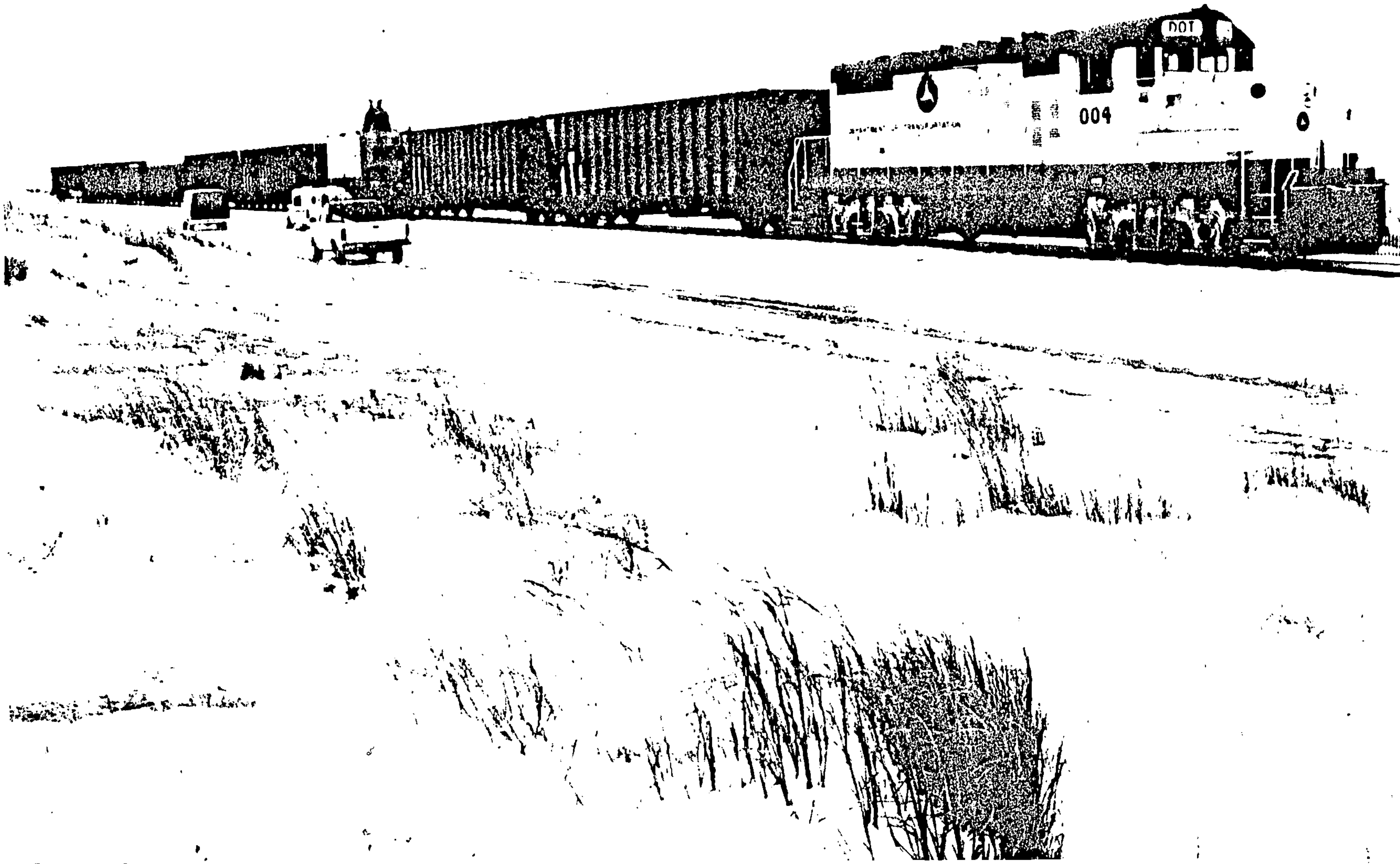

Figure 2.9 View of Test Consist #1 at Site #1 (Photo: L. Discenza, BMD/TRW)

of Transportation facility operated by the Association of American Railroads. The TTC was chosen for this program so that vibration tests could be conducted under controlled conditions with the support of Test Center personnel. Extraneous sources of ground and airborne vibrations could be minimized on the TTC grounds. A map of the TTC facility with test sites noted is shown in Figure 2.10.

2.2.3 Test Activities

The field tests were conducted to investigate the effects of the following conditions:

1. Background Vibration Tests. These measurements characterize the vibration environment for the case of the locomotive not running and over the range of ambient wind speed conditions, including minimum wind speed conditions (less than 3 mi/hr).

2. Coupled Locomotive Idling Tests. Using a 4-axle diesel electric locomotive, measure the vibration response during normal idle (approximately 300 rpm) and fast idle (900-1100 rpm). Measurements were made for the conditions of coupler slack "loose" and bunched.

3. Uncoupled Locomotive Idling Tests. Using the same locomotive, measure the vibration response at low idle speed with the locomotive uncoupled and moved away from the test car by three distances.

4. Influence of Test Car Location in Train Consist. Based on the results of the previous tests, the test car was moved to a different position in the train consist, and vibration measurements made for conditions of low idle and coupler slack bunched.

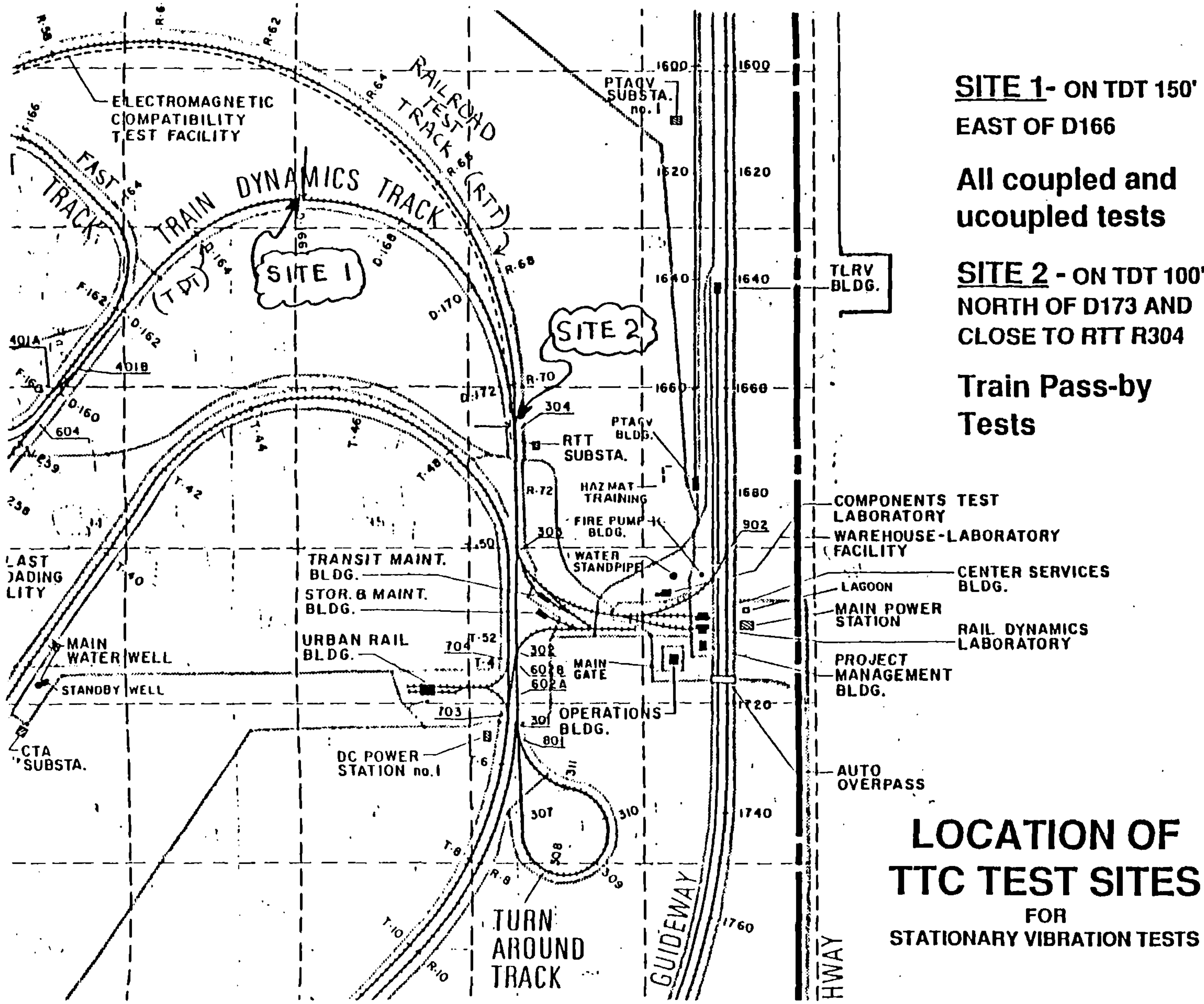

FIGURE 2.10 LOCATION OF STATIONARY VIBRATION TEST SITES
AT THE TRANSPORTATION TEST CENTER
(Courtesy: AAR/TTC, BMD/TRW)

5. Influence of Passing Train. The test train consist was modified so that the test car was at the end, and then was moved in close to the 13-ft clearance point of a turnout, which gave a separation distance over the length of the test car of about 13 to 16 ft. A moving train consist (Consist #3) was run past the test car at speeds from 5 mi/hr to 45 mi/hr.

6. Influence of Locomotive Design. Vibration measurements were made at different idle speeds and with bunched coupler slack using a 6-axle GE locomotive type to provide a comparison of vibration levels with the 4-axle EMD locomotive.

An summary of Rail Garrison Stationary Vibration Test conditions is given in Table 2.1. Specific tests conducted with the 4-axle EMD locomotive are given in Table 2.2 for both positions of the Test Car in the consist (Configurations I and II). Tests with the 6-axle GE locomotive are defined in Table 2.3, and tests with the passing train (Consist #3) are defined in Table 2.4.

2.2.4 Data Reduction and Analysis

It was originally intended that some data reduction and analysis would be done on-site, using a Hewlett-Packard Model 5423A Spectrum Analyzer with a digital plotter. This analyzer was not available at the time of tests because of other project commitments. An HP Model 3582A spectrum analyzer was used instead. However, because of the adverse weather conditions encountered during the test week, data reduction was deferred until the return to Battelle's laboratories.

The complete data set, seven recorded channels for each test, was run out in time-history format on oscillograph charts so that data quality could be checked. Segments of the three- to five-minute recordings could then be chosen, free of spurious transients (such as tape dropout), for averaging and analysis.

TABLE 2.1 RAIL GARRISON STATIONARY VIBRATION TESTS -- TEST CONDITIONS

Total No. of Individual Tests:	57
Average Test Record:	5 min.
Total Time of Test Records:	4 hrs. - 45 min.
Total Real Time Testing:	20 hrs.
Total No. of Rail Cars Involved:	22
Locomotives: 3 Hopper Cars:	17
Tank Car: 1 Flat car (8 axle):	1
No. of Test Sites:	2
Weather During Tests	
Top Wind Speed:	45 mph +
Average Day Time Wind Speed:	20 - 30 mph (1 st day)
	Below 5 mph (2 nd day)
Average Evening Wind Speed:	Below 4 mph
Average Day Time Temperature:	20 - 28 F
Average Evening Temperature:	10 - 20 F

Test Ballast and Rail Type

Track Ballast: Slag from CFI
Car Ballast: Expanded Shale (3/4" to 1" Crushed)
Rail Weight: 136 #/yd

TABLE 2.2 TEST SEQUENCE - VEHICLE STATIONARY VIBRATION TESTS

I. Coupled and Uncoupled EMD Locomotive Idling Tests

Locomotive: EMD (GP9, 1800 Horsepower) and Consist # 1
(All tests on Bolted Jointed Track)

Test No.	Test Car Position	Ground Measurement Location	Coupler Condition	Separation Distance (ft)	Idle * Speed	Comments
1,2,3,4	Configur. I	Test Car	Loose	0	IDLE, 8, 4	Winds 20 to 30 mph.
5,6,7	" "	" "	Bunched	" "	IDLE, 8, 4	Winds 20 to 30 mph.
11,12, 13 **	" "	" "	" "	" "	IDLE, 8, 4	Winds calm.
8,9,10	" "	" "	Uncoupled ***	0	IDLE, 8, 4	Winds 20 to 30 mph.
14,15,16**	" "	" "	" "	" "	IDLE, 8, 4	Winds calm.
17,18,19	" "	" "	" "	200	IDLE, IDLE, 8	
20,21	" "	" "	" "	100	IDLE, 8	
22, 23, 24	" "	Locomotive	Coupled ***	0	IDLE, 8, IDLE	
34, 35	" "	" "	" "	" "	IDLE, 8	Lat. & Vert. Grnd. Acc.
36, 37	" "	" "	" "	" "	IDLE, 8	Long. & Vert. Grnd. Acc.
25,26,27	Configur. II	Test Car	Loose	0	IDLE,8,4	
28,29,30	" "	" "	Bunched	" "	IDLE, 4	
31, 32, 33	" "	" "	Uncoupled ***	0	IDLE, 8, 4	

* Throttle setting during engine idle. Varies from IDLE, 1,2,..,8 (300 to 900 RPM)

** Tests repeated in the evening after daytime winds subsided from a steady 20 to 30 mph with gusts of 40 mph to below 4 mph.

*** Applies to Locomotive. Co[illegible]s on other cars are bunched.

(Courtesy: L. Discenza, BMD/TRW)

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TABLE 2.3 TEST SEQUENCE - VEHICLE STATIONARY VIBRATION TESTS

II. Coupled and Uncoupled GE Locomotive Idling Tests

Locomotive: GE (U30C, 3000 Horsepower) and Consist # 1

Test No.	Test Car Position	Ground Measurement Location	Coupler Condition	Separation Distance (ft)	Idle * Speed	Comments
38,39,40	Configur. II	Locomotive	Coupled ***	0	IDLE, 8, 4	
41,42,43	" "	" "	" "	" "	IDLE, 8	
44	Removed	Background	N/A	N/A	N/A	W/ generator running
45	" "	" "	" "	" "	" "	W/out generator running
46,47,48	Configur. I	Test car	Bunched	0	8, IDLE, 4	
49,50	" "	" "	Uncoupled ***	" "	IDLE, 8	

* Throttle setting during engine idle. Varies from IDLE, 1,2,..,8 (425 to 1025 RPM)

** Tests repeated in the evening after daytime winds subsided from a steady 20 to 30 mph with gusts of 40 mph to below 4 mph.

*** Applies to Locomotive. Couplers on other cars are bunched. Courtesy: L. Discenza, BMD/TRW)

TABLE 2.4 TEST SEQUENCE - VEHICLE STATIONARY VIBRATION TESTS

III. Train Consist Pass-By Tests

Passing Locomotive: EMD (GP40-2, 3000 Horsepower) and Consist # 2
Stationary Locomotive: GE (U30C, 3000 Horsepower) and Consist # 3

Test No.	Test Car Position	Ground Measurement Location	Coupler Condition	Separation Distance (ft)	Idle * Speed	Passing Train Consist # 3
51	Configur. I	Test Car	Bunched	0	IDLE	Speed: 45 mph Throttle Power Setting: 6
52	" "	" "	" "	" "	" "	Speed: 35 mph Throttle Power Setting: 6
53	" "	" "	" "	" "	" "	Speed: 25 mph Throttle Power Setting: 6
54	" "	" "	" "	" "	" "	Speed: 15.2 mph Throttle Power Setting: 8
55	" "	" "	" "	" "	" "	Speed: 5.7 mph Throttle Power Setting: 5
56	Removed	Background	N/A	N/A	N/A	W/ generator running
57	" "	" "	" "	" "	" "	W/out generator running.

(Courtesy: L. Discenza, BMD/TRW)

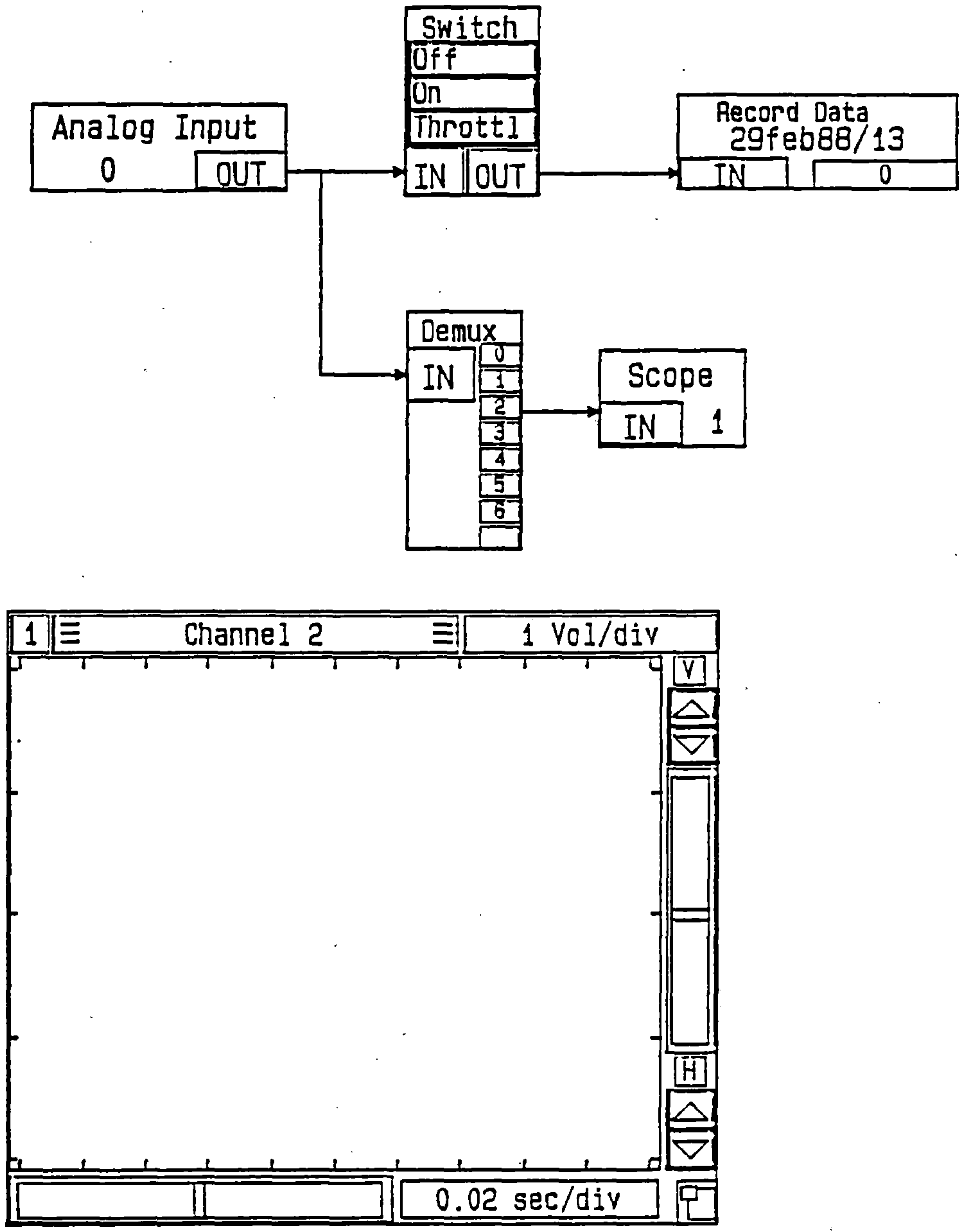

FIGURE 2.11 MASSCOMP MC-500 COMPUTER SYSTEM SET-UP STATE FOR A/D CONVERSION, RECORDING AND MONITORING

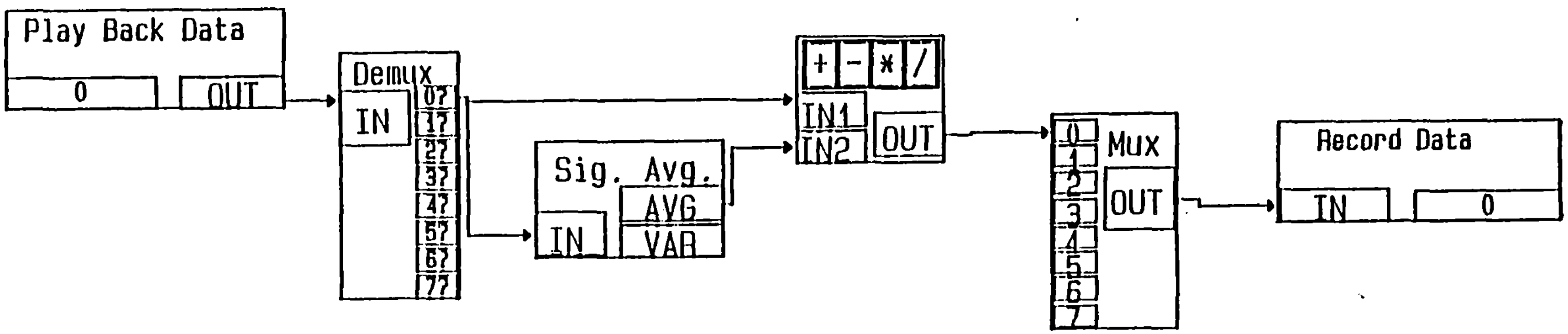

FIGURE 2.12 MASSCOMP MC-500 COMPUTER SYSTEM SET-UP STATE FOR DETRENDING ACCELERATION DATA SEGMENTS

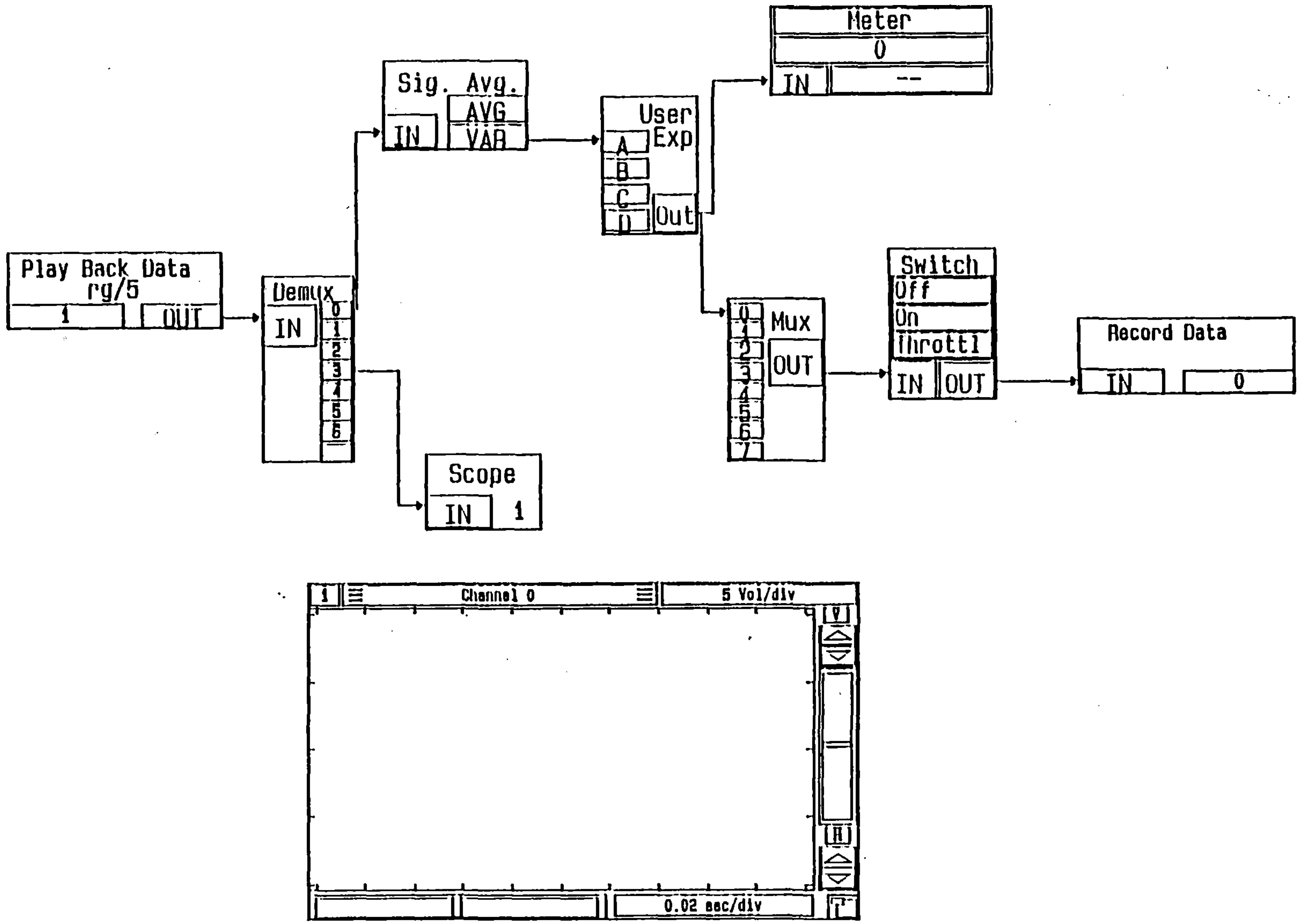

FIGURE 2.13 MASSCOMP MC-500 COMPUTER SYSTEM SET-UP STATE FOR CALCULATING VARIANCE AND ROOT-MEAN-SQUARE VALUES FROM ACCELERATION DATA SEGMENTS

A preliminary analysis of representative data samples was conducted, at the request of BMD/TRW, to establish root-mean-square (rms) values in the 0-100 Hz frequency range. The Hewlett-Packard 5420A and 5423A analyzers were used to calculate these preliminary values. Further analysis of the data has indicated that at least some of these preliminary values are suspect due to d.c. voltage offsets in some of the recordings combined with the relatively coarse frequency resolution of the analyzers (0.39 Hz at a 100-Hz bandwidth). Therefore the contribution to the rms value below about twice the frequency resolution was not accurate and in some cases affected the overall rms values calculated in the preliminary analysis.

Further analysis was conducted using the MASSCOMP MC-500 computer system, which allowed the processing of all seven channels of data simultaneously. Each test segment of analog data was filtered to minimize aliasing effects, then digitized and stored in memory, as shown in the computer monitor set-up state, Figure 2.11, for a single channel. A 4-pole Butterworth filter (24 dB/octave) was used with each channel, set at 200 Hz (the -3 dB point), with a sampling rate of 500 samples/second. The chosen segments of data were then detrended, removing the d.c. component, before storage on disk. This process is illustrated (for a single channel) in Figure 2.12. These digital data records were then used in further analyses to generate power spectra (PSDs), mean square and rms values. Additional records were processed on the HP 5420A analyzer to compute cross correlation and transfer functions. A typical set-up state on the MASSCOMP for calculating rms acceleration is shown in Figure 2.13.

3.0 TEST RESULTS

3.1 Test Sequence RMS Accelerations

Root-mean-square (rms) values of 200-Hz filtered acceleration for the different test conditions were calculated by the MASSCOMP MC-500 computer system as described in Section 2.2.4. A key to the test sequence numbers, with specific test conditions and comments, is given in Table 3.1. The rms acceleration values (in micro-g's) are given in Table 3.2 in a matrix of Data Channel versus Run Number.

During the runs in which the ground accelerometers were positioned under the locomotive axle, the car-body accelerometer cables were disconnected at the signal conditioner outputs; and therefore open-circuit noise was recorded on these five channels. This noise level ranged from 7 to 19 micro-g's rms equivalent when processed along with the signals from Channels 6 and 7. Recordings were later made at Battelle with shorted inputs on all seven channels. These recordings were analyzed and found to be 7 micro-g's rms equivalent or less as a system electrical noise floor.

3.1.1 Background RMS Accelerations

Background vibration levels were recorded at Test Site 1 (Runs 44, 45) and Test Site 2 (Runs 56, 57) as a baseline for the stationary vibration tests.. At Site 1, the Test Train had been moved back to the Operations Building area. Accelerometers on Channels 1 through 5 were therefore on the track, all measuring ground vibration levels. The FAST train was in operation, about 1.5 miles away; and the Kohler generator was situated about 100 ft away (about 10 ft off the track) on a foam rubber pad. Tests were run first with the generator on (Run 44), then off (Run 45). Channels 1-3 were run normally on batteries with the battery charger on, Channels 4 and 5 were run on battery power only, and Channels 6 and 7 were run normally on a.c. power. In this case, higher rms values on Channels 6 and 7 (Run 44) may reflect a combination of ground rod vibrations and actual seismic vibrations from the generator and distant FAST train activities. With Channels 6 and 7 on battery power, however, unreasonably high rms values were measured which have been attributed to the amplifier drift in response to switching from a.c. to d.c. power.

At Site 2, the Test Car was left at the site, and the Test Train locomotive was pulled at least a mile away. The run-by train (Consist 3) was stationed even a further distance from the site. The Kohler

TABLE 3.1 KEY TO TEST SEQUENCE NUMBER --
VEHICLE STATIONARY VIBRATION TESTS

Test No.	Consist No.	Test Car Position	Ground Accels.	Coupler Condition	Separation Distance	Throttle (Notch)	Comments on Tests
1	1	1	Test Car	Loose	0 ft	Idle	Winds 30-40 mph, gusts 50+
2						Idle	Winds 20-30 mph
3						8	
4						4	
5	1	1	Test Car	Bunched	0	Idle	Winds 15-30 mph
6						8	
7						4	
8	1	1	Test Car	Bunched	0	Idle	Winds 5-10 mph
9				(GP9 Loco.		8	Winds < 5 mph
10				Uncoupled)		4	Calm (wind 0 mph)
11	1	1	Test Car	Bunched	0	Idle	Repeat runs with winds < 5 mph
12				(GP9 Loco.		8	
13				Coupled)		4	
14	1	1	Test Car	Bunched	0	Idle	Repeat runs, winds calm
15				(GP9 Loco.		8	
16				Uncoupled)		4	
17	1	1	Test Car	Bunched	200	Idle	Locomotive separated from train
18						Idle	
19						8	
20					100	Idle	Winds 0-5 mph
21						8	
22	1	1	GP9	Bunched	0	Idle	Ground accel's under rear loco-
23				(GP9 Loco.		8	motive wheelset (AGY, AGZ); winds
24				Coupled)		Idle	0-5 mph (Camper running, Run 24)
25	1	2	Test Car	Loose	0	Idle	Alternate test car position, winds
26						8	0-3 mph
27						4	
28	1	2	Test Car	Bunched	0	Idle	Winds 0-3 mph
29						8	
30						4	

TABLE 3.1 KEY TO TEST SEQUENCE NUMBER (CONTINUED)

Test No.	Consist No.	Test Car Position	Ground Accels.	Coupler Condition	Separation Distance	Throttle (Notch)	Comments on Tests
31	1	2	Test Car	Bunched	0	Idle	Transient accel bursts noted;
32				(GP9 Loco.		8	related to train "creaking"
33				Uncoupled)		4	(thermal, brakes, whatever)
34	1	2	GP9	Bunched	0	Idle	AGY, AGZ (no can over ground accel-
35				(GP9 Loco.		8	erometers, but winds calm)
36				Coupled)		Idle	AGX, AGZ
37						8	
38	1	2	U30C	Bunched	0	Idle	Tests with 6-axle, 4-cycle
39				(U30C Loco.		8	GE U30C locomotive; AGY, AGZ,
40				Coupled)		4	No can over accelerometers
41						Idle	AGX, AGZ
42						8	
43						8	Can over accelerometers
44	--	--	No Train	----	--	--	Background, generator on
45							Background, generator off
46	1	1	Test Car	Bunched	0	8	
47				(U30C Loco.)		Idle	
48						4	
49	1	1	Test Car	Bunched	0	Idle	
50				(U30C Loco.		8	
				Uncoupled)			
51	2,3	3	Test Car	Bunched	0	Idle	Passing train 45 mph, Notch 6
52				(U30C Loco.		Idle	Passing train 35 mph, Notch 6
53				Coupled)		Idle	Passing train 25 mph, Notch 6
54						Idle	Passing train 15 mph, Notch 8
55						Idle	Passing train 6 mph, Notch 5
56	--	--	No Train	-----	--	--	Background, generator on
57							Background, generator off

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TABLE 3.2 ROOT-MEAN-SQUARE ACCELERATION VALUES FOR RAIL GARRISON STATIONARY VIBRATION TESTS

Run No.	1 ACX	2 ACY	3 ACZ	4 ATY	5 ATZ	6 AGY	7 AGZ
	Recorded Acceleration Data Channels — Micro-g's (rms)						
1	380	223	298	228	228	280	205
2	206	84	125	119	105	72	44
3	265	152	228	165	201	166	141
4	276	129	163	169	143	111	43
5	173	72	148	98	110	91	27
6	307	251	247	161	247	175	174
7	539	463	292	345	483	121	65
8	155	61	94	36	49	36	25
9	227	148	239	83	138	58	79
10	150	61	88	43	58	18	26
11	186	197	177	69	192	132	35
12	202	146	281	55	150	222	308
13	186	687	431	86	670	90	128
14	176	83	119	53	78	153	39
*15	197	118	208	65	140	83	121
16	221	166	103	77	69	61	52
17	182	61	110	41	71	a	29
*18	158	43	91	28	42	a	20
*19	172	60	109	35	64	a	61
*20	190	76	119	43	70	a	31
*21	186	86	140	53	99	a	104
22	--	--	--	--	--	b	537
23	--	--	--	--	--	4060	3621
24	--	--	--	--	--	1058	708
25	58	22	35	21	24	21	20
26	61	36	65	29	42	21	30
27	109	37	56	61	41	19	19
28	69	33	73	36	42	27	43
29	75	54	87	52	74	33	27
30	140	120	113	95	156	38	28

Notes: * -- An "event" noted during run (thermal "creaking", brake system, whatever)
a -- Apparent bad cable connection
b -- Questionable (low) data value

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TABLE 3.2 ROOT-MEAN-SQUARE ACCELERATION VALUES (CONTINUED)

	Recorded Acceleration Data Channels						
Run No.	1 ACX	2 ACY	3 ACZ	4 ATY	5 ATZ	6 AGY	7 AGZ
	Micro-g's (rms)						
31	117	82	122	84	116	40	26
32	58	30	46	20	32	22	32
33	115	58	75	69	87	24	26
34	--	--	--	--	--	2019	958
35	--	--	--	--	--	9151	6741
36	--	--	--	--	--	955#	820
37	--	--	--	--	--	5974#	6500
38	--	--	--	--	--	324	413
39	--	--	--	--	--	8100	2019
40	--	--	--	--	--	746	445
41	--	--	--	--	--	675#	464
42	--	--	--	--	--	2147#	1867
43	--	--	--	--	--	2539#	2342
44	50	12	20	24	17	149	189
45	21	12	16	21	14	c	c
46	580	1605	1295	177	1778	a	a
*47	194	108	106	106	122	171	95
*48	168	154	167	102	191	143	57
*49	232	108	101	96	104	139	3
50	179	179	156	108	124	99	135
%51	7157	3271	14111	7832	16890	d	16910
%52	6980	2617	13522	9400	17200	d	14390
%53	6080	2481	14093	8400	20800	d	15280
%54	5540	1902	8354	5100	12700	d	9790
%55	4032	854	3131	3076	4960	d	3802
56	143	51	63	17	65	d	52
57	28	26	21	17	67	c	c

Notes:
* -- An "event" noted during run (thermal "creaking", brake system, whatever)
a -- Apparent bad cable connection
b -- Questionable (low) data value
c -- Questionable (high) data value (on batteries, not stabilized during run)
d -- Ground rod poorly supported laterally (51 Hz vibr.)
-- AGX recorded instead of AGY (X = along track)
% -- Quasi-steady-state rms value during train pass-by

generator, again on a foam rubber pad, was located about 50 ft away orthogonal to the test car, and the buzzing of a nearby electrical power transformer was clear audible. Changes in level in Channels 1-3 between generator on (Run 56) and off (Run 57) could therefore reflect actual changes due to generator vibrations, or could simply be due to battery charger versus no charger power levels. Poor lateral support of the ground rod at Site 2 caused excessive vibration at about 51 Hz so that channel 6 data are unreliable. Again, the amplifiers for Channels 6 and 7 appear not to have stabilized after the switch to batteries (Run 57), and consequently no data are available.

3.1.2 Operating RMS Accelerations

The rms values in Table 3.2 were evaluated to select test runs and specific channels for further analysis. Those with higher rms values were analyzed for frequency spectral characteristics by PSD analysis. Run 46, the U30C locomotive in Notch 8 with bunched couplers, appeared to present a worst-case condition and was used to generate examples of cross-correlation and transfer function analysis.

Rms values were calculated from areas under the PSD curves, as a quality check to verify the values in Table 3.2. This also allowed a comparison of rms values in different frequency bandwidths. Values for representative runs (Runs 11, 12, 13, 46 and 48) in the 200+, 100 and 20-Hz bandwidths are compared in Table 3.3. It can be seen that under some operating conditions, a large portion of the acceleration power resides within the 0-20 Hz bandwidth.

The effects of specific operating conditions can be deduced to some degree from the rms acceleration values in Tables 3.2 and 3.3. Some of these effects are as follows:

- <u>Wind Effects.</u> The highest winds occurred during Run 1, and this run shows higher rms values on all channels than other engine-idle runs. However, significant increases in data acquisition sensitivity (gain changes) occurred between Runs 1

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TABLE 3.3 COMPARISON OF ROOT-MEAN-SQUARE ACCELERATION VALUES IN DIFFERENT FREQUENCY BANDWIDTHS

Run No.	1 ACX	2 ACY	3 ACZ	4 ATY	5 ATZ	6 AGY	7 AGZ
	Recorded Acceleration Data Channels, Micro-g's (rms)						
	0 to 200+ Hz (-3 dB) Bandwidth						
11	186	197	177	69	192	132	35
12	203	146	282	55	150	222	308
13	186	687	431	86	670	90	128
46	580	1605	1295	177	1778	a	a
48	168	154	167	102	191	143	57
	0 to 100 Hz Bandwidth (Area Under PSD Curve)						
11	162	181	161	50	184	132	25
12	162	92	287	--	--	218	306
13	172	660	398	69	669	73	123
46	570	1607	1293	--	--	a	a
48	131	147	146	57	174	142	55
	0 to 20 Hz Bandwidth (Area Under PSD Curve)						
11	40	164	129	43	166	20	17
12	26	55	65	19	61	41	146
13	79	615	370	65	630	40	104
46	532	1498	1210	124	1664	a	a
48	95	116	123	27	142	46	45

Note: a -- apparent cable problem (no signal) and 2 (and between Runs 9 and 10). Consequently, the measurement accuracy for Run 1 may be less than that for Run 2 and on. High wind gusts during Run 1 (gusts to 73 mph were recorded) did not seem directly correlated in time histories with bursts of measured acceleration.

- Engine Speed. Significant increases in ground vibration were recorded when engine speed was increased to Notch 8 (about 840 rpm for the GP9 locomotive, about 1000 rpm for the U30C locomotive). Higher test-car body accelerations were measured, however, with the GP9 engine in Notch 4 as engine rotation frequency approached a resonance near 8 Hz. This can be seen in Runs 7 and 13. With the U30C locomotive, operation in Notch 8 produced the highest car-body response (Run 46), since the engine firing frequency (half the rotation frequency) then approached the 8-Hz resonance. Based on assumed car and track characteristics, we believe this 8-Hz resonance is associated with a bending mode of the test car body and/or the rigid-body vibration of the loaded car (snubbers locked) on the track effective stiffness.

- Engine Type. The significant difference between the two locomotives is the two-stroke-cycle engine in the GP9, producing firing and rotational vibrations at the same frequencies, versus the four-stroke-cycle engine in the U30C, producing "half-harmonics" by firing every other stroke. Generally higher vibration levels were produced by the U30C locomotive under similar operating conditions. This may, however, been more a function of engine age and condition.

- Coupler Slack. Generally higher rms acceleration levels were measured with the engine coupled, couplers and draft gear bunched. The draft gear may be a significant load path, although the comparison of longitudinal accelerations from Runs 8-10 (uncoupled) versus Runs 11-13 (coupled, bunched) is inconclusive.

- <u>Locomotive Distance</u>. Removing the locomotive from the train by a distance of 100 to 200 ft did reduce the car acceleration levels monotonically for the fast-idle (Notch 8) condition. The trend was not as clear for the low-idle condition, particularly for the car longitudinal response.

3.2 Acceleration Power Spectral Density

To present the acceleration power spectral density (PSD) data analyses, we have chosen a log-linear format with a common 12-decade ordinate (acceleration power) from 1E-16 to 1E-4 g^2/Hz. This range includes the maximum and minimum acceleration levels for all runs, and all curves may be compared directly without change of scale. We prefer to use a linear scale on the abcissa (frequency), so that the lower-frequency portion of the bandwidth is not accentuated where data resolution is poorer. Operating spectra are shown first in the 0-100 Hz bandwidth, then in the 0-20 Hz bandwidth to provide greater resolution in the low frequency range. For the 100-Hz spectra, the filters were set at a 200-Hz (-3 dB) break frequency with a 500-per-second sampling; while for the 20-Hz spectra, a 20-Hz break frequency and 50 samples/second were used. For a few selected cases, the 20-Hz bandwidth car body acceleration data have been plotted with a 0.01 to 10 Hz log frequency scale to show the lowest-frequency spectral peaks.

3.2.1 Background Acceleration Levels

Background acceleration PSDs for the Site 1 location are given in Figures 3.1 through 3.3 for Run 44, the Site 1 location with the Kohler generator supplying a.c. power. These spectra show a background vibration "noise floor" below 1E-13 g^2/Hz, with spectral peaks rising one to two orders of magnitude above this level. There are in all channels a five-Hz spectral peak with strong harmonics, plus a distinct peak at 57 Hz. A strong 80-Hz peak is also found in car body lateral and vertical acceleration, but over the leading trucks only.

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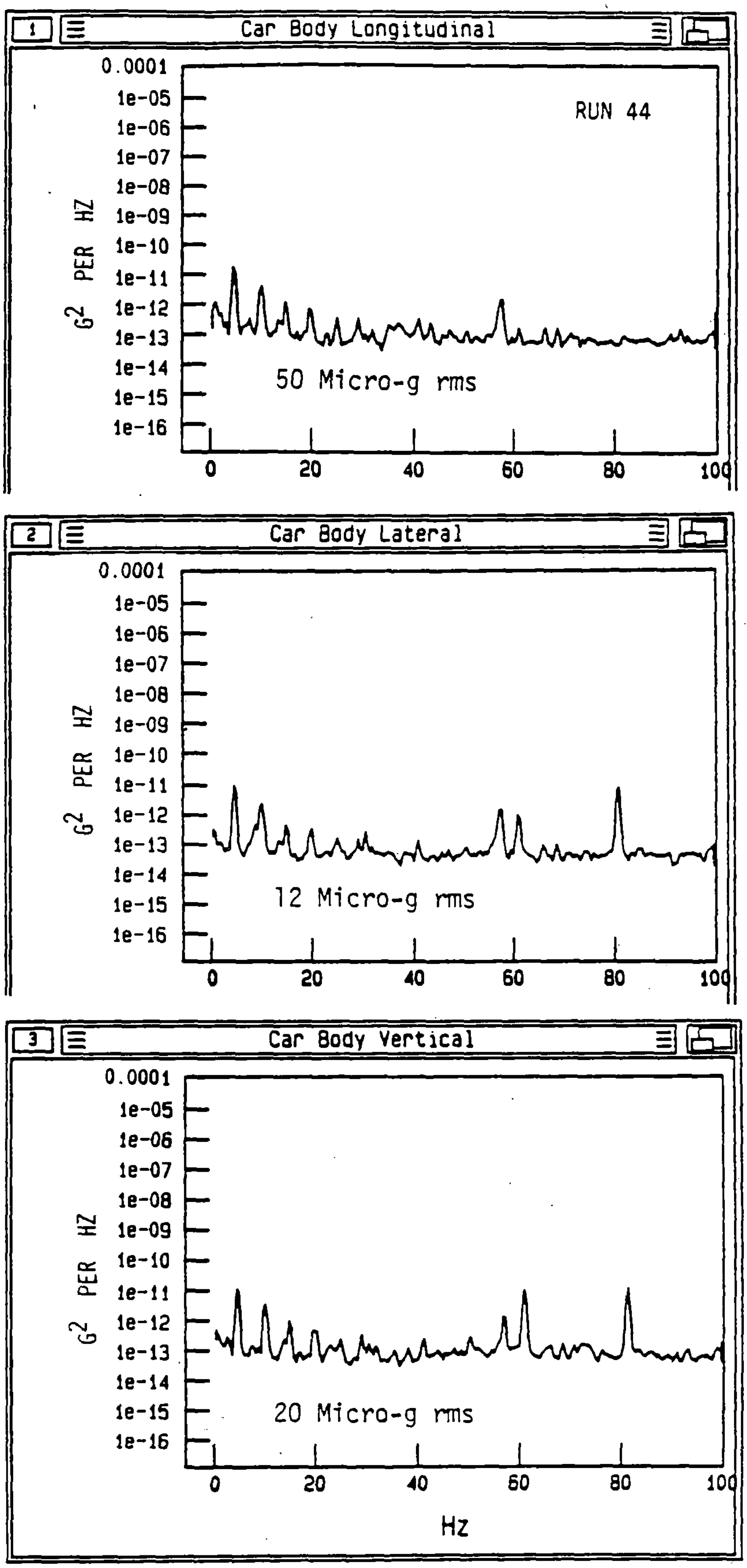
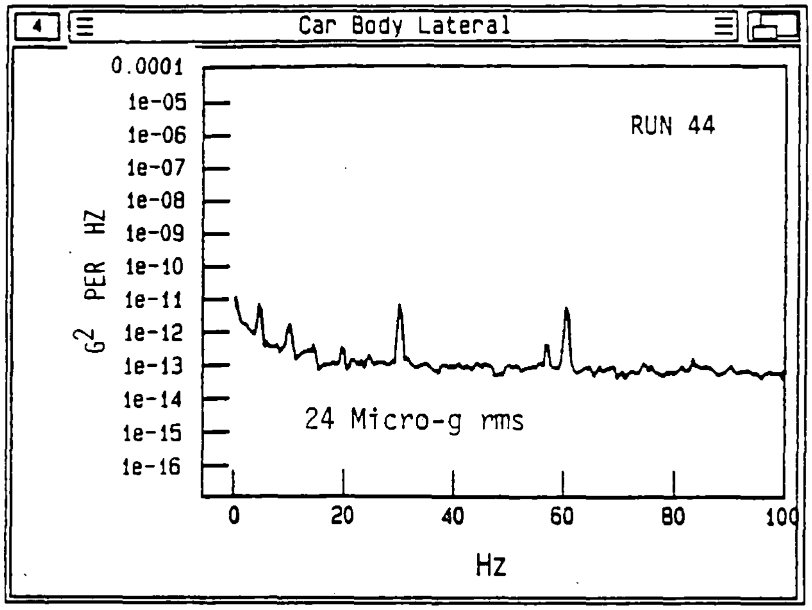


FIGURE 3.1 BACKGROUND ACCELERATION PSDs AT SITE #1,
GENERATOR ON, CAR BODY OVER LEADING TRUCK



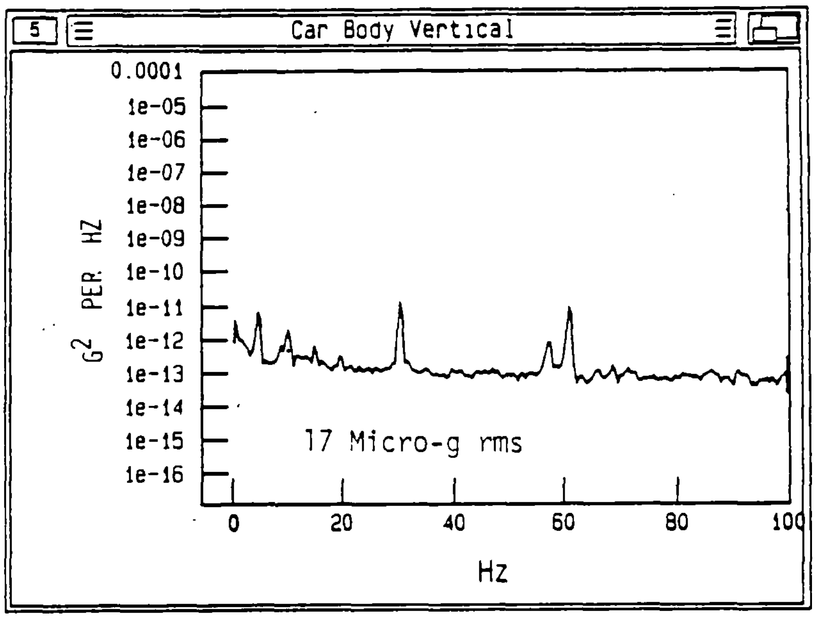


FIGURE 3.2 BACKGROUND ACCELERATION PSDs AT SITE #1, GENERATOR ON, CAR BODY OVER TRAILING TRUCK

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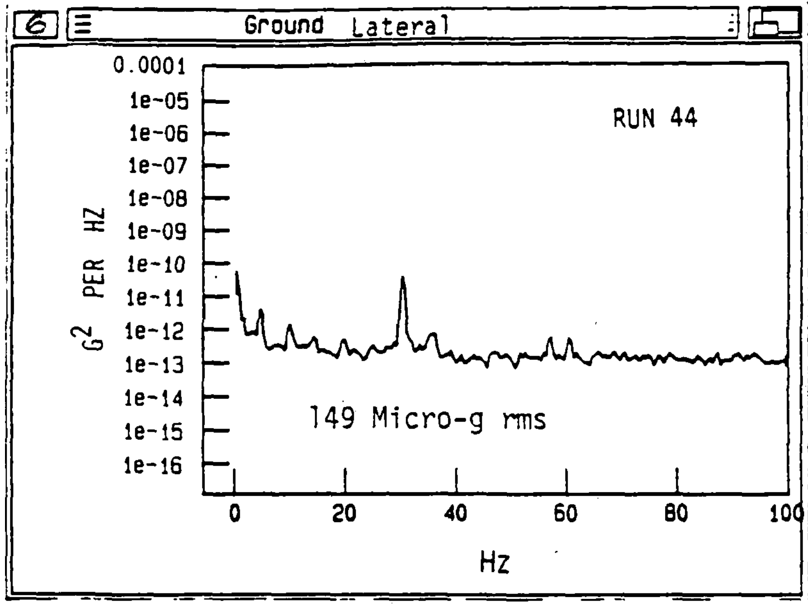


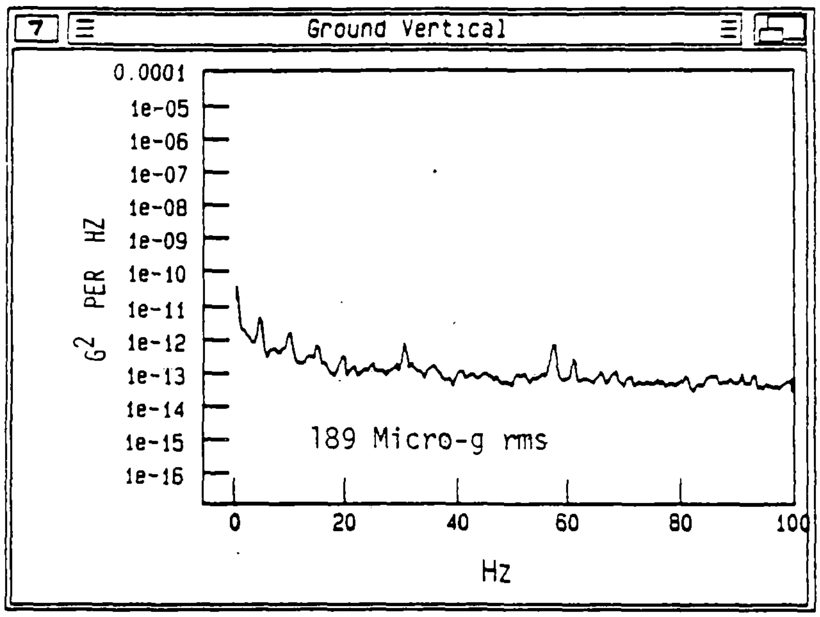


FIGURE 3.3 BACKGROUND ACCELERATION PSDs AT SITE #1, GENERATOR ON, BALLAST UNDER LEADING CAR AXLE

The background acceleration levels with the generator turned off are seen in Figures 3.4 and 3.5. Relatively little difference can be seen in Channels 1-3 (Figures 3.1 versus 3.4), except that the 60-Hz spectral peak disappears with the generator off. In the battery-powered Channels 4-5 (Figures 3.2 versus 3.5), strong 30- and 60-Hz spectral peaks are seen which disappear when the generator is turned off. The 57-Hz peak, however, is unaffected and is therefore unrelated to the a.c. power generation. This trailing end of the car was physically closer to the generator. A prominent 30-Hz peak in ground lateral acceleration PSD (Figure 3.3) can also be seen. The 30- Hz signal is therefore related (seismically and/or acoustically) to the firing frequency of the 4-cycle, 3600-rpm generator; while the 60-Hz signal is related to the 3600-rpm rotational speed.

3.2.2 Operating Acceleration Levels

Typical acceleration power spectra are shown in Figures 3.6 through 3.8 from Run 11, with the GP9 locomotive running at engine idle speed, train couplers bunched, and with winds less than 5 mph. Spectra in Figure 3.6 show the orthogonal acceleration power at the car body over the leading truck-pair span bolster centerplate. Similar spectra for accelerations over the trailing truck-pair are given in Figure 3.7. Ground (track ballast) vibration spectra are shown in Figure 3.8. A strong low-frequency spectral peak at 8-Hz can be seen in these figures, particularly in the car-body lateral acceleration. This peak may indicate the natural frequency of the car as a seismic mass responding to very low levels of excitation, with truck springs essentially locked, or may also be due to flat car transverse bending or torsional flexure modes. The engine firing and rotational speed (about 300 rpm, 5 Hz) does not show up as a particularly strong spectral peak in this run.

Spectra from Run 12 are shown in Figures 3.9 and 3.10, showing the effects of higher engine speed (the controller in Notch 8) on vibration levels. In this run, the fundamental and harmonics of the engine firing and rotational speed (about 780 rpm, 13 Hz) can be seen clearly, particularly in the ground vertical accelerations. No particularly

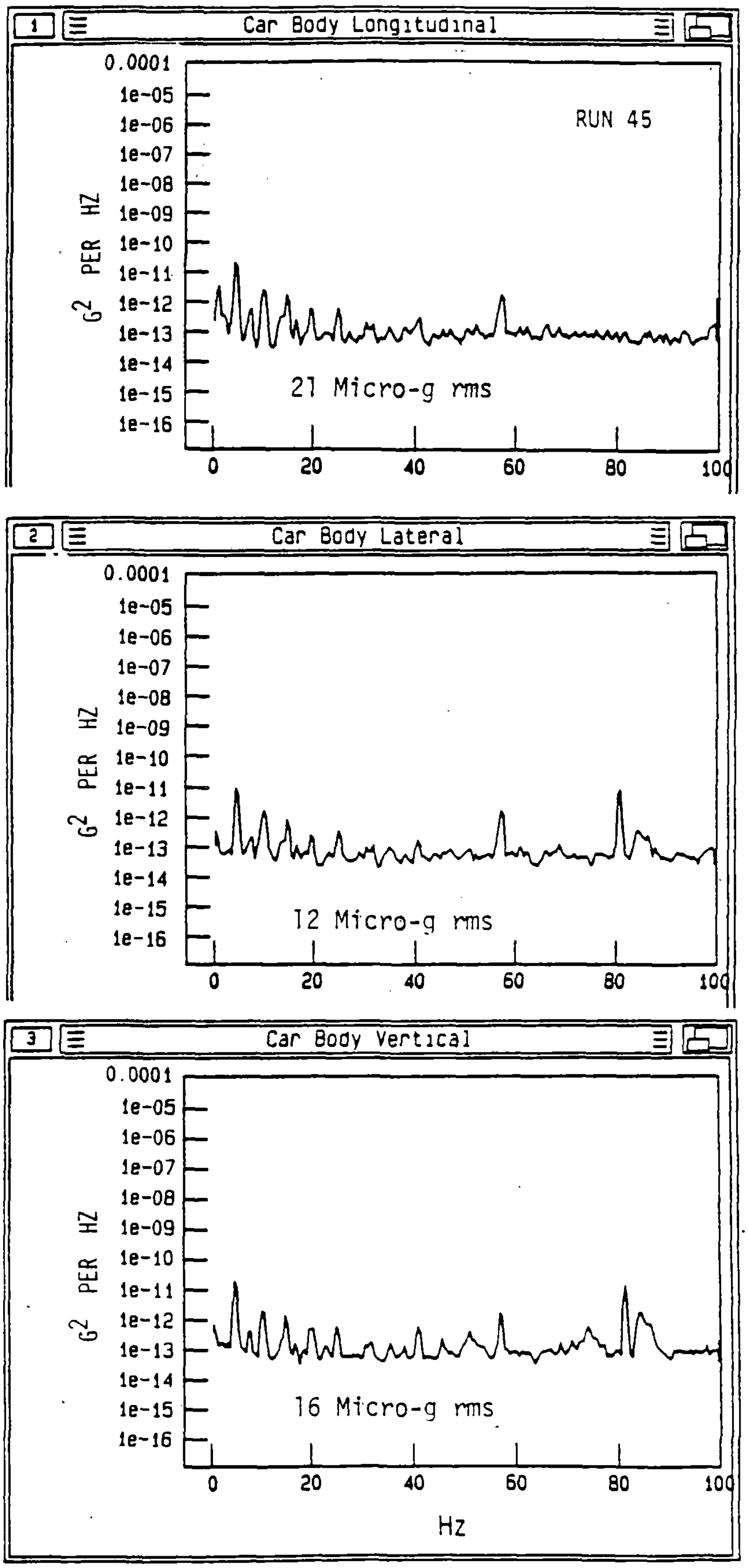


FIGURE 3.4 BACKGROUND ACCELERATION PSDs AT SITE #1, GENERATOR OFF, CAR BODY OVER LEADING TRUCK

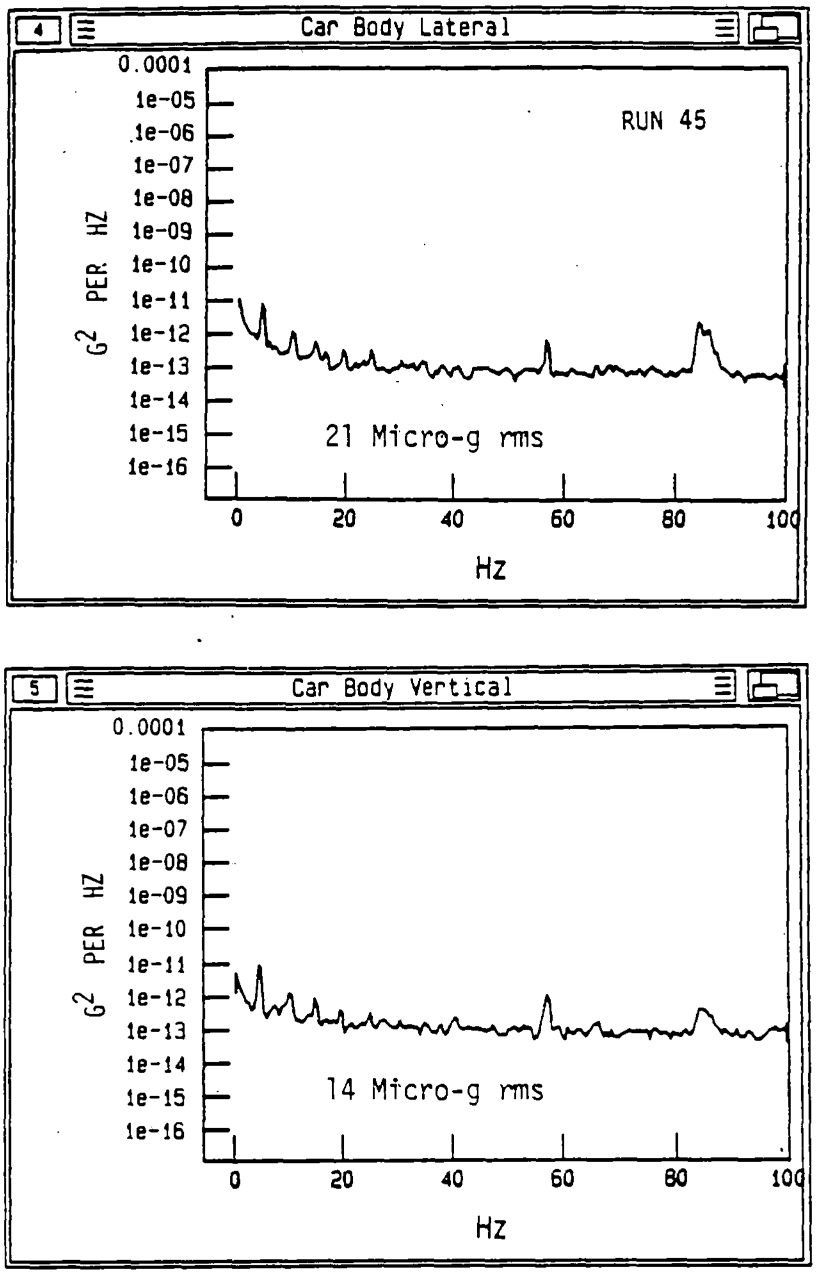
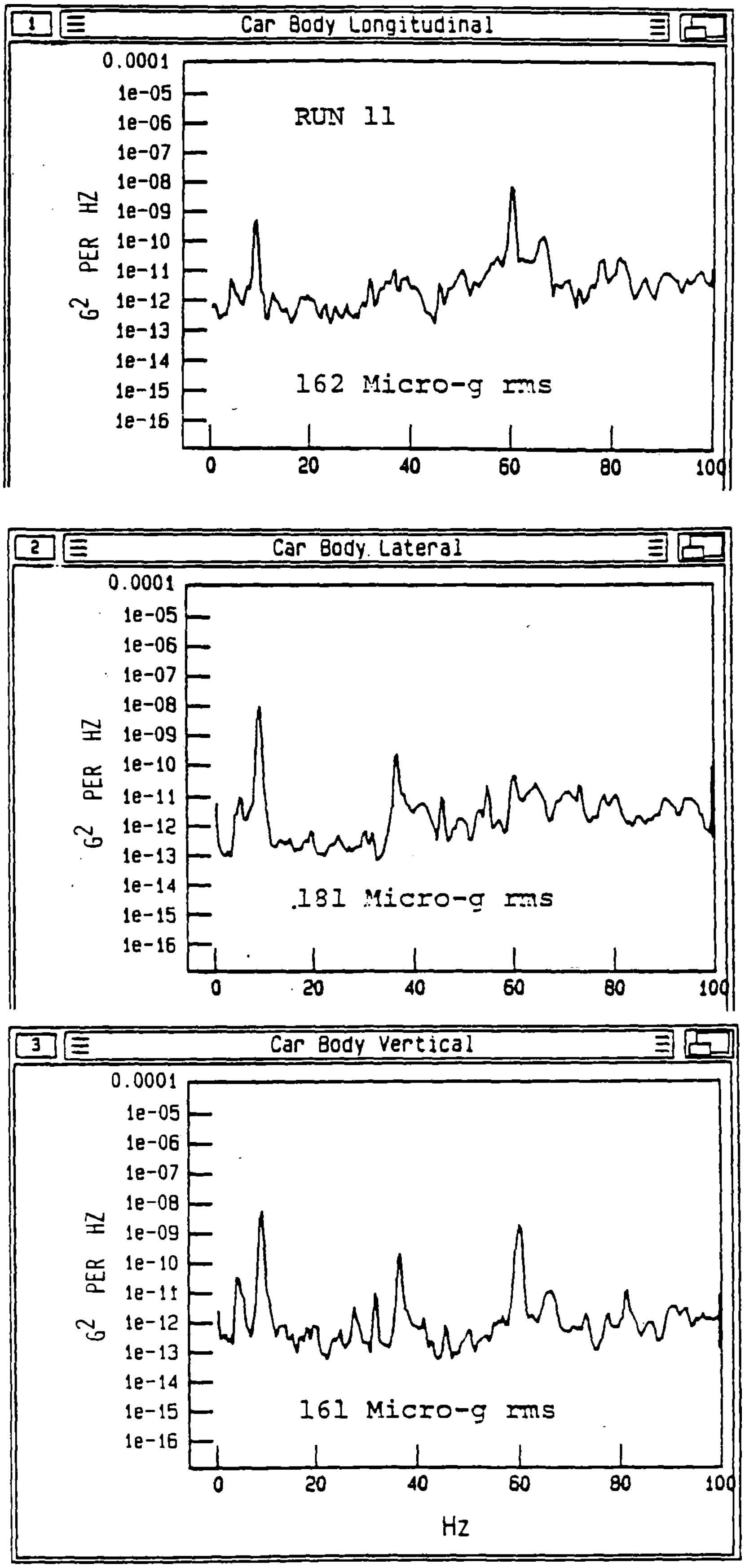
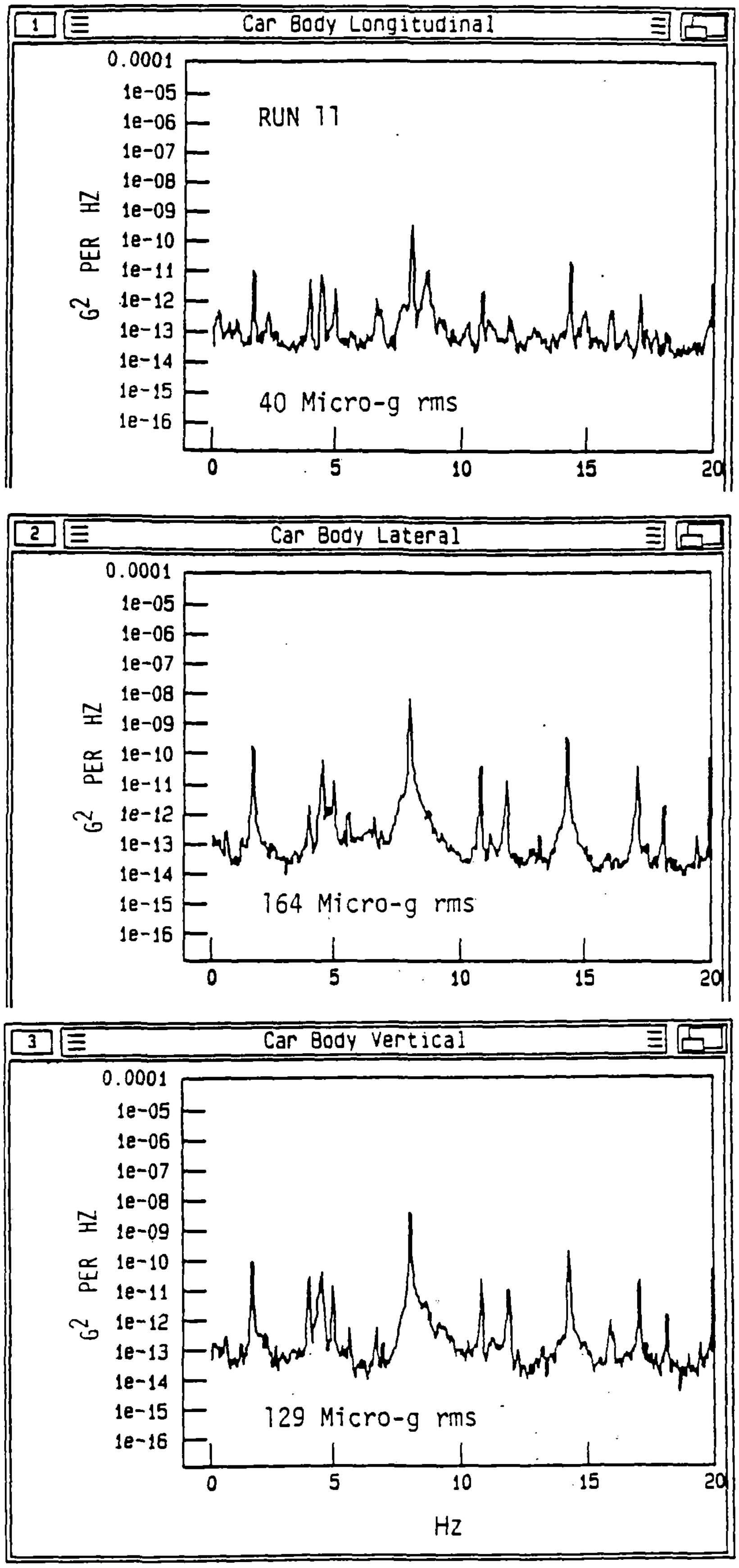


FIGURE 3.5 BACKGROUND ACCELERATION PSDs AT SITE #1, GENERATOR OFF, CAR BODY OVER TRAILING TRUCK



a. 0-100 Hz Bandwidth

FIGURE 3.6 CAR BODY ACCELERATION PSDs OVER LEADING TRUCK, GP9 LOCOMOTIVE IN IDLE, COUPLERS BUNCHED, NO WIND



b. 0-20 Hz Bandwidth

FIGURE 3.6 (CONTINUED)

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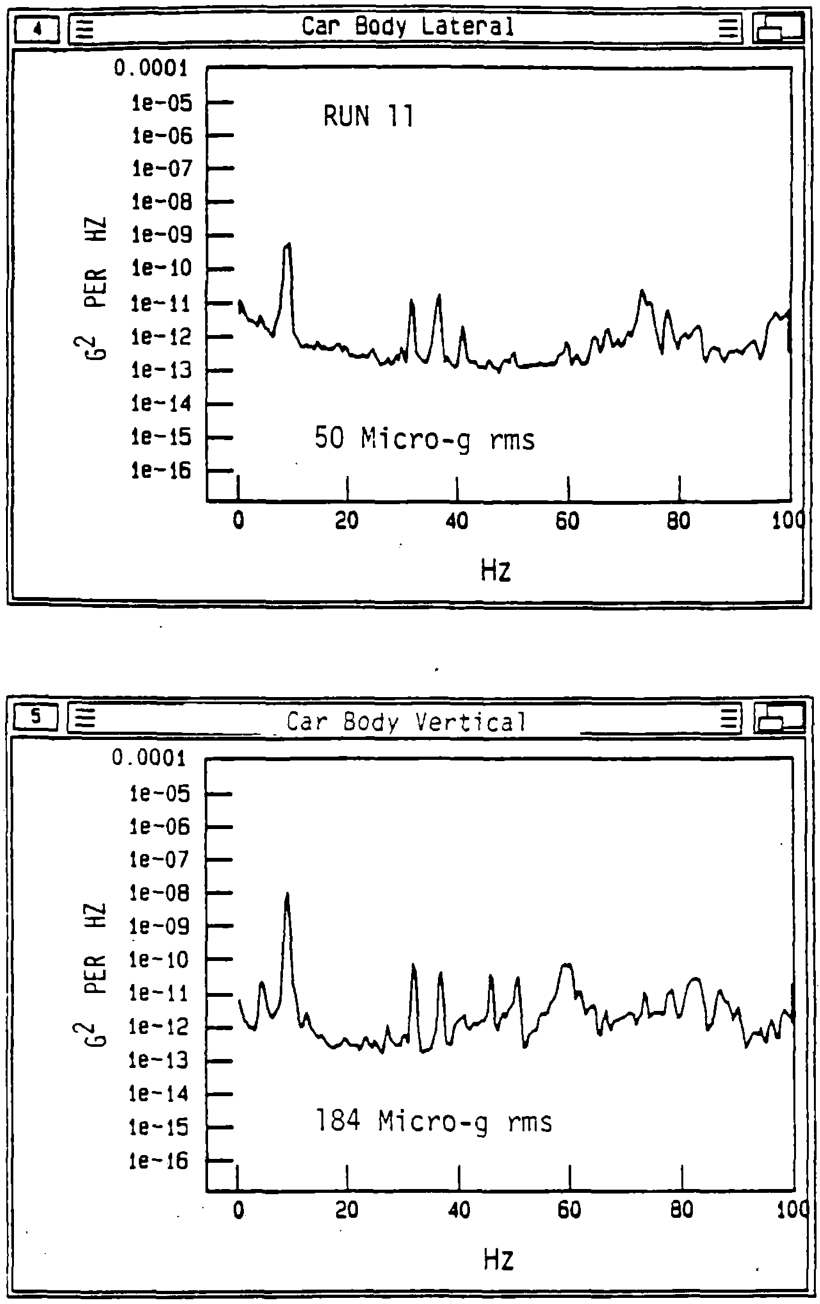
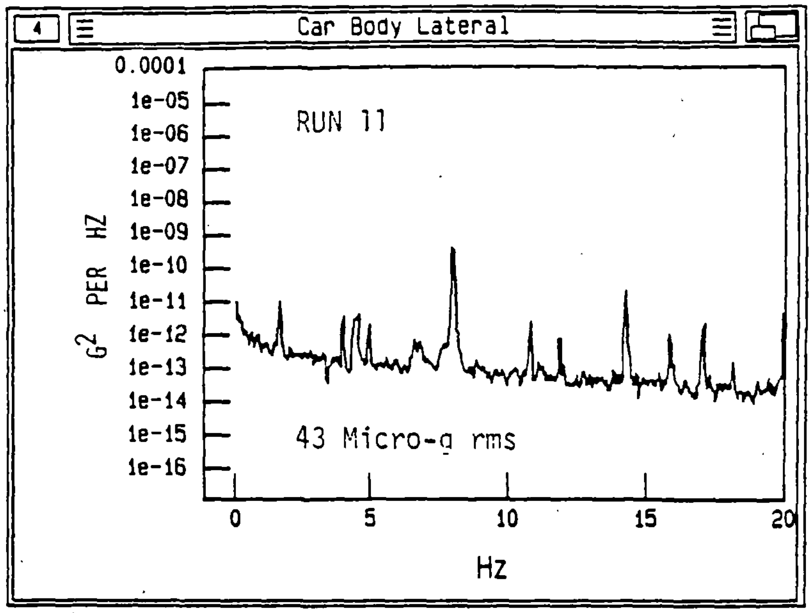
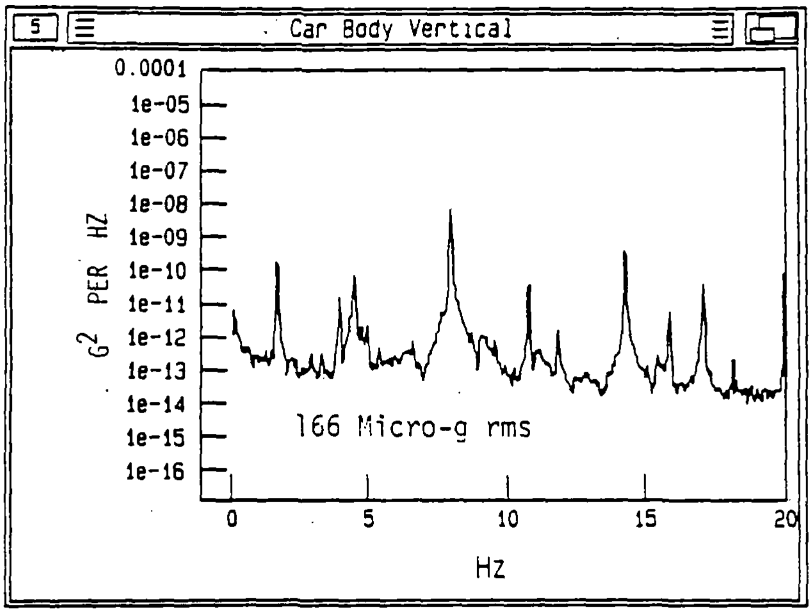


a. 0-100 Hz Bandwidth

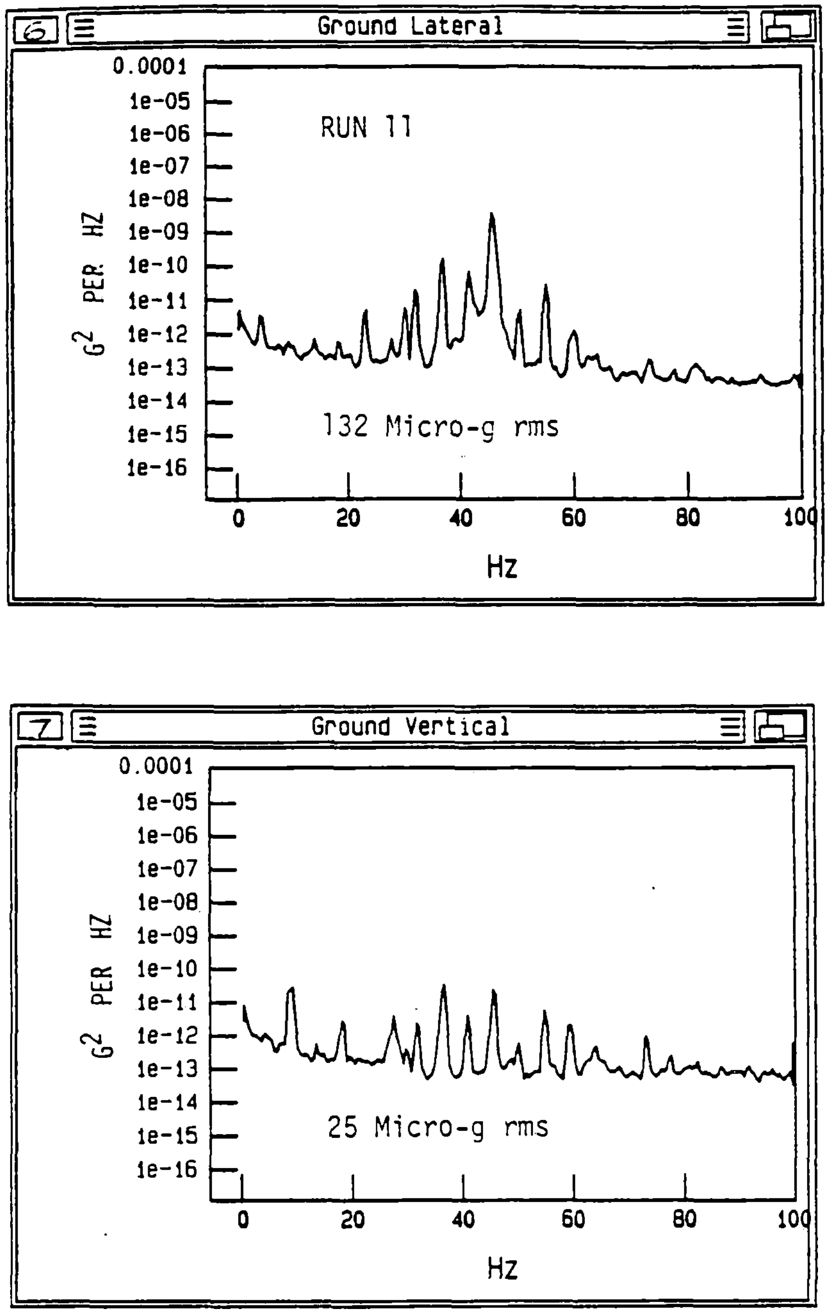
FIGURE 3.7 CAR BODY ACCELERATION PSDs OVER TRAILING TRUCK, GP9 LOCOMOTIVE IN IDLE, COUPLERS BUNCHED, NO WIND





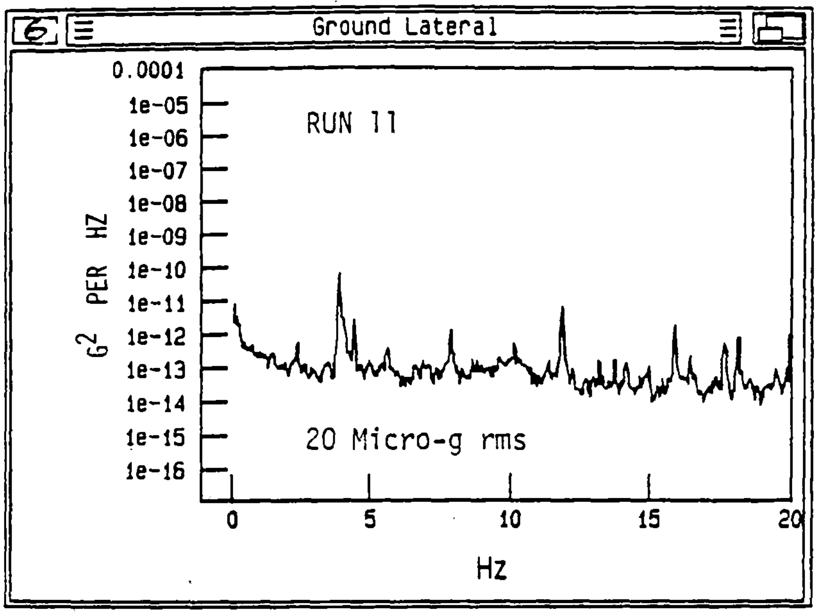
b. 0-20 Hz Bandwidth

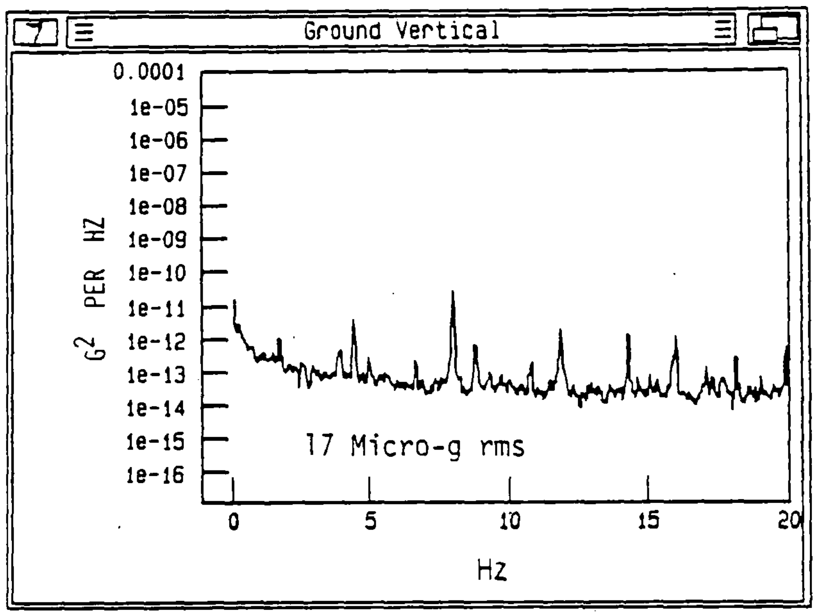
FIGURE 3.7 (CONTINUED)



a. 0-100 Hz Bandwidth

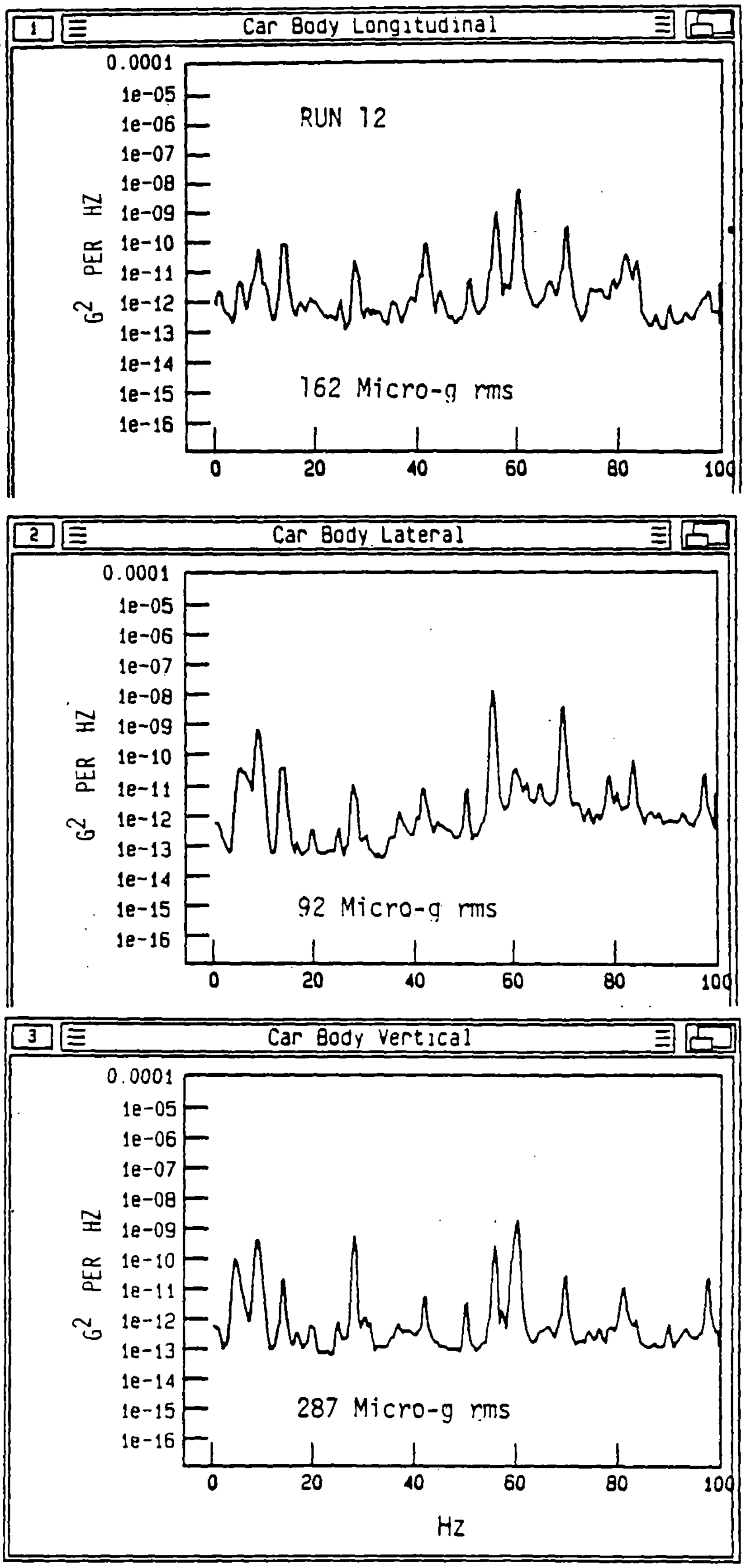
FIGURE 3.8 BALLAST ACCELERATION PSDs UNDER LEADING CAR AXLE, GP9 LOCOMOTIVE IN ENGINE IDLE, COUPLERS BUNCHED





b. 0-20 Hz Bandwidth

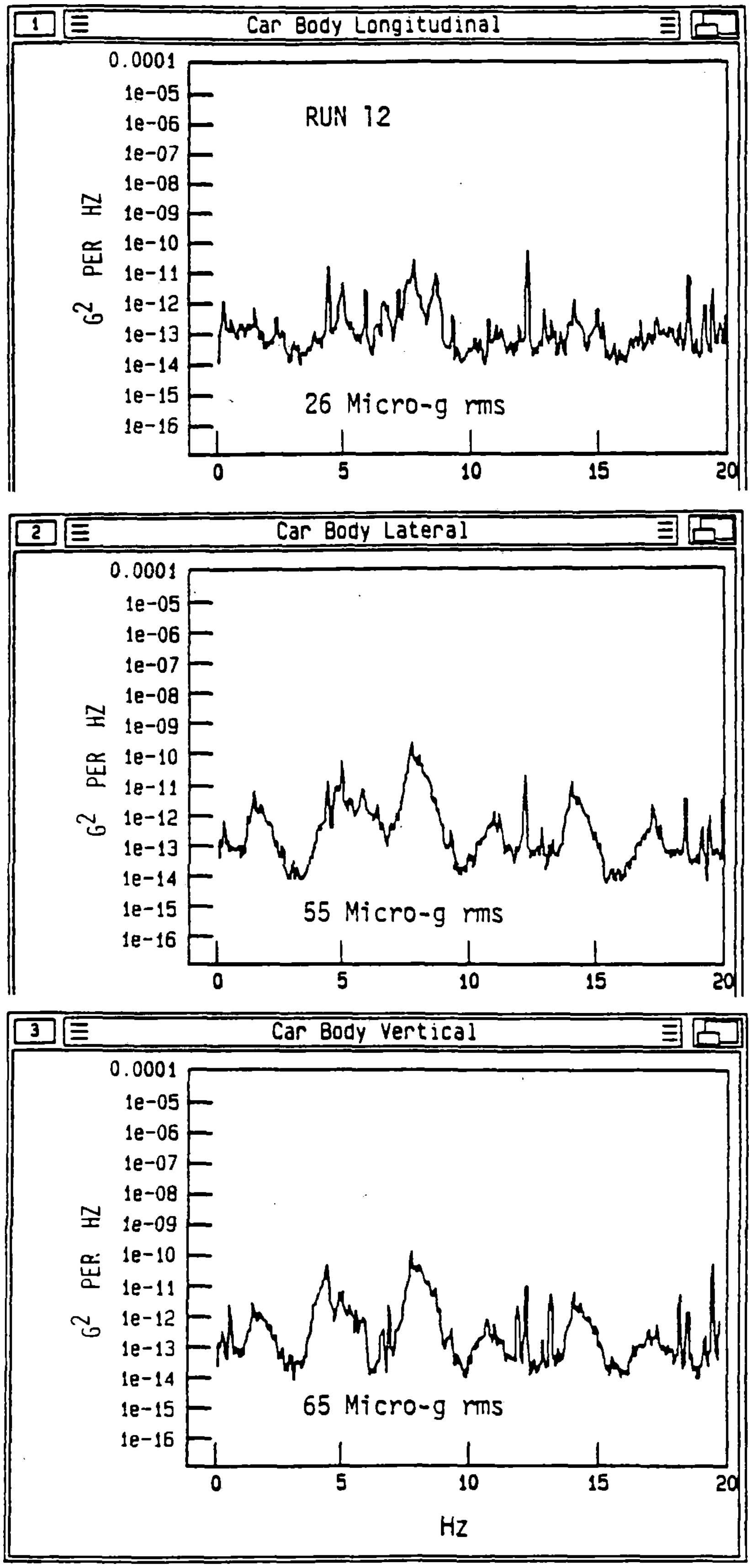
FIGURE 3.8 (CONTINUED)



a. 0-100 Hz Bandwidth

FIGURE 3.9 CAR BODY ACCELERATION PSDs OVER LEADING TRUCK, GP9 LOCOMOTIVE IN NOTCH 8, COUPLERS BUNCHED

DRAFT



b. 0-20 Hz Bandwidth

FIGURE 3.9 (CONTINUED)

DRAFT

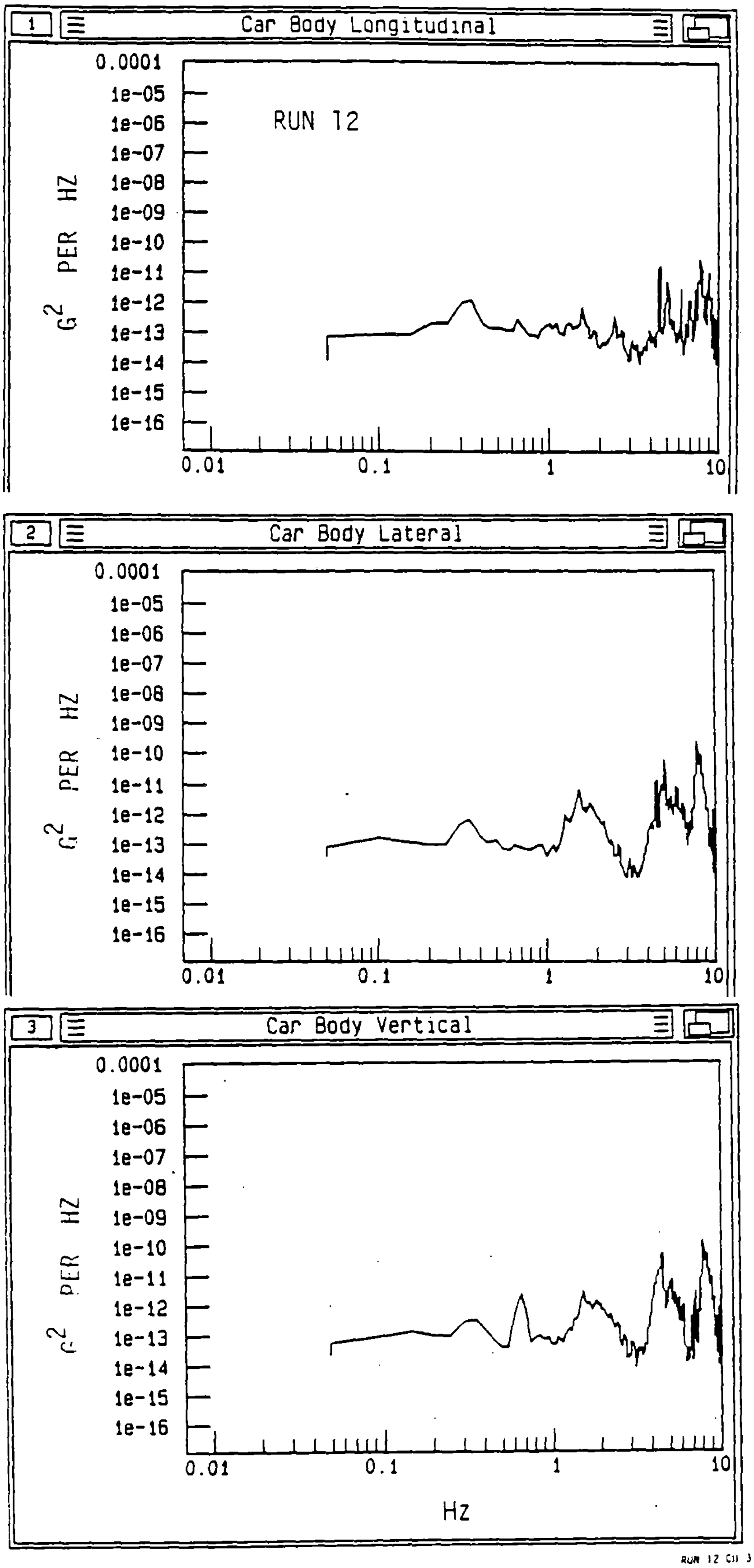
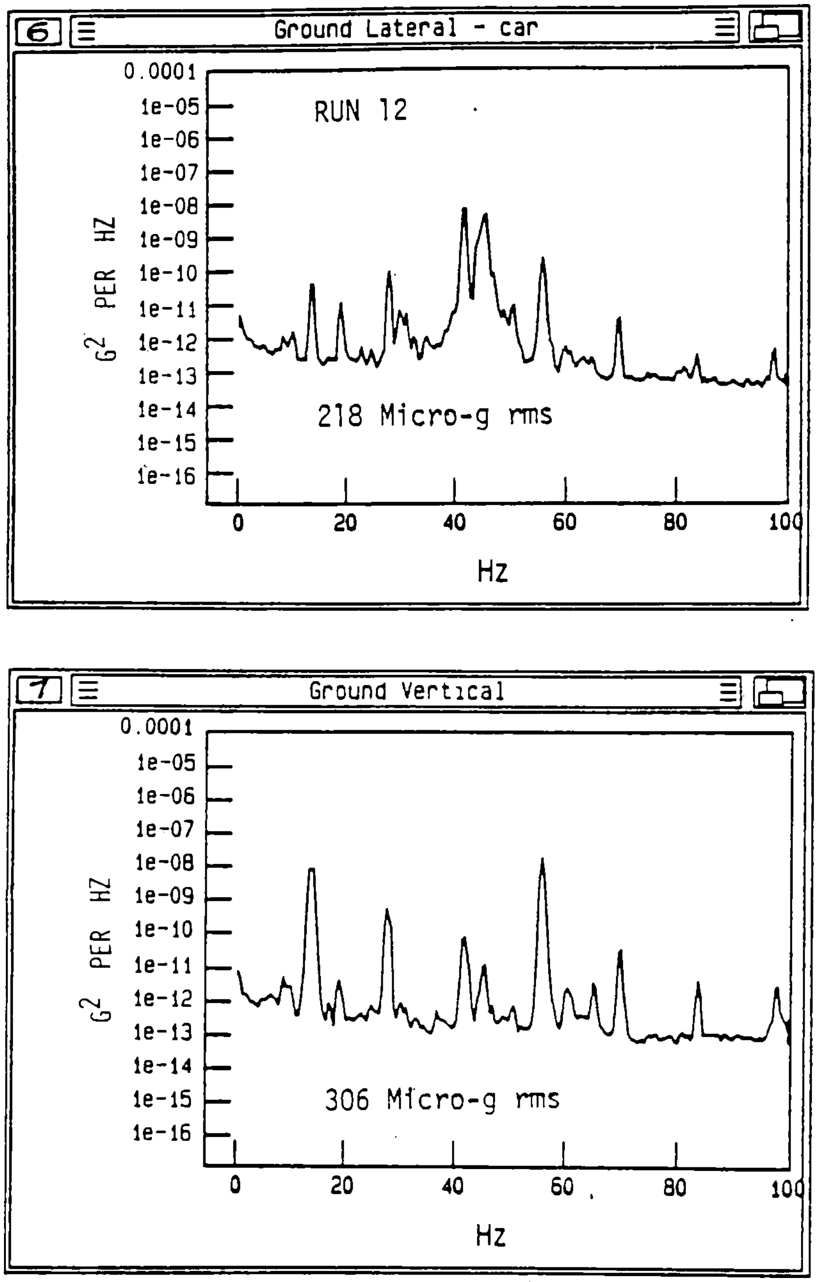
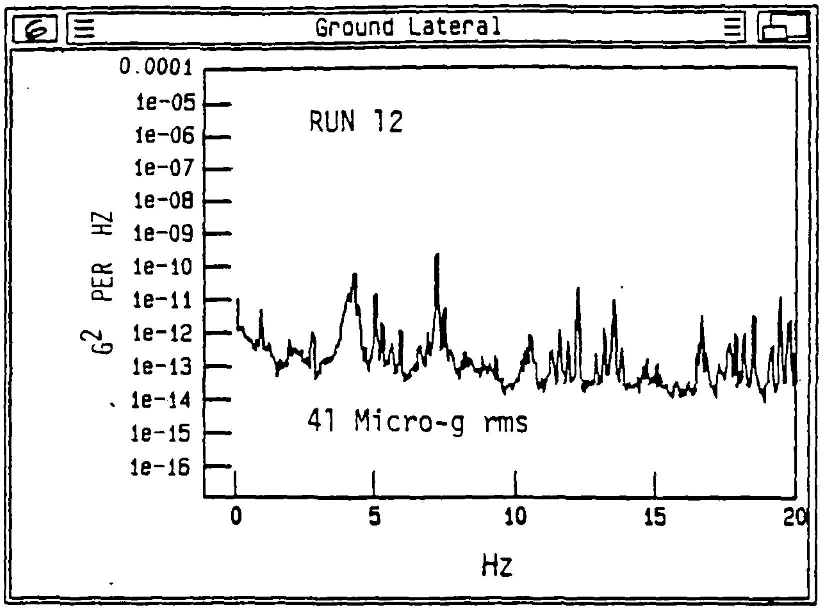


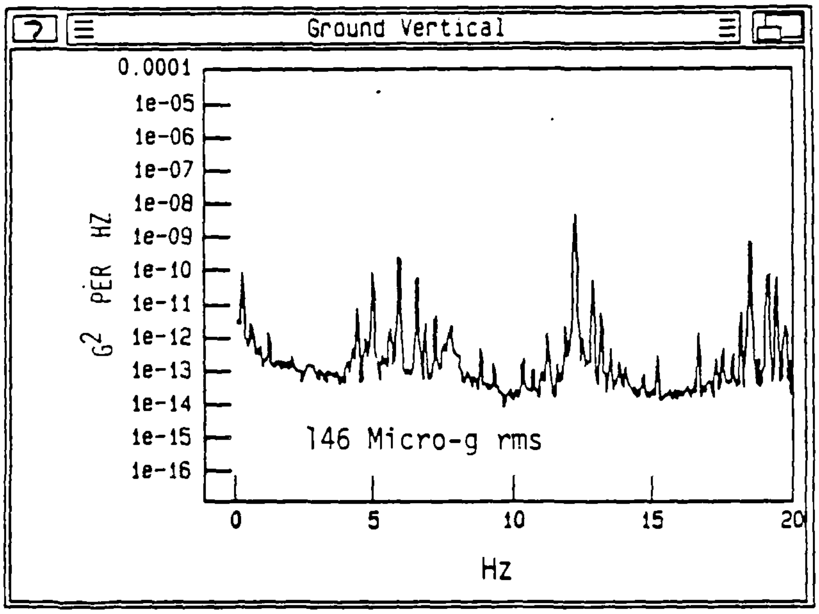
FIGURE 3.9 (CONTINUED)



a. 0-100 Hz Bandwidth

FIGURE 3.10 BALLAST ACCELERATION PSDs UNDER LEADING CAR AXLE, GP9 LOCOMOTIVE IN NOTCH 8, BUNCHED COUPLERS





b. 0-20 Hz Bandwidth

FIGURE 3.10 (CONTINUED)

strong car-body resonances were excited, however. In Figures 3.11 through 3.13, Run 13, a strong car-body response is seen at about 7.5 Hz with the engine controller in Notch 4 (450-500 rpm). Again, strong harmonics of engine speed can be seen throughout the 0-100 Hz range. The generally higher vibration levels appear to have moved the friction snubbers, so that a resonant peak near 1.1 Hz, typical of a loaded car body on the truck springs, was excited.

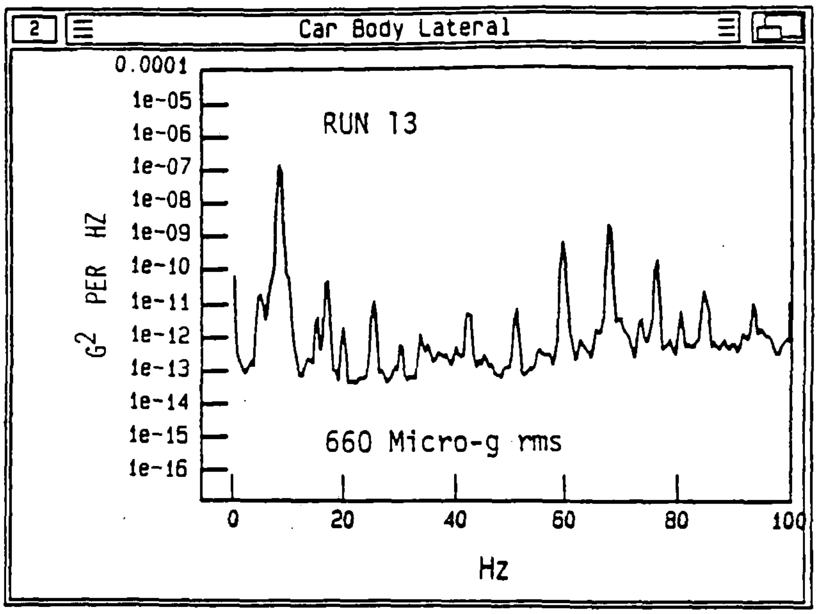
For comparison between the two locomotives, car body acceleration PSDs with the U30C locomotive are shown in Figures 3.14 through 3.16. Much stronger harmonic content and higher spectral peaks are seen with the U30C in Notch 8 (Figure 3.14) than with the GP9 (Figure 3.9). In Notch 4, however, the U30C does not excite the 8-Hz resonance (Figure 3.15) as strongly as the GP9 (Figure 3.11).

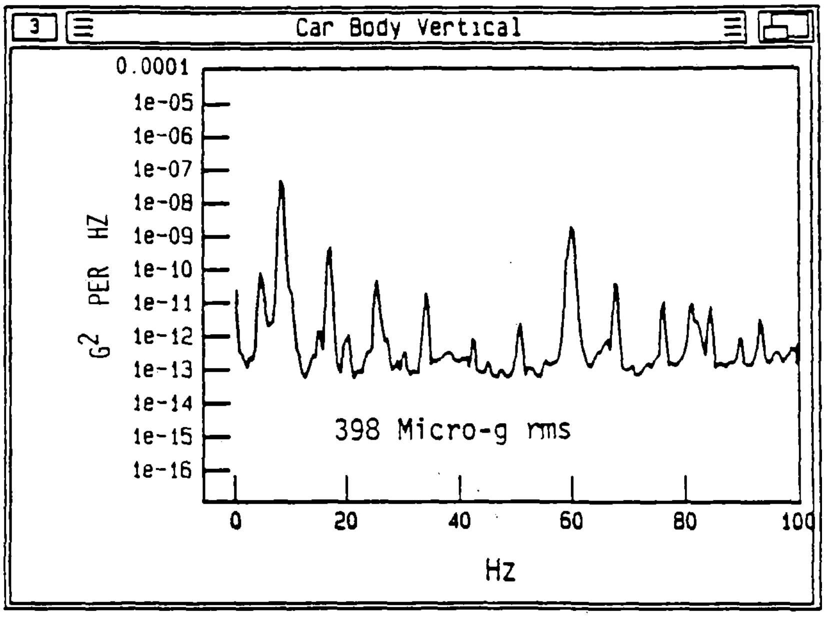
Ground vibration spectra directly under the locomotive trailing axle are shown in Figures 3.17 (the GP9) and 3.18 (the U30C), both in Notch 8. The two-stroke EMD Model 567C engine of the GP9, Figure 3.17, produces a fundamental frequency around 14 Hz (840 rpm) with strong harmonics of engine speed. The somewhat higher engine speed of the four-stroke GE Model FDL-16 engine of the U30C, Figure 3.18, produces a strong fundamental frequency around 17 Hz (1020 rpm) with "half harmonics" from firing every other revolution.

3.3 Transient Acceleration Events

3.3.1 Test Train Transient Events

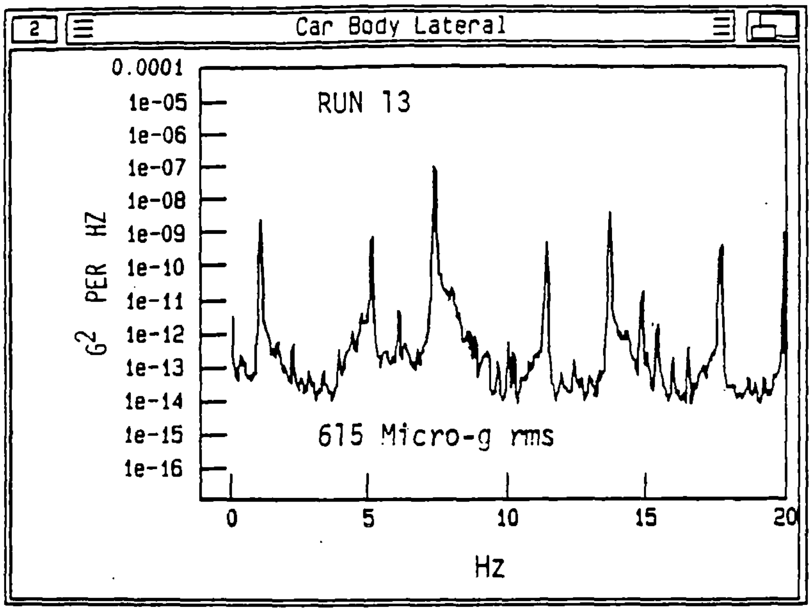
During the course of the field tests, relatively large-amplitude transient events were noted in the acceleration data. These events were attributed to various "creaks and groans" in the car structure (possibly thermal expansion/contraction events), train brake system transients, and other naturally-occurring phenomena. An example of the time history of one such event, which occurred between Runs 38 and 39, is shown in Figure 3.19, along with the spectral analysis of the event. A strong 142-Hz response was excited in car body lateral response, while the vertical

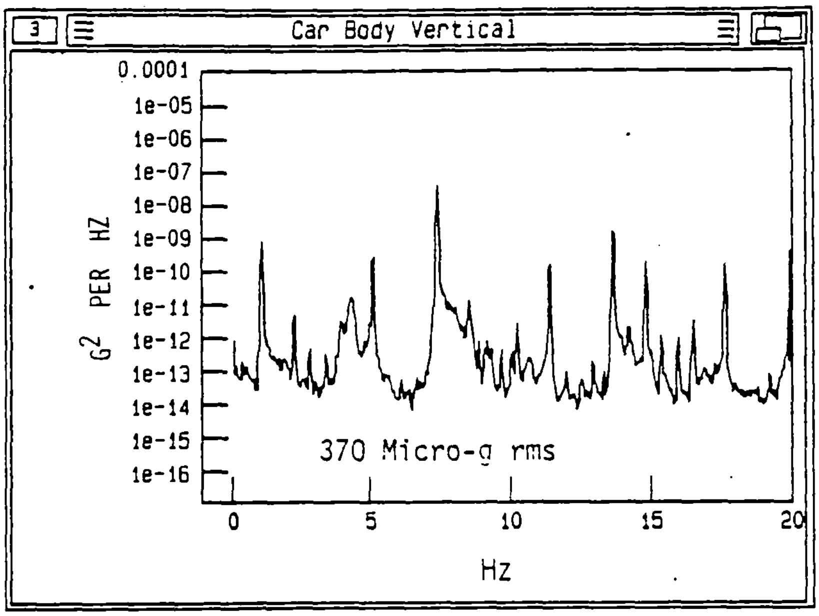




a. 0-100 Hz Bandwidth

FIGURE 3.11 CAR BODY ACCELERATION PSDs OVER LEADING TRUCK, GP9 LOCOMOTIVE IN NOTCH 4, COUPLERS BUNCHED





b. 0-20 Hz Bandwidth

FIGURE 3.11 (CONTINUED)

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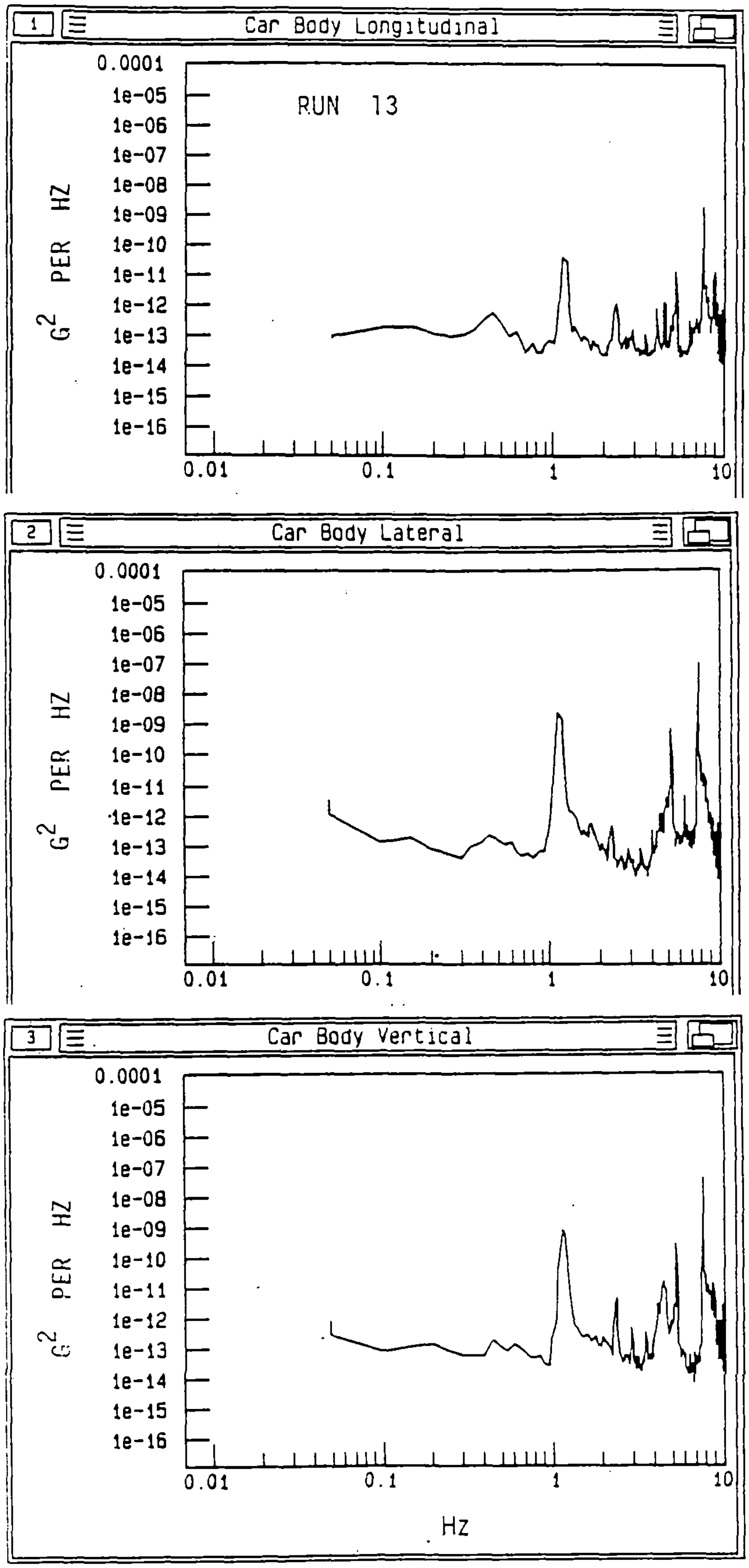
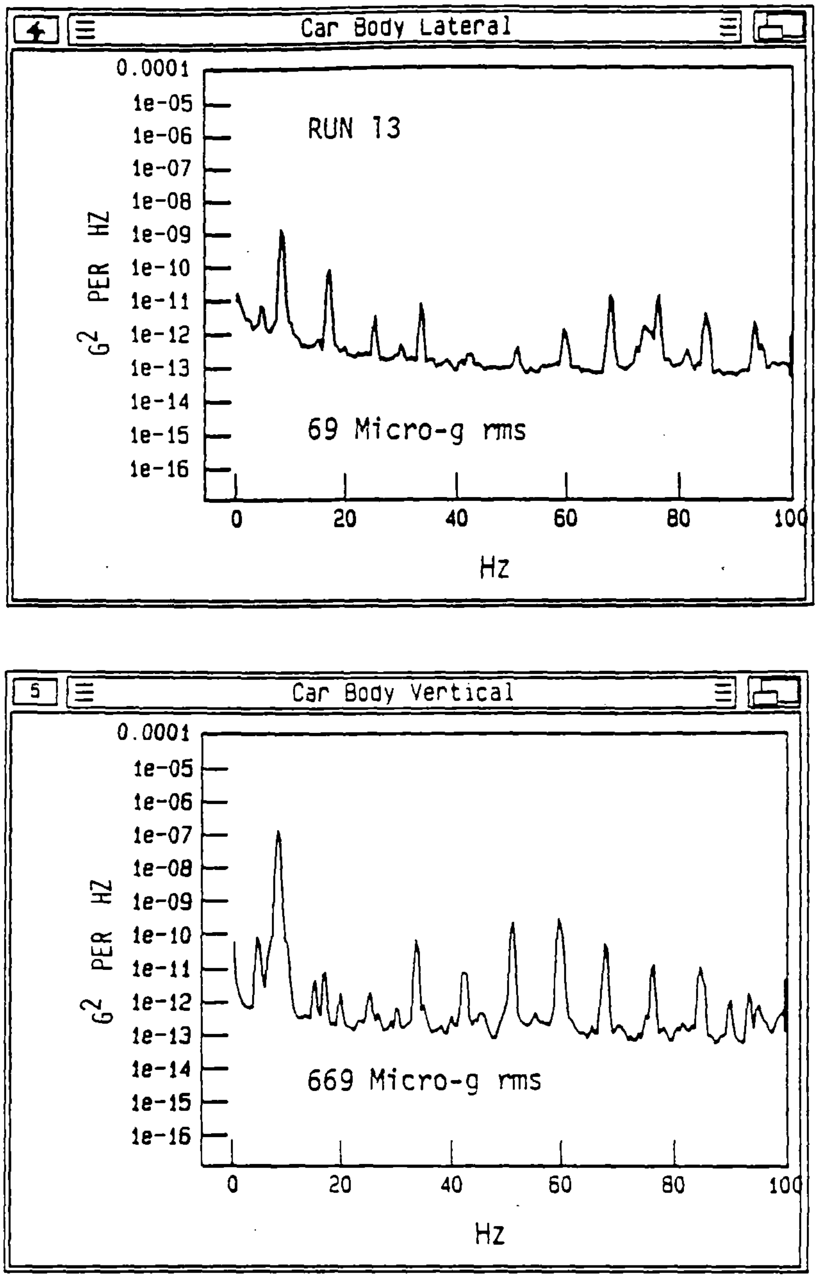
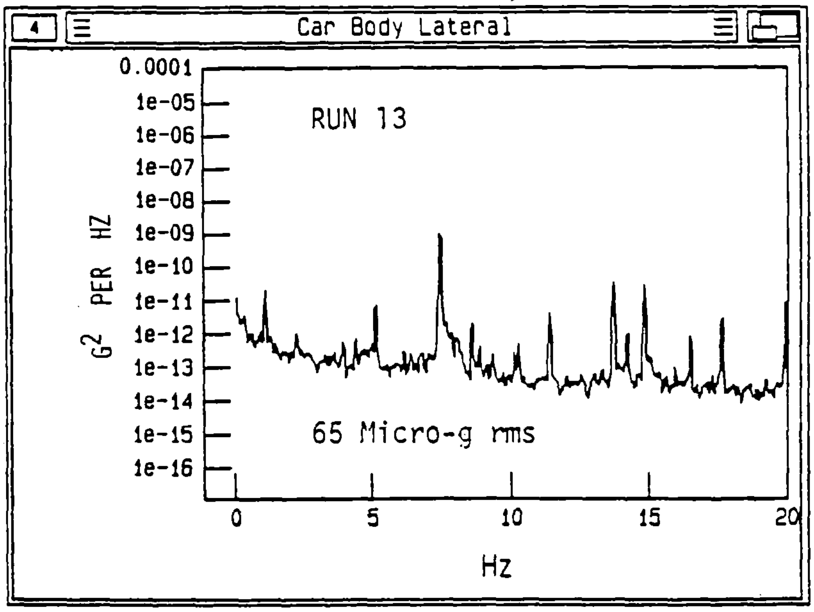


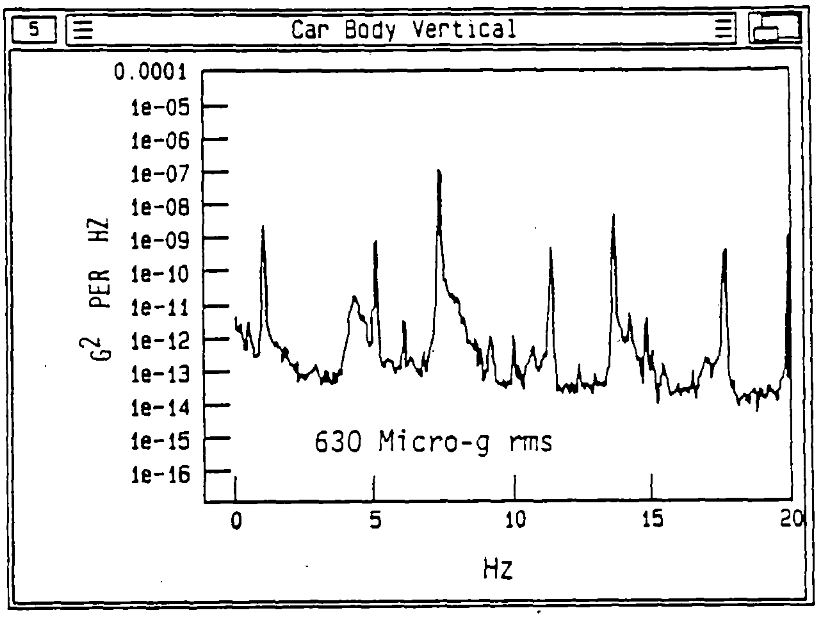
FIGURE 3.11 (CONTINUED)



a. 0-100 Hz Bandwidth

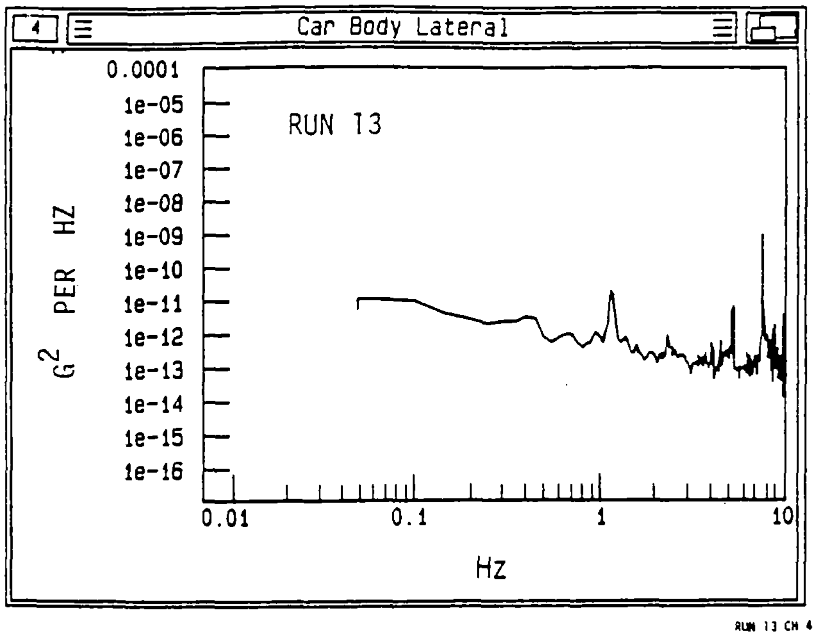
FIGURE 3.12 CAR BODY ACCELERATION PSDs OVER TRAILING TRUCK, GP9 LOCOMOTIVE IN NOTCH 4, COUPLERS BUNCHED





b. 0-20 Hz Bandwidth

FIGURE 3.12 (CONTINUED)



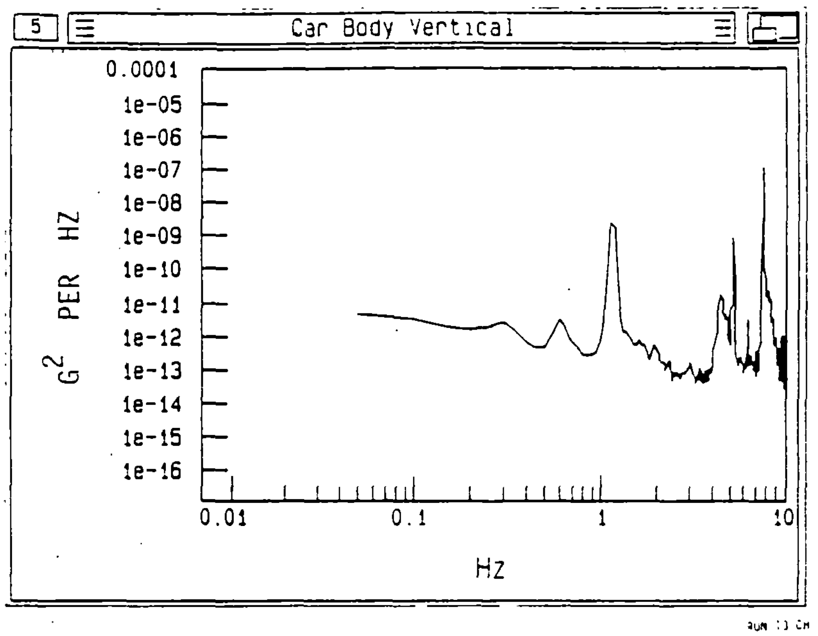
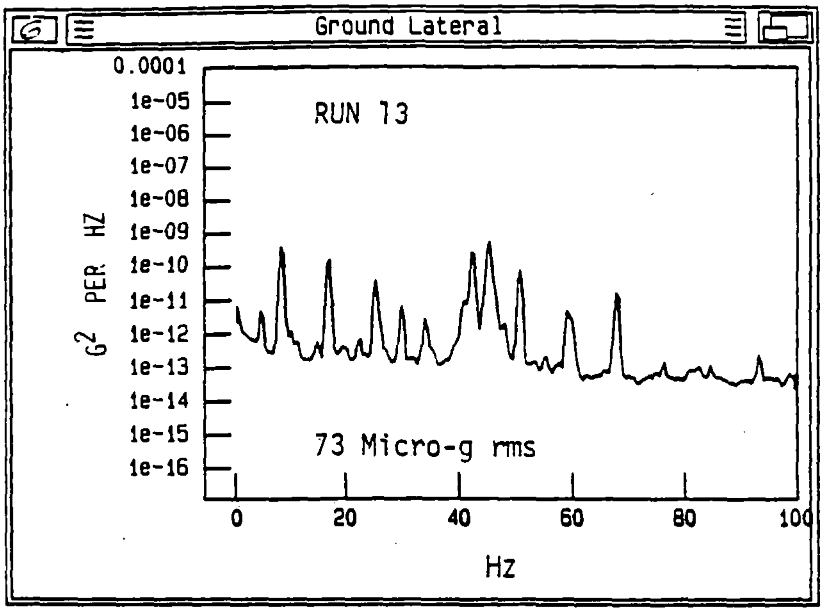
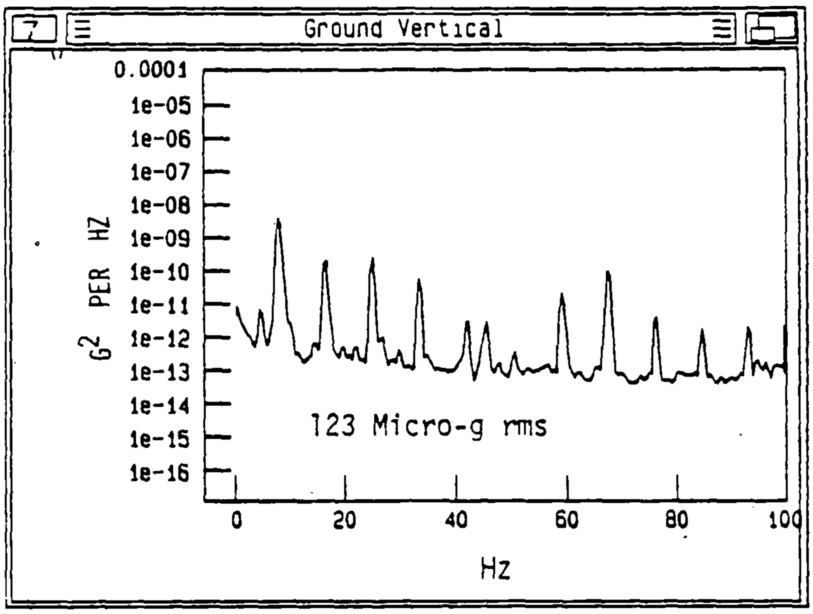


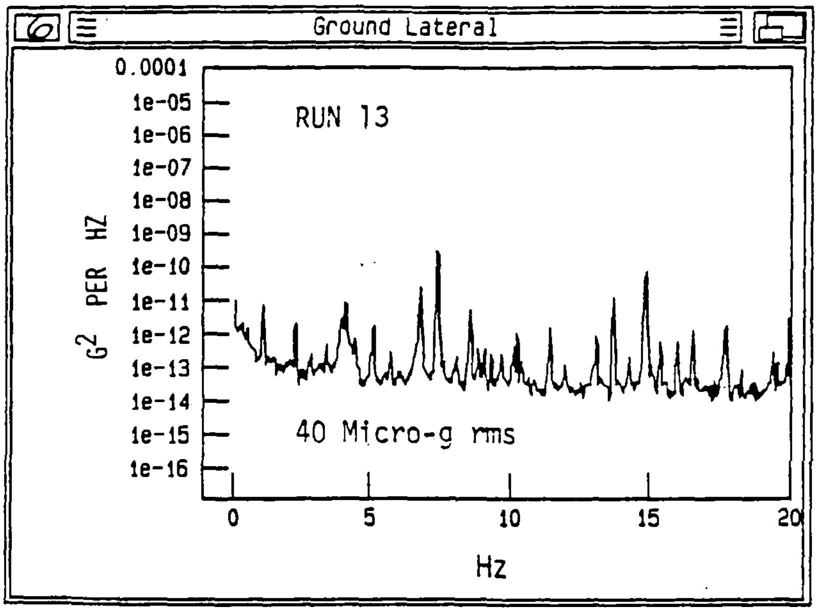
FIGURE 3.12 (CONTINUED)

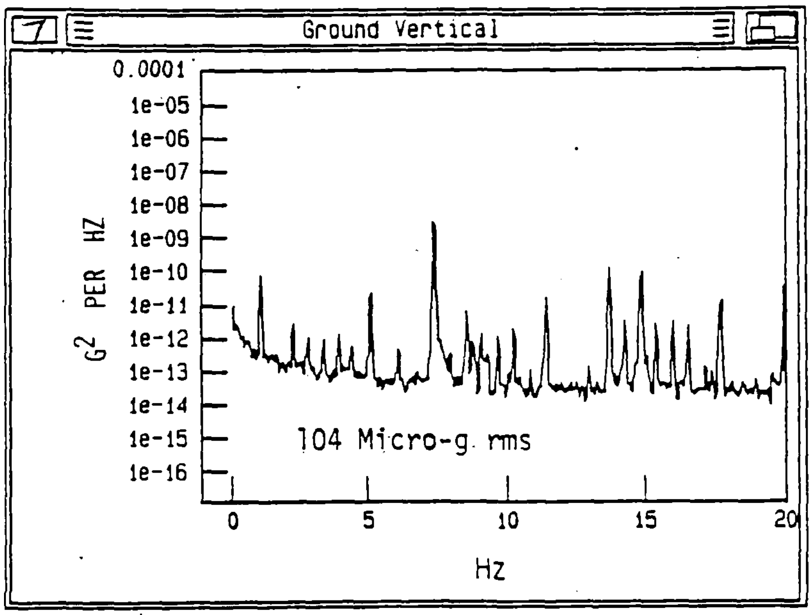




a. 0-100 Hz Bandwidth

FIGURE 3.13 BALLAST ACCELERATION PSDs UNDER LEADING CAR AXLE, GP9 LOCOMOTIVE IN NOTCH 4, COUPLERS BUNCHED

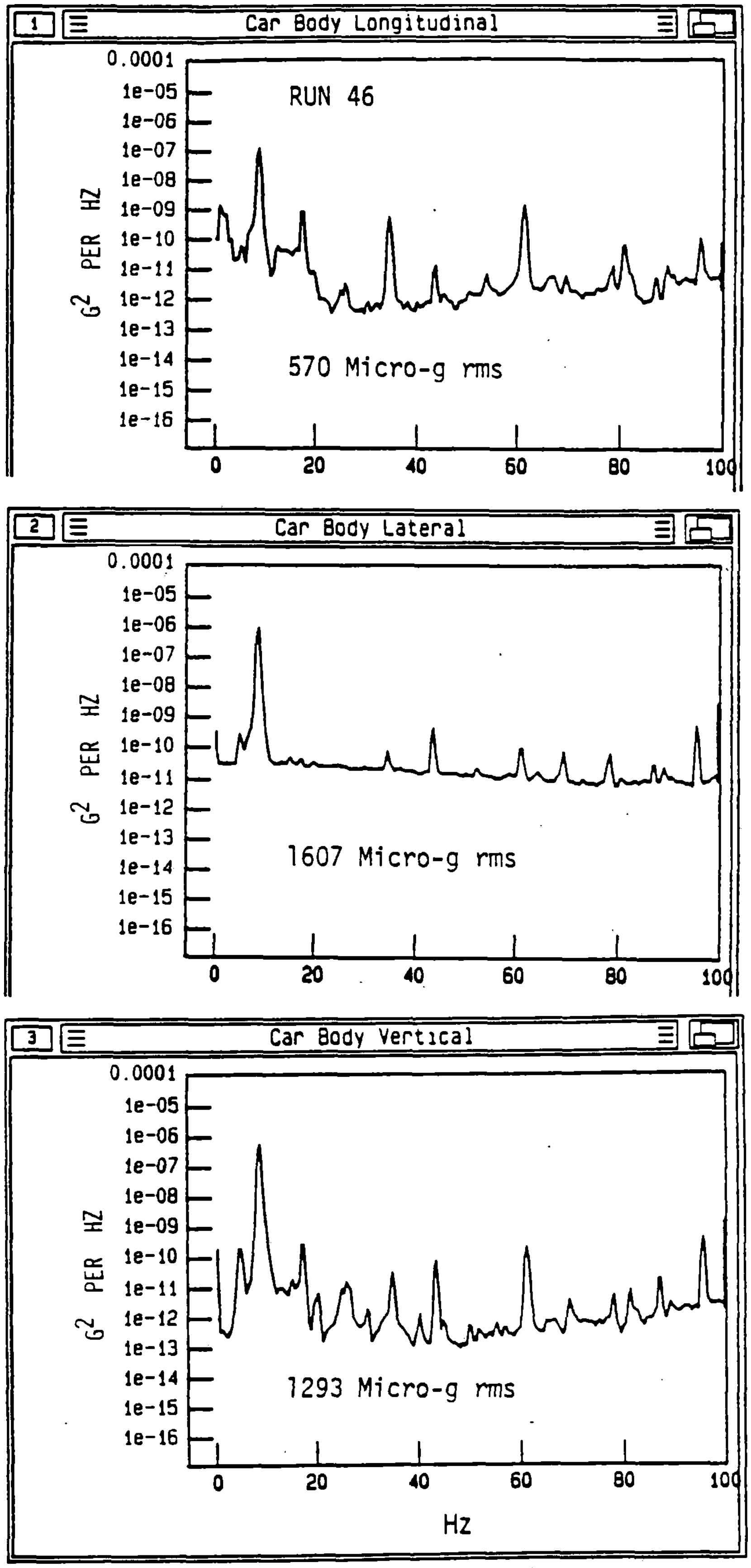




b. 0-20 Hz Bandwidth

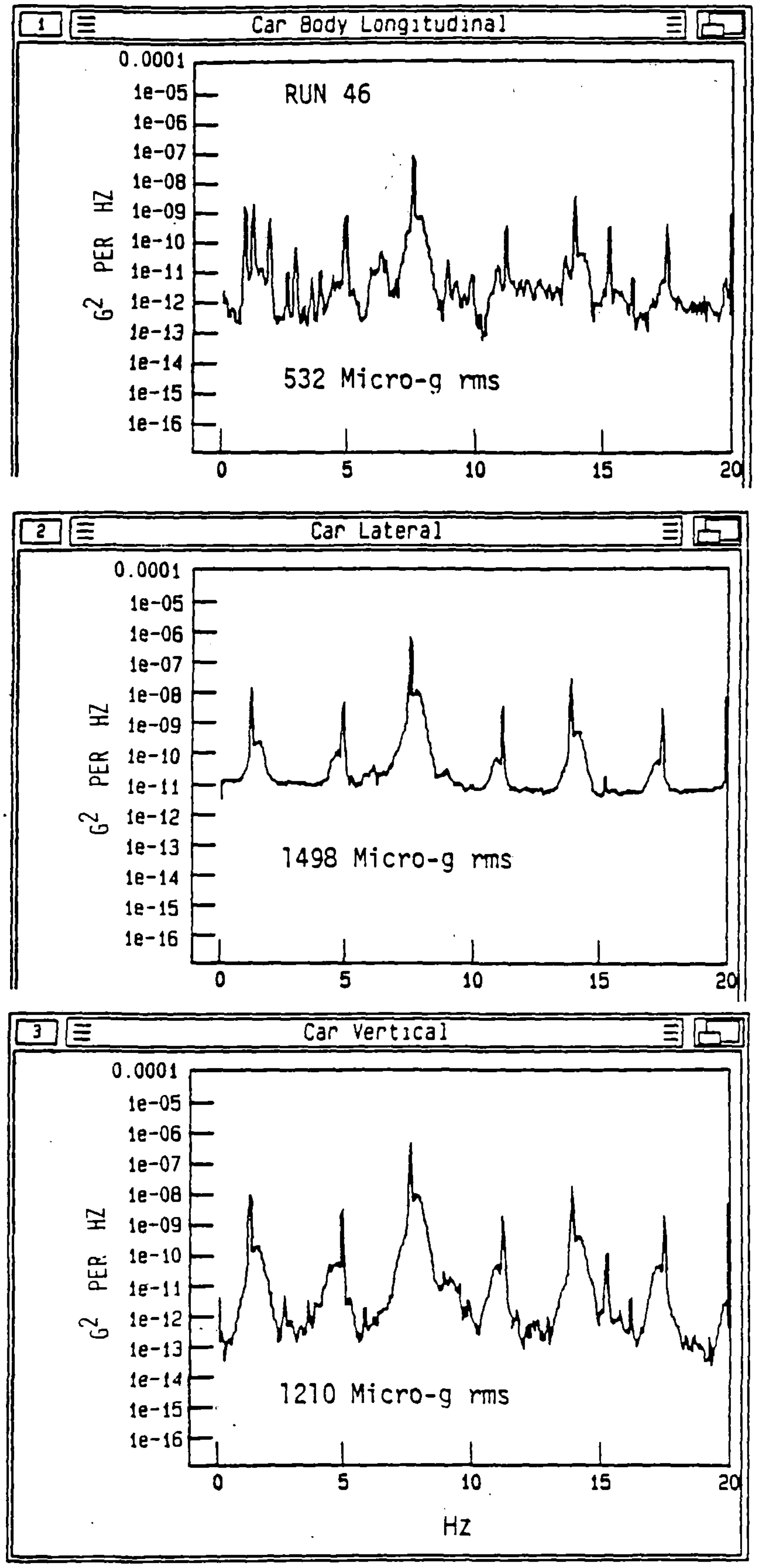
FIGURE 3.13 (CONTINUED)

DRAFT



a. 0-100 Hz Bandwidth

FIGURE 3.14 CAR BODY ACCELERATION PSDs OVER LEADING TRUCK, U30C LOCOMOTIVE IN NOTCH 8, COUPLERS BUNCHED



b. 0-20 Hz Bandwidth

FIGURE 3.14 (CONTINUED)

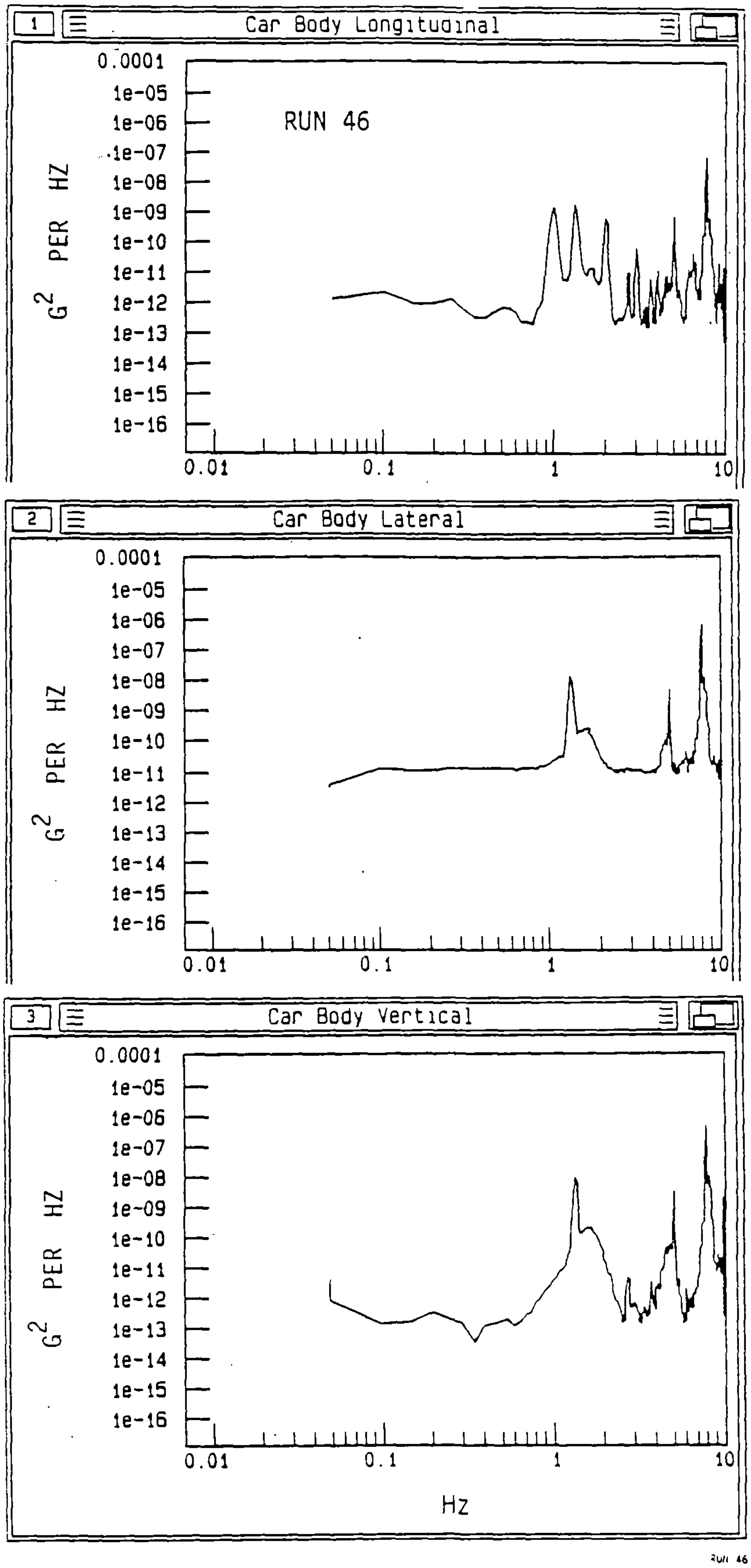
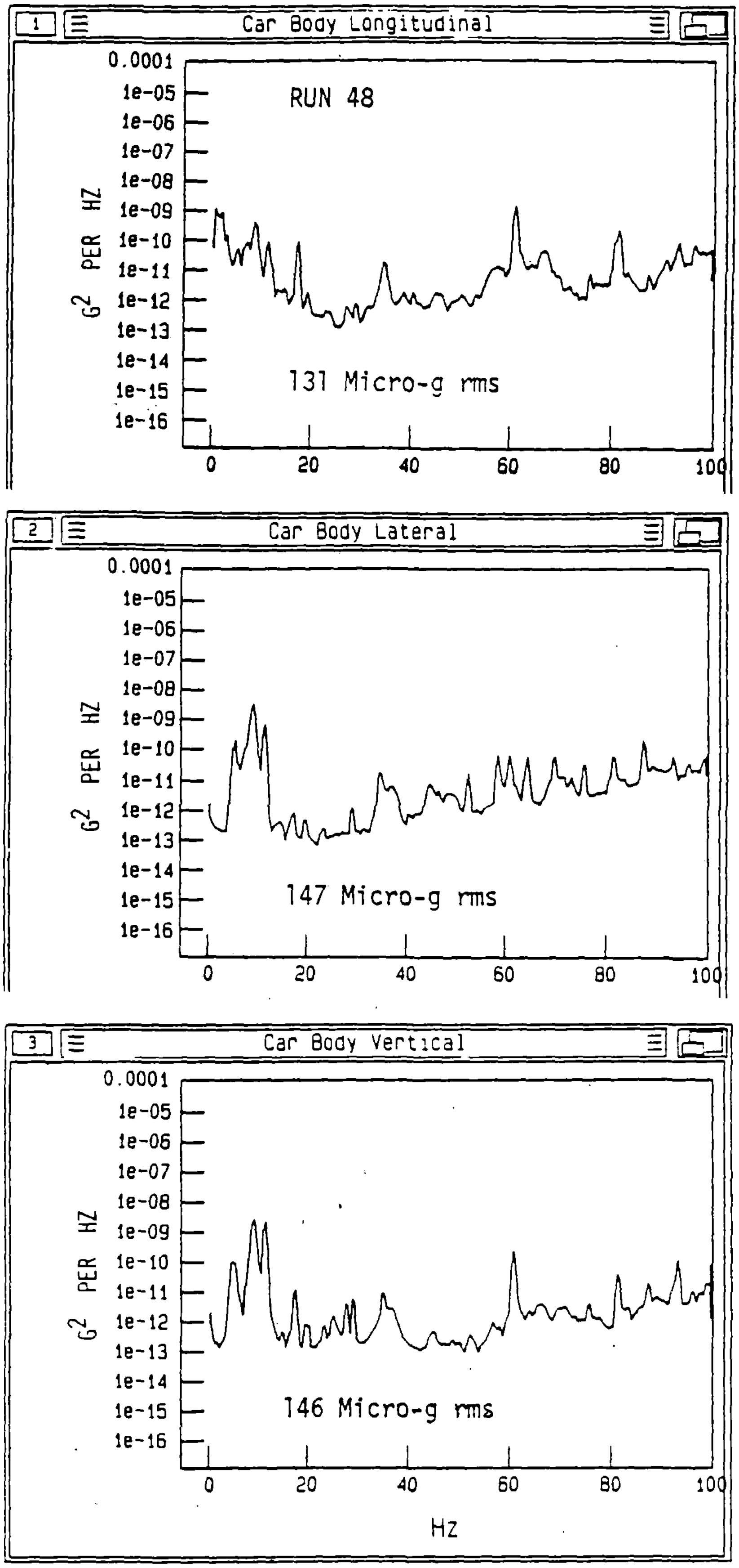


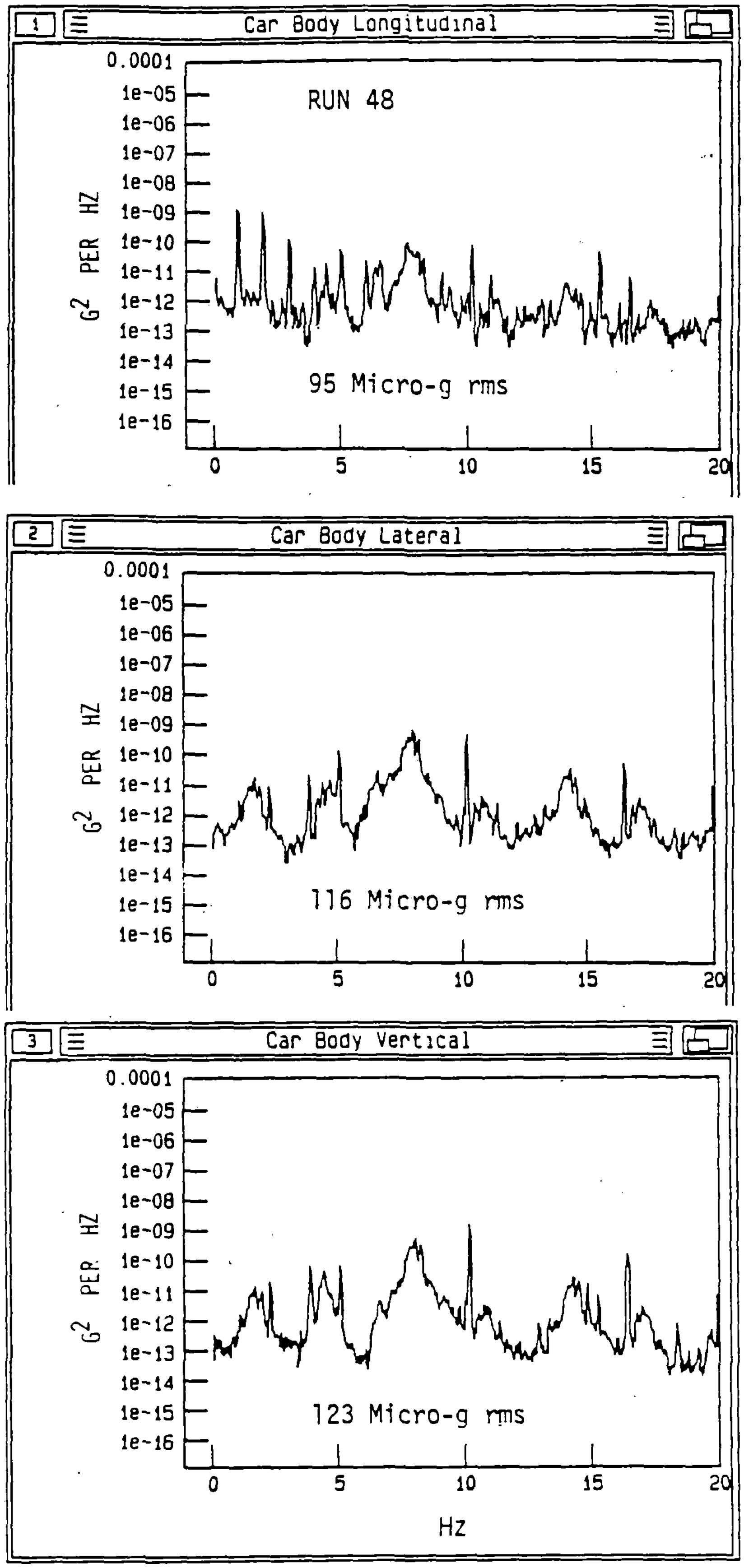
FIGURE 3.14 (CONTINUED)



a. 0-100 Hz Bandwidth

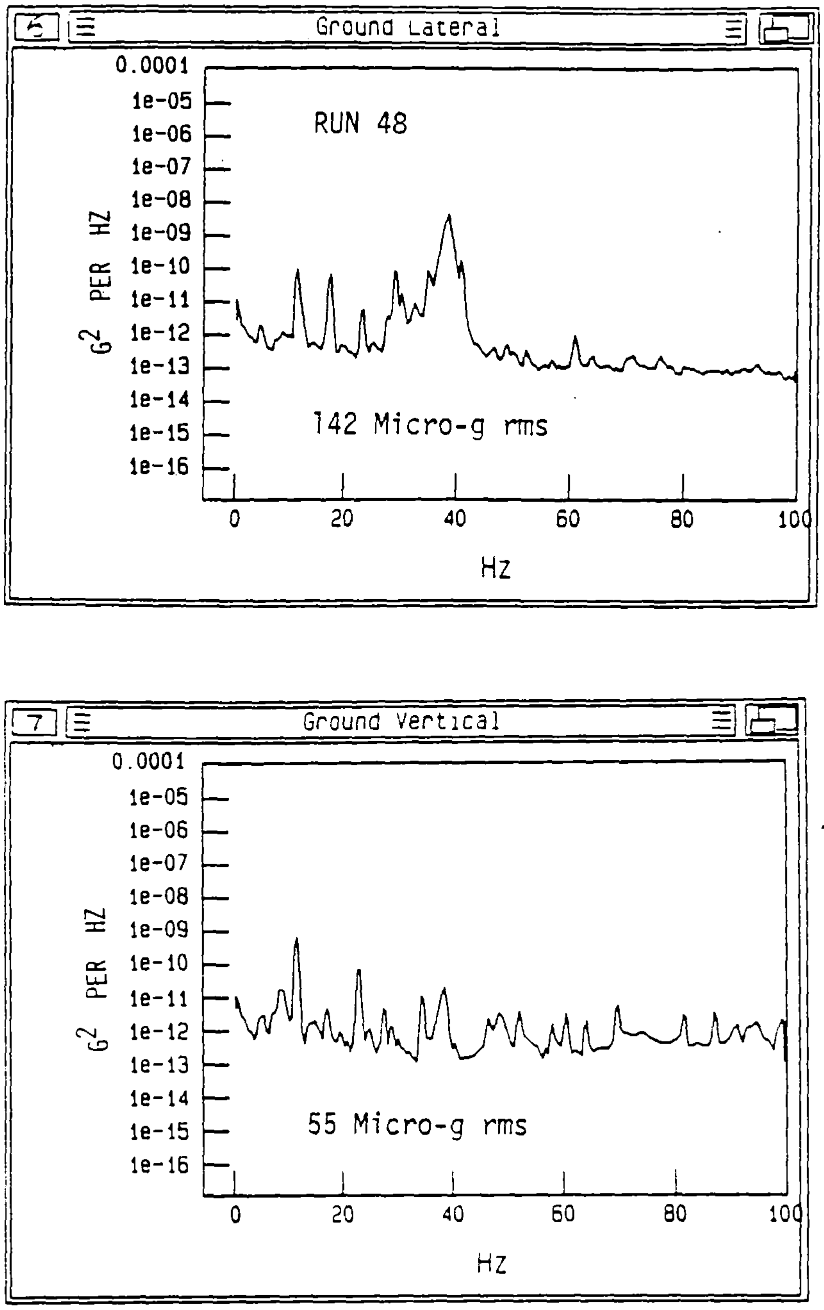
FIGURE 3.15 CAR BODY ACCELERATION PSDs OVER LEADING TRUCK, U30C LOCOMOTIVE IN NOTCH 4, COUPLERS BUNCHED

DRAFT



b. 0-20 Hz Bandwidth

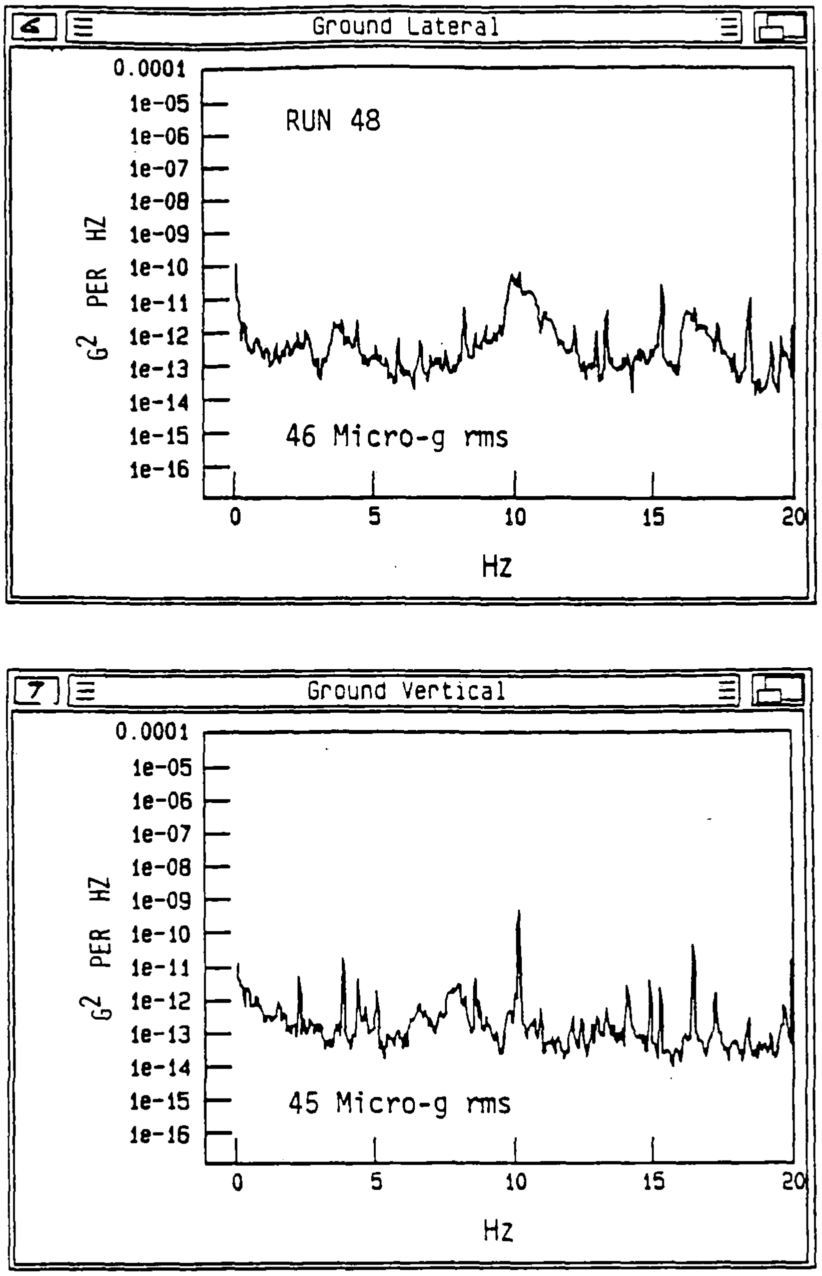
FIGURE 3.15 (CONTINUED)



a. 0-100 Micro-g rms

FIGURE 3.16 BALLAST ACCELERATION PSDs UNDER LEADING CAR AXLE, U30C LOCOMOTIVE IN NOTCH 4, COUPLERS BUNCHED

DRAFT



b. 0-20 Hz Bandwidth

FIGURE 3.16 (CONTINUED)

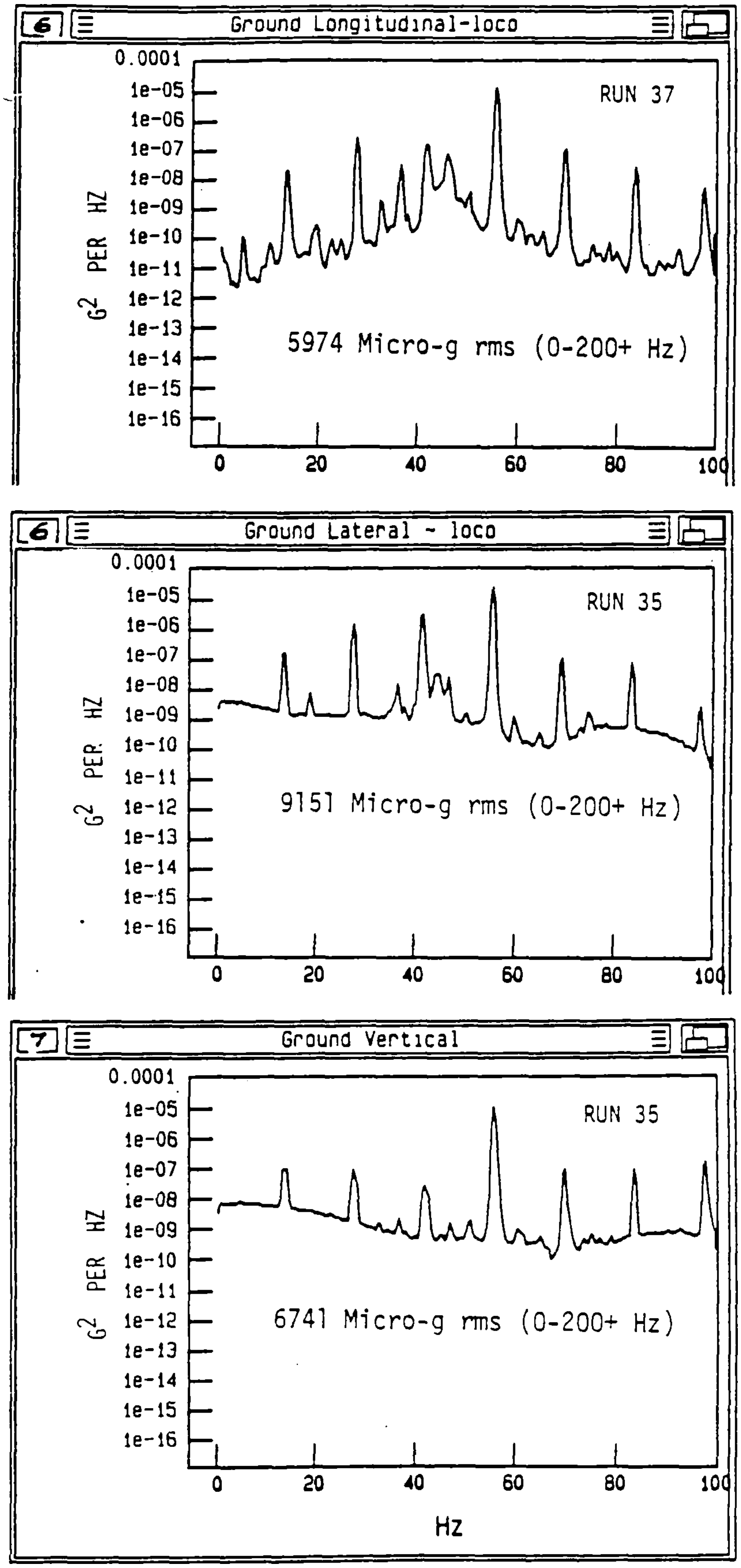


FIGURE 3.17 BALLAST ACCELERATION PSDs UNDER GP9 TRAILING LOCOMOTIVE AXLE, NOTCH 8, BUNCHED COUPLERS

DRAFT

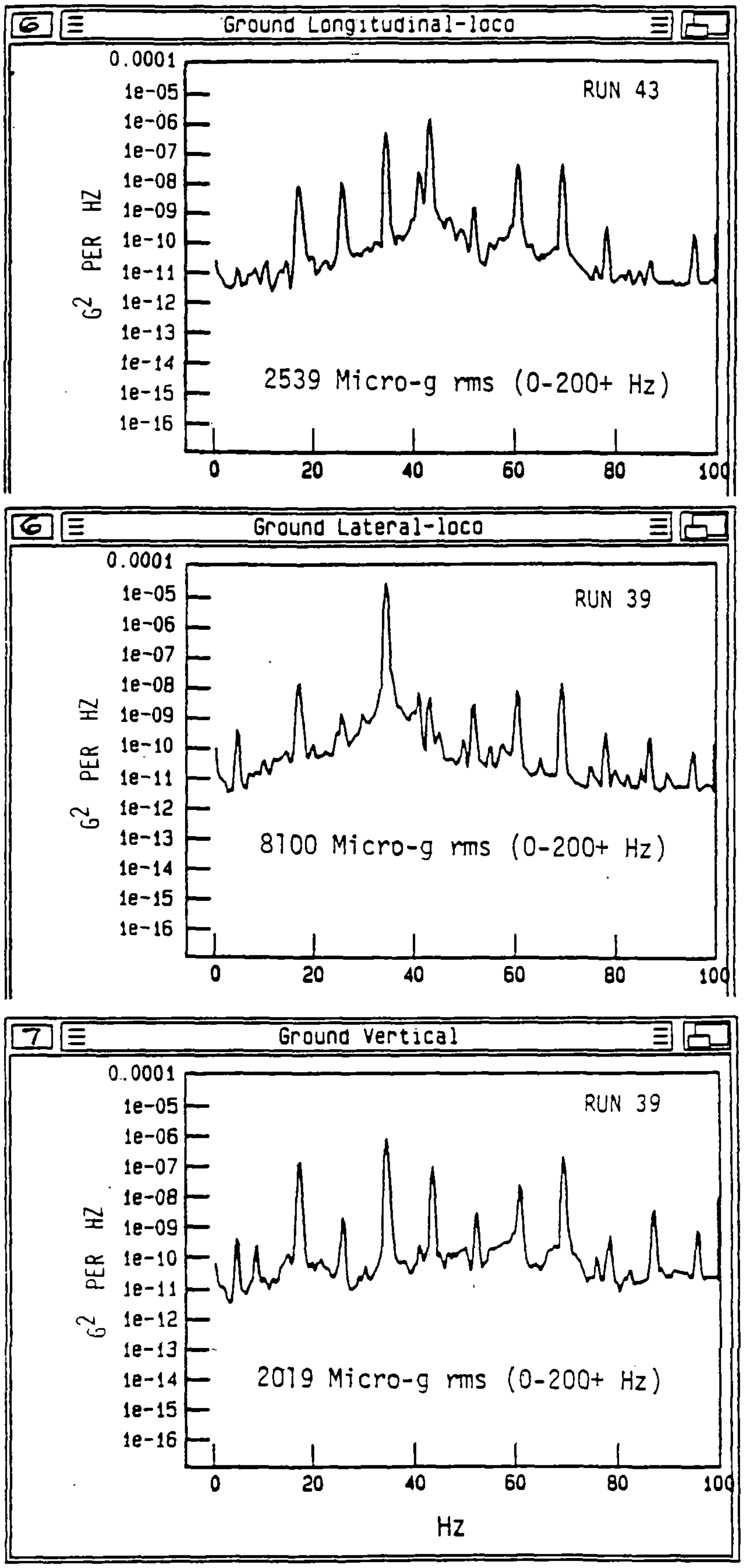
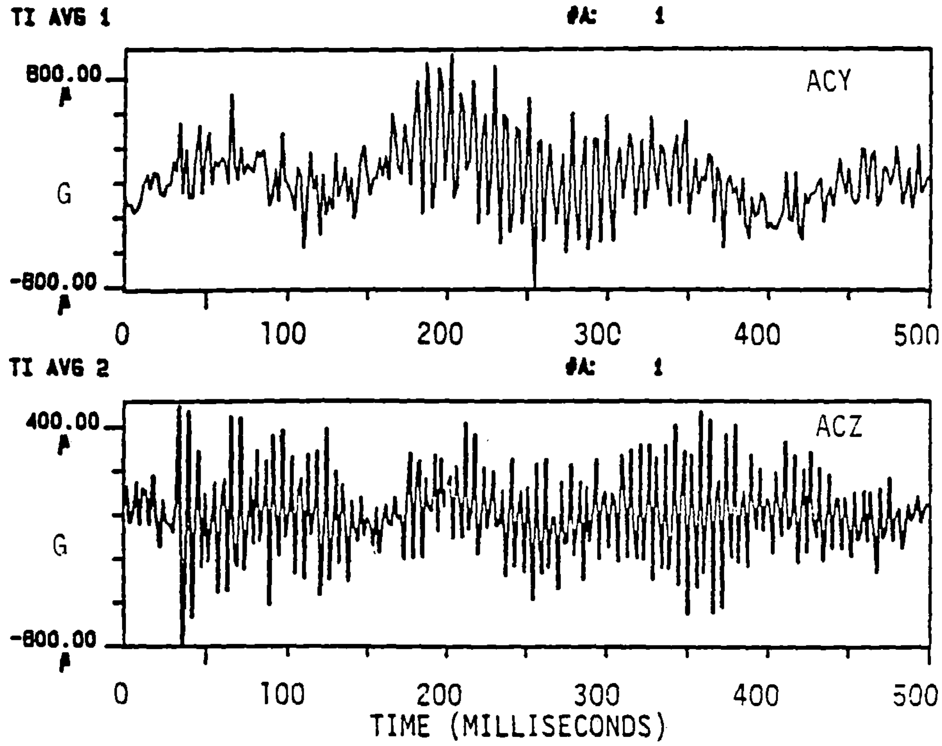
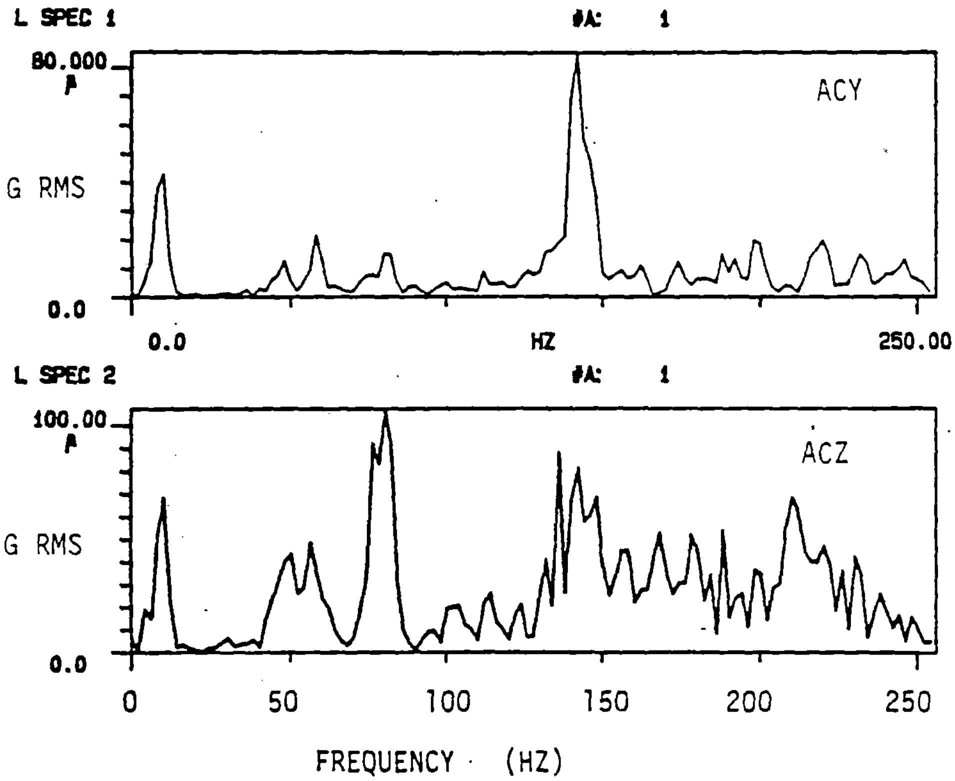


FIGURE 3.18 BALLAST ACCELERATION PSDs UNDER U30C TRAILING LOCOMOTIVE AXLE, NOTCH 8, BUNCHED COUPLERS



a. Event Time History



b. Event Frequency Spectrum

FIGURE 3.19 TIME HISTORIES AND FREQUENCY SPECTRA OF TYPICAL RANDOM TRANSIENT EVENTS response exhibits a strong 80-Hz peak. The maximum acceleration levels exceeded 1000 micro-g peak-to-peak during this event.

3.3.2 Train Pass-By Events

The vibration levels due to a train passing on an adjacent track were produced by Consist #3, a GP40-2 locomotive and 10 loaded freight cars, at speeds from 5 to 45 mph. Since track separations at TTC were greater than the desired 14 ft, the trailing end of the Test Car was moved as close a possible to the clearance limit at a turnout from the Railroad Test Track (RTT) to the Train Dynamics Track.

Time histories of the seven data channels for Run 51, the 45-mph pass-by, are shown in Figures 3.20 through 3.22, filtered at 200 Hz. The most severe response (ground and car body vertical accelerations) occurred from rough wheel profiles (wheel flats) on the ninth car of the train, a hopper car (UP 41374). Frequency response analyses of response under the last two cars, Figures 3.23 through 3.25, show a high, broadband spectrum due to these impulsive wheel loads.

Expanded time histories of the three highest acceleration channels, Channels 5 through 7, are shown in Figure 3.26. These time histories are reproduced from the light-beam oscillograph at the maximum recording bandwidth. A strong 51-Hz oscillation is seen in the ground lateral acceleration. We believe that in this location the rod was not supported properly in the lateral direction by the frozen ballast, and that the 51-Hz component is simply the rod itself responding to ground accelerations. We have therefore ignored Channel 6 (AGX) data from Site #2.

Maximum vertical accelerations during the pass-by runs are listed in Table 3.4 from the oscillograph traces of Channels 5 and 7, the car body and ground vertical accelerations. (Note that the ground acceleration was located under the opposite end of the car, near Channel 3.) Maximum peak-to-peak excursions were noted under the passing flat wheel and under the "good wheels" on the rest of the train (these latter peaks are probably related to switch frog or point impacts within the turnout).

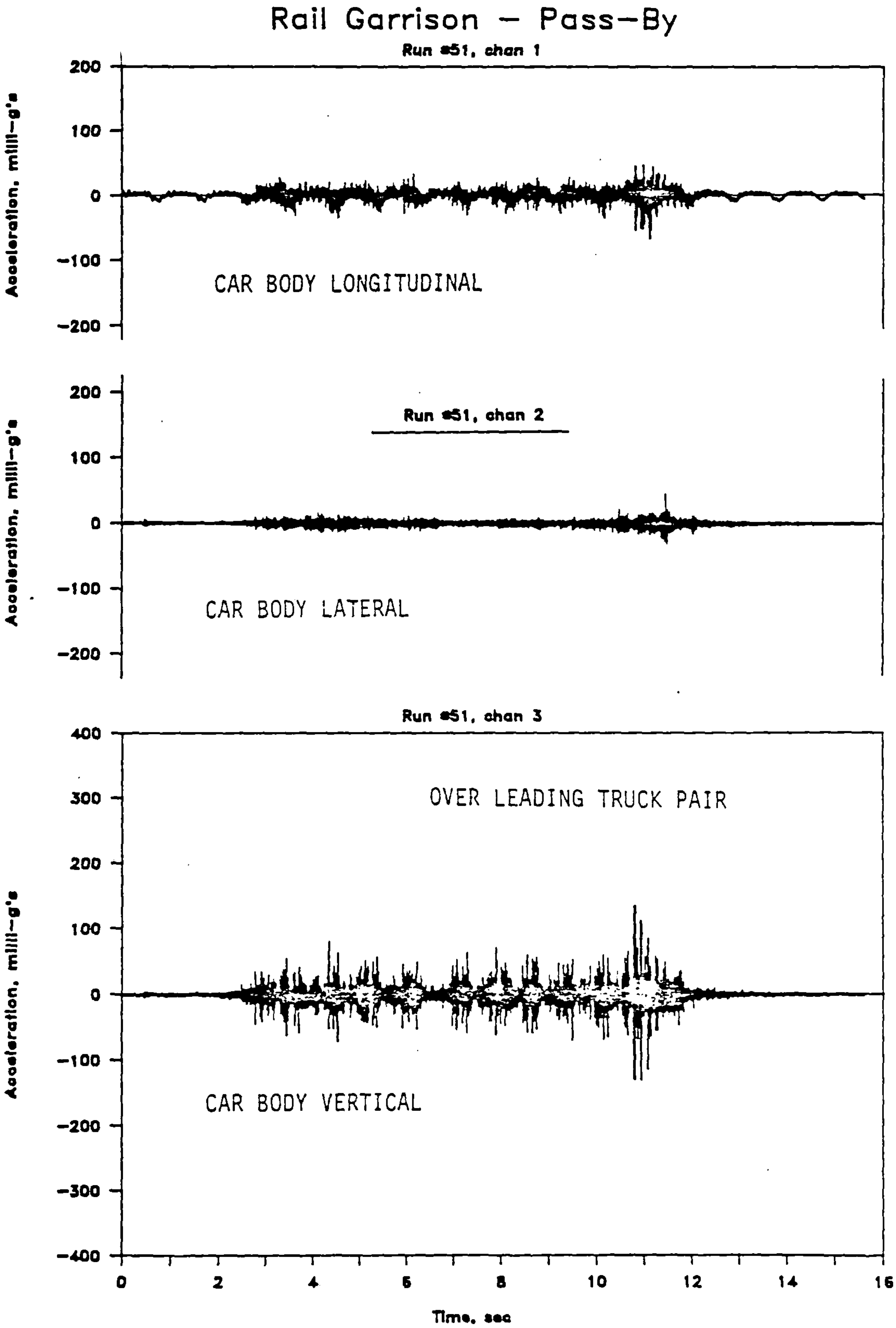


FIGURE 3.20 TIME HISTORIES OF CAR BODY ACCELERATION RESPONSE OVER LEADING TRUCK DURING CONSIST #3 45-MPH PASS-BY

DRAFT

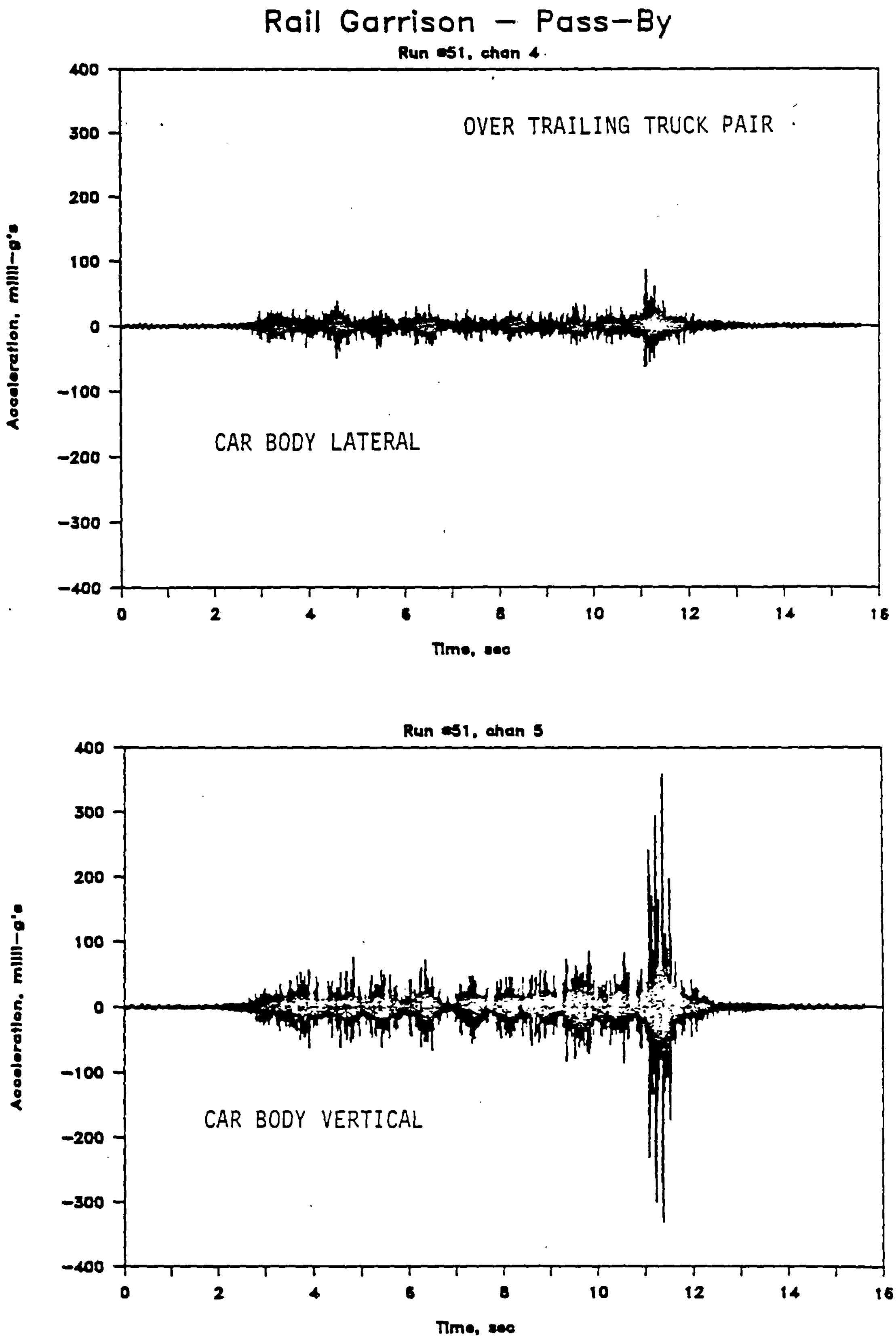


FIGURE 3.21 TIME HISTORIES OF CAR BODY ACCELERATION RESPONSE OVER TRAILING TRUCK DURING CONSIST #3 45-MPH PASS-BY

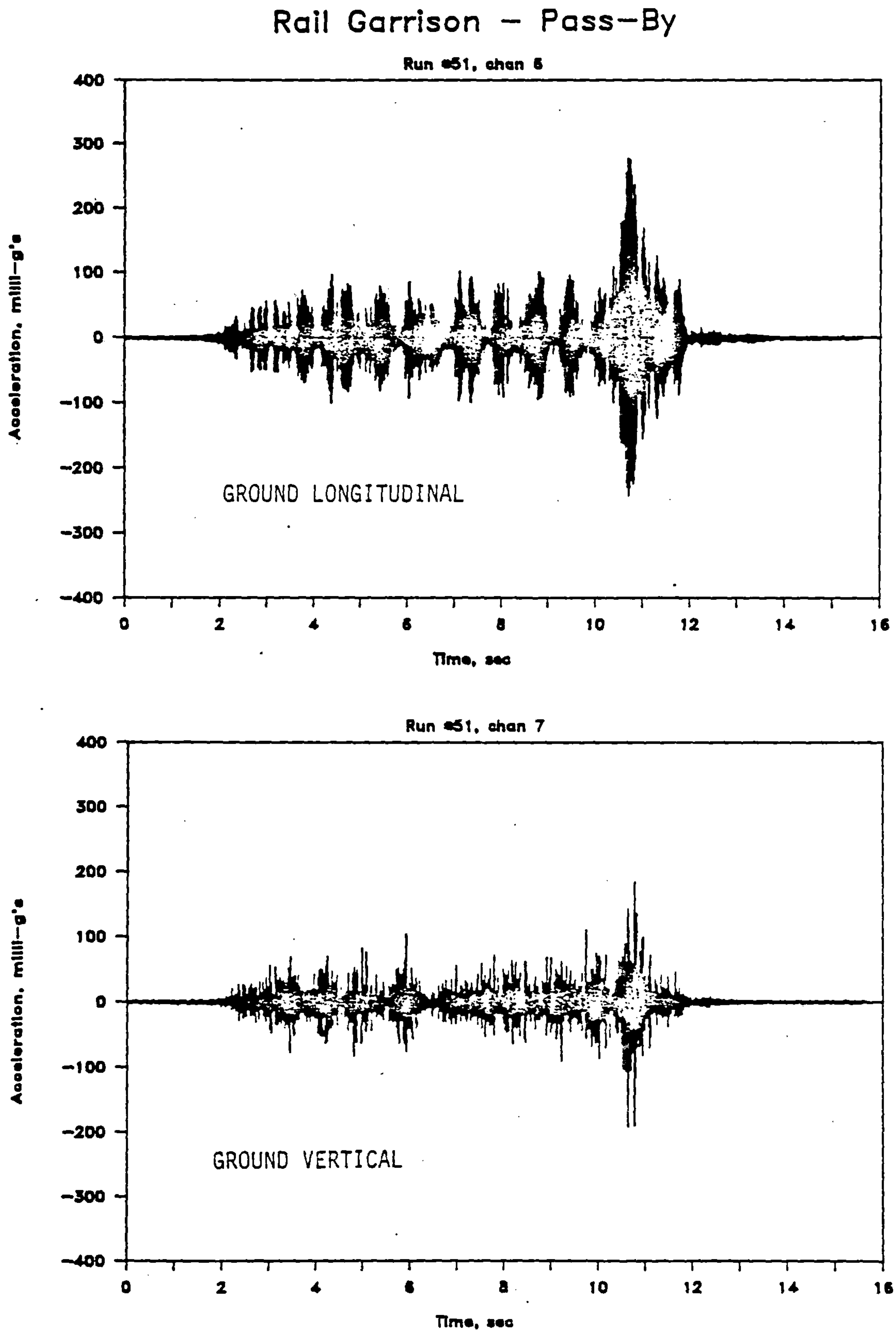


FIGURE 3.22 TIME HISTORIES OF BALLAST ACCELERATION RESPONSE UNDER LEADING TRUCK DURING CONSIST #3 45-MPH PASS-BY

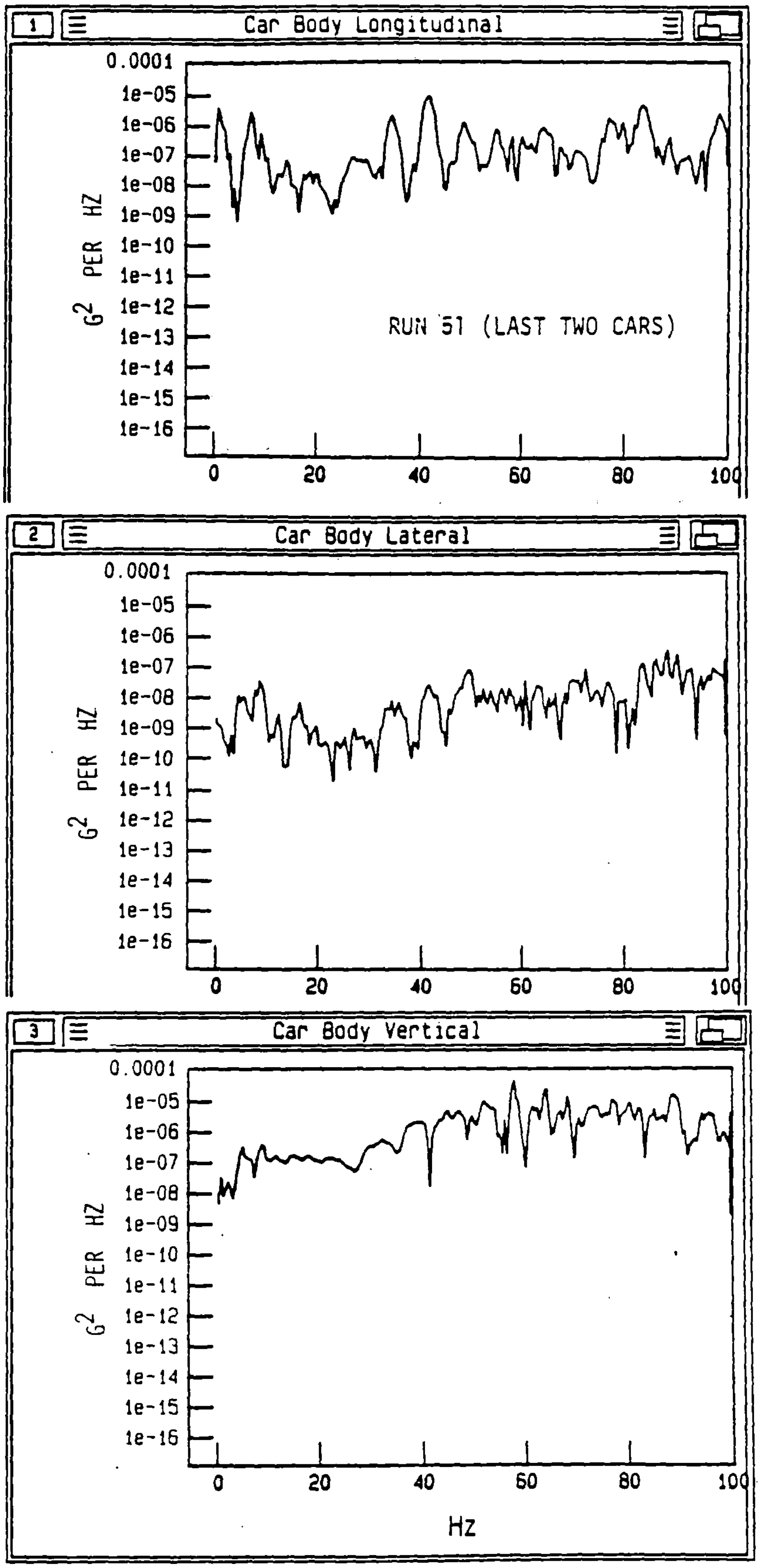
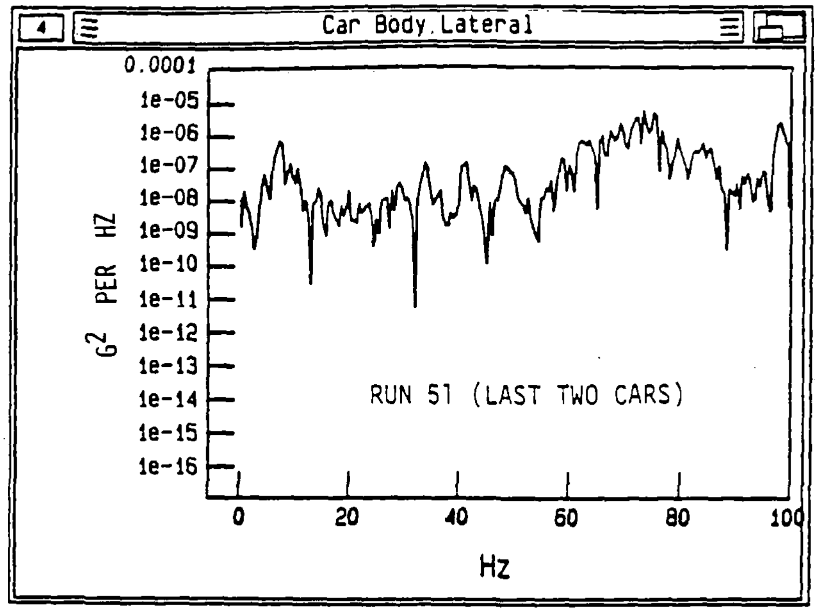


FIGURE 3.23 CAR BODY ACCELERATION PSDs OVER LEADING TRUCK DURING CONSIST #3 45-MPH PASS-BY



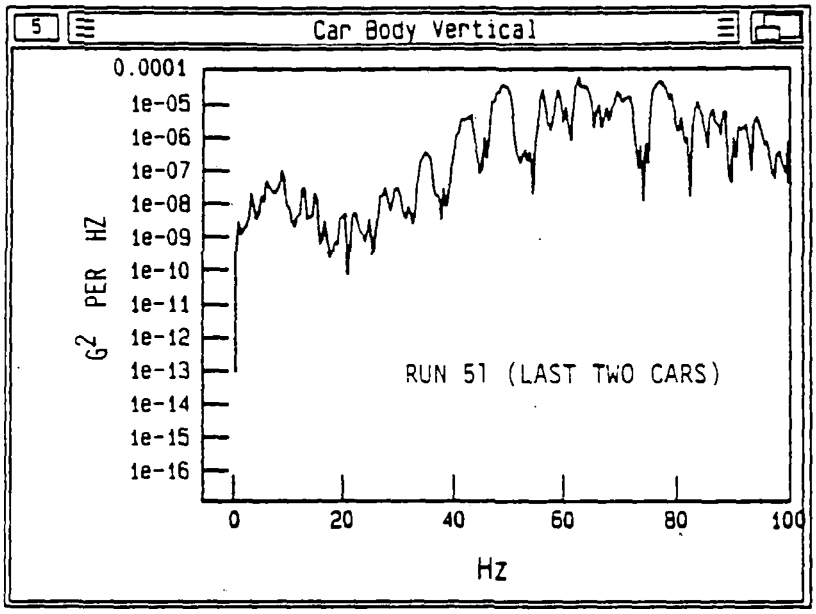
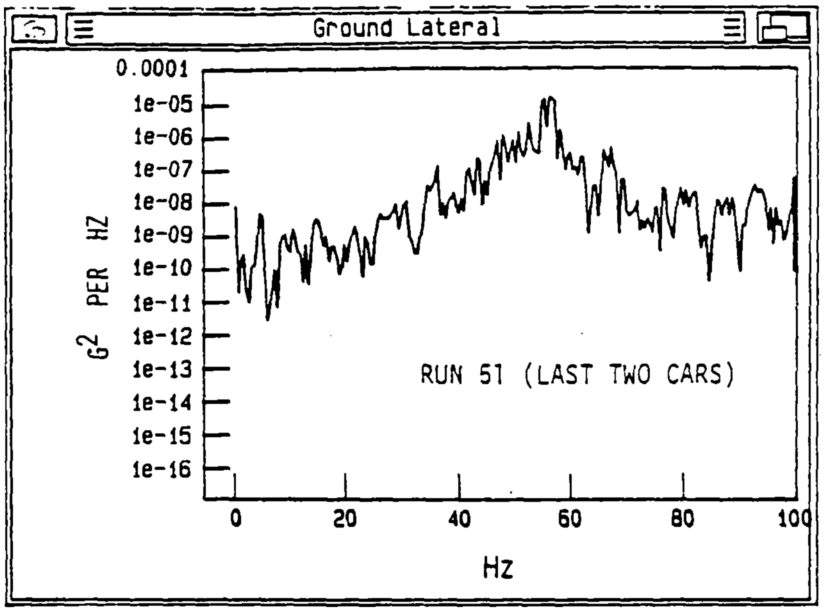


FIGURE 3.24 CAR BODY ACCELERATION PSDs OVER TRAILING TRUCK DURING CONSIST #3 45-MPH PASS-BY

DRAFT



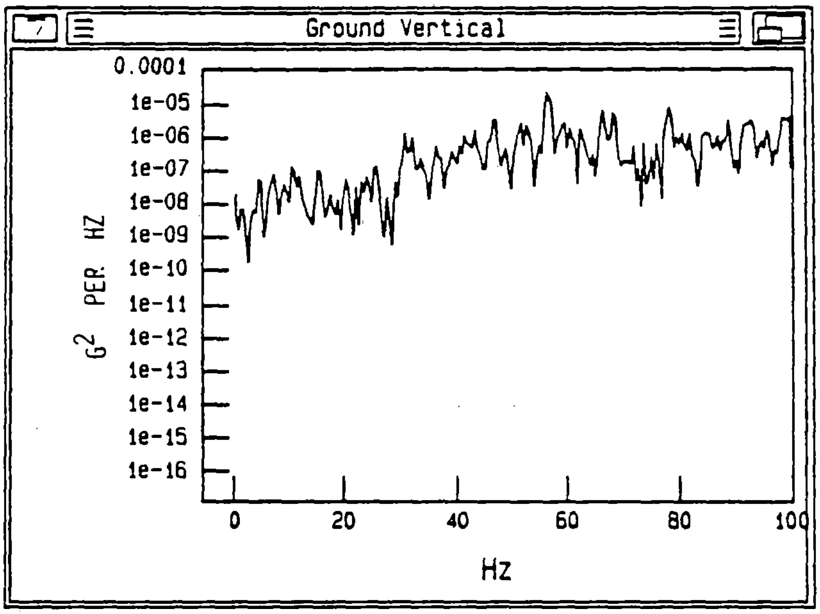


FIGURE 3.25 BALLAST ACCELERATION PSDs UNDER LEADING TRUCK DURING CONSIST #3 45-MPH PASS-BY

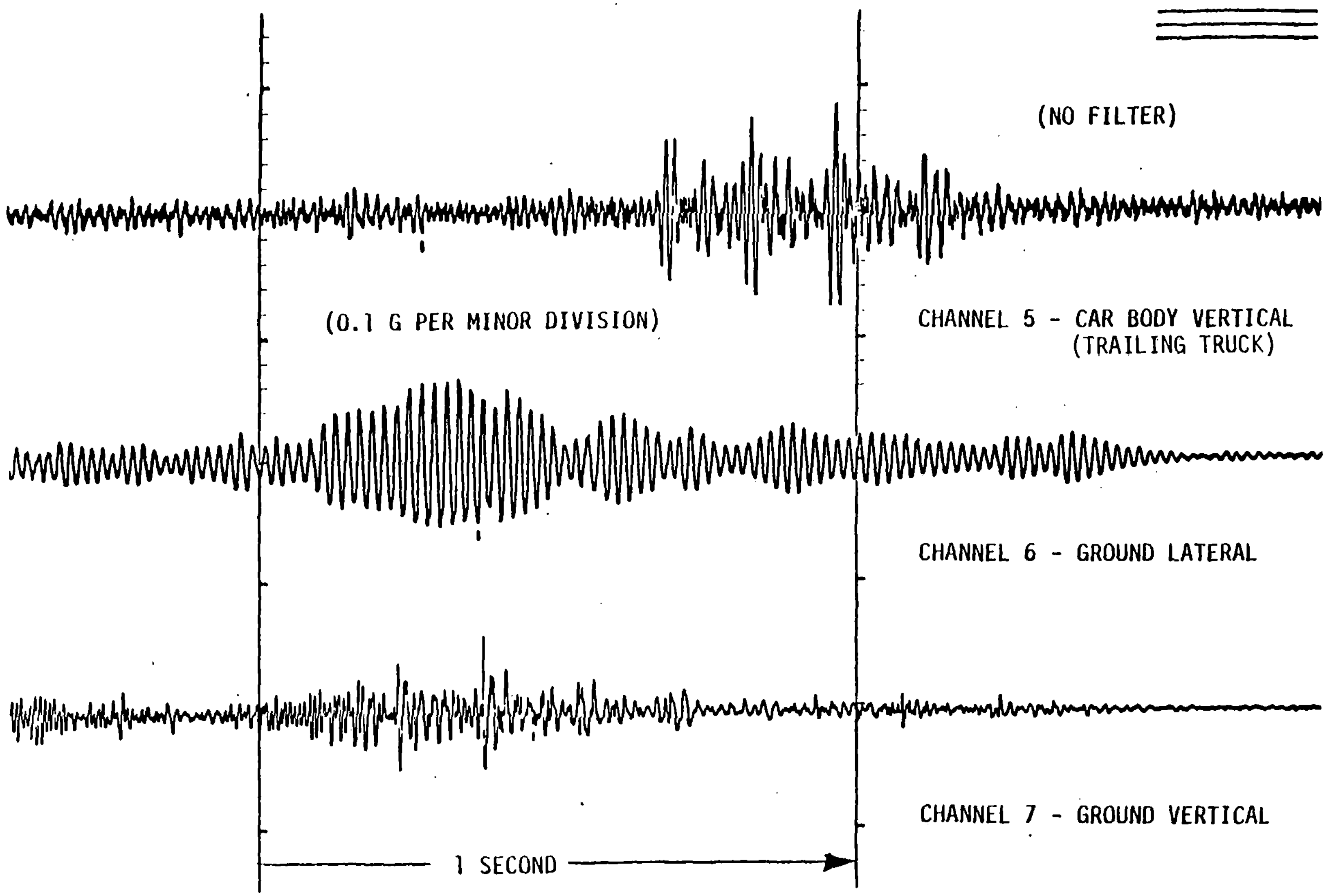


FIGURE 3.26 ACCELERATION TIME HISTORIES FROM
RUN #51, CONSIST #3 45-MPH PASS-BY

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TABLE 3.4 MAXIMUM VERTICAL ACCELERATIONS DURING TRAIN CONSIST #3 PASS-BY AT SITE #2

		Milli-g's Peak-to-Peak				
		Channel 5 (ATZ)		Channel 7 (AGZ)		
Run No.	Speed (mph)	Flat Wheels	Good Wheels	Flat Wheels	Good Wheels	Filter
51	45	816	195	531	231	None
52	35	732	312	429	187	
53	25	465	346	399	183	
54	15	317	177	190	136	
55	6	73	78	68	83	
51	45	745	190	414	195	200 Hz
51	45	665	166	292	175	100
51	45	49		39		20

The flat wheel shows a monotonic increase in response acceleration with speed; while the car body response to "good wheels" shows a resonance near 25 mph related to the roll response of the passing hopper cars.

Wheels were examined on the pass-by train consist, and all were found to be in good condition except one wheel on the ninth car. This wheel had shelly spots, but was not condemnable by current AAR standards (Rule 41, AAR Interchange Rules). Recent studies by Battelle and Salient Systems, Inc. (of Worthington, Ohio) have found that these "thumper" wheel profiles typically have tread radial runout errors 10 to 16 inches in length (which makes them difficult to detect visually), and 0.030 to 0.200 inch in depth. Statistically, about 1 wheel in 1000 in revenue freight service will produce wheel/rail impact loads greater than 70,000 lb peak. Battelle's simulation of track structure response to these types of wheel profiles has predicted crosstie and ballast accelerations typically 30 to 50 g peak-to-peak directly under the wheel. From the measurements, there is considerable attenuation of these flat wheel impacts with distance. The response, for example, at the near end of the car (Channel 5, ATZ) was 816 milli-g, peak-to-peak, while the more distant end of the car (Channel 3, ACZ), was 313 milli-g,p-p.

3.4 Transfer Function and Cross-Correlation

Run 46, the U30C locomotive in Notch 8 with bunched couplers, was chosen for transfer function and cross-correlation analysis since this run presents rather high rms acceleration values. For these analyses, the HP 5420A spectrum analyzer was utilized.

Vertical acceleration spectra at the ballast and at the car body nearby are shown in Figure 3.27. The strong 8-Hz spectral peak in car body vertical response has been discussed in Section 3.2.2, and may be a car rigid-body or body-bending mode. This peak is missing in the track ballast vertical acceleration PSD, indicating that the primary source of excitation is through the bunched couplers or acoustically through the air. The spectral peak slightly below the 8-Hz car-body resonance is probably associated with the 4-stroke-cycle engine firing frequency, half

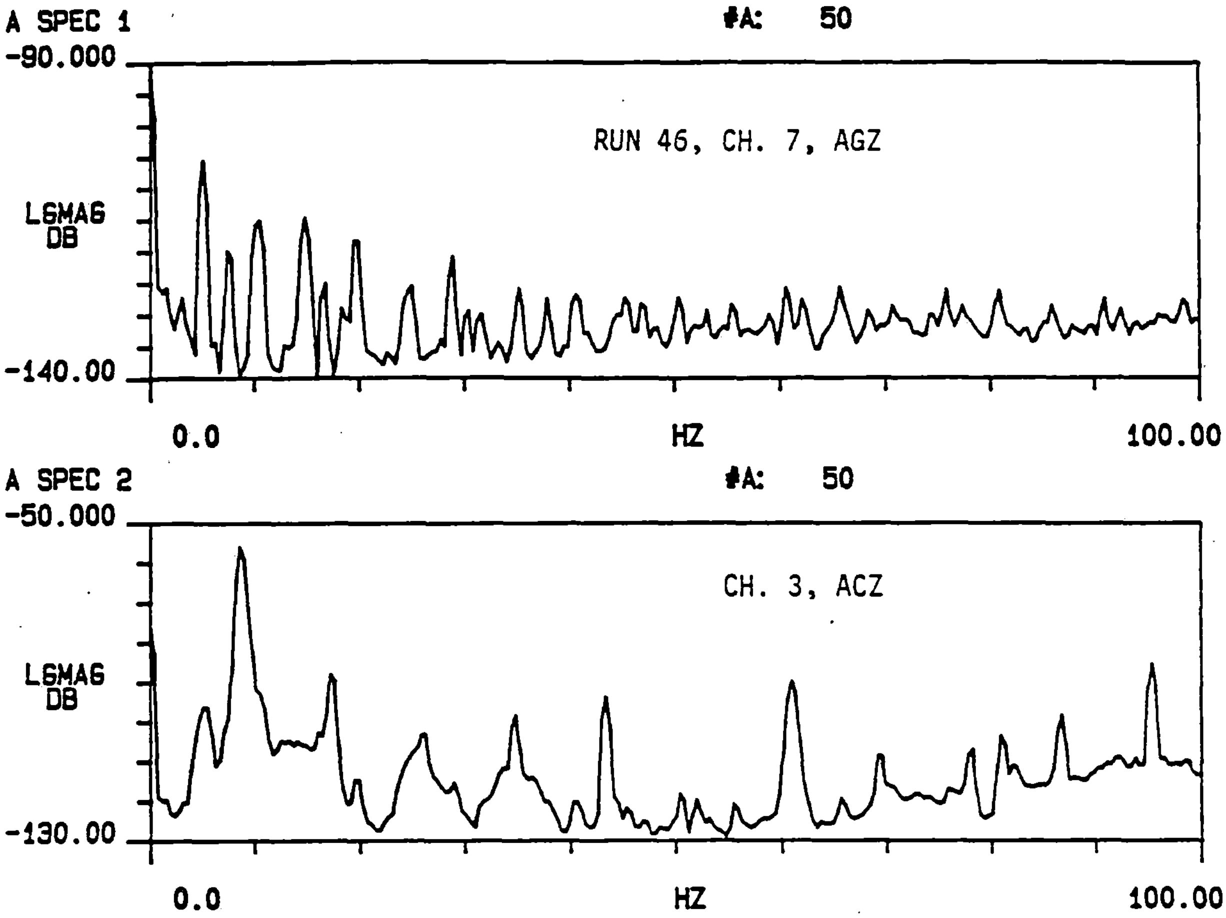

FIGURE 3.27 BALLAST AND CAR BODY VERTICAL ACCELERATION SPECTRA OVER 0-100 HZ BANDWIDTH (HP 5420A)

the design 1025 rpm maximum rotation speed. The transfer function analysis in Figure 3.28 shows little coherence between ballast and car body accelerations, again indicating that the excitation is through the bunched couplers or acoustically through the air.

Lateral acceleration spectra are similarly shown in Figure 3.29 for ballast and nearby car body. Again, the strong 8.5 Hz spectral peak is seen in the car body response. Transfer function analysis shown in Figure 3.30 again shows little coherence between ballast and car body at this peak.

Cross-correlations between the orthogonal axes of car body acceleration reponse are shown in Figure 3.31. This figure shows the strong response to a single frequency, 8.64 Hz, with no evidence of significant random vibration components during this run segment. From the relationship:

$$R_{xy}(\ ) = (1/2)\ x_o\ y_o \cos(\quad + \ )$$

The values of R_{xy} from Figure 3.31 can be used to derive the orthogonal acceleration values:

a_x = 1188 micro-g's peak

a_y = 3671 micro-g's peak

a_z = 1226 micro-g's peak

These three values then give a vector acceleration value of 4049 micro-g's peak acting at this location. Note that the results from the cross-correlation analysis show the y (lateral) axis to dominate, while the x and z axes are roughly equal in magnitude. Results from the MASSCOMP analysis (Table 3.3 and Figure 3.14) show the y and z axes roughly equal, with the x axis lower. The HP 5420A analyzer uses a 256-line analysis, versus the MASSCOMP 1024-line analysis; and therefore the cross-

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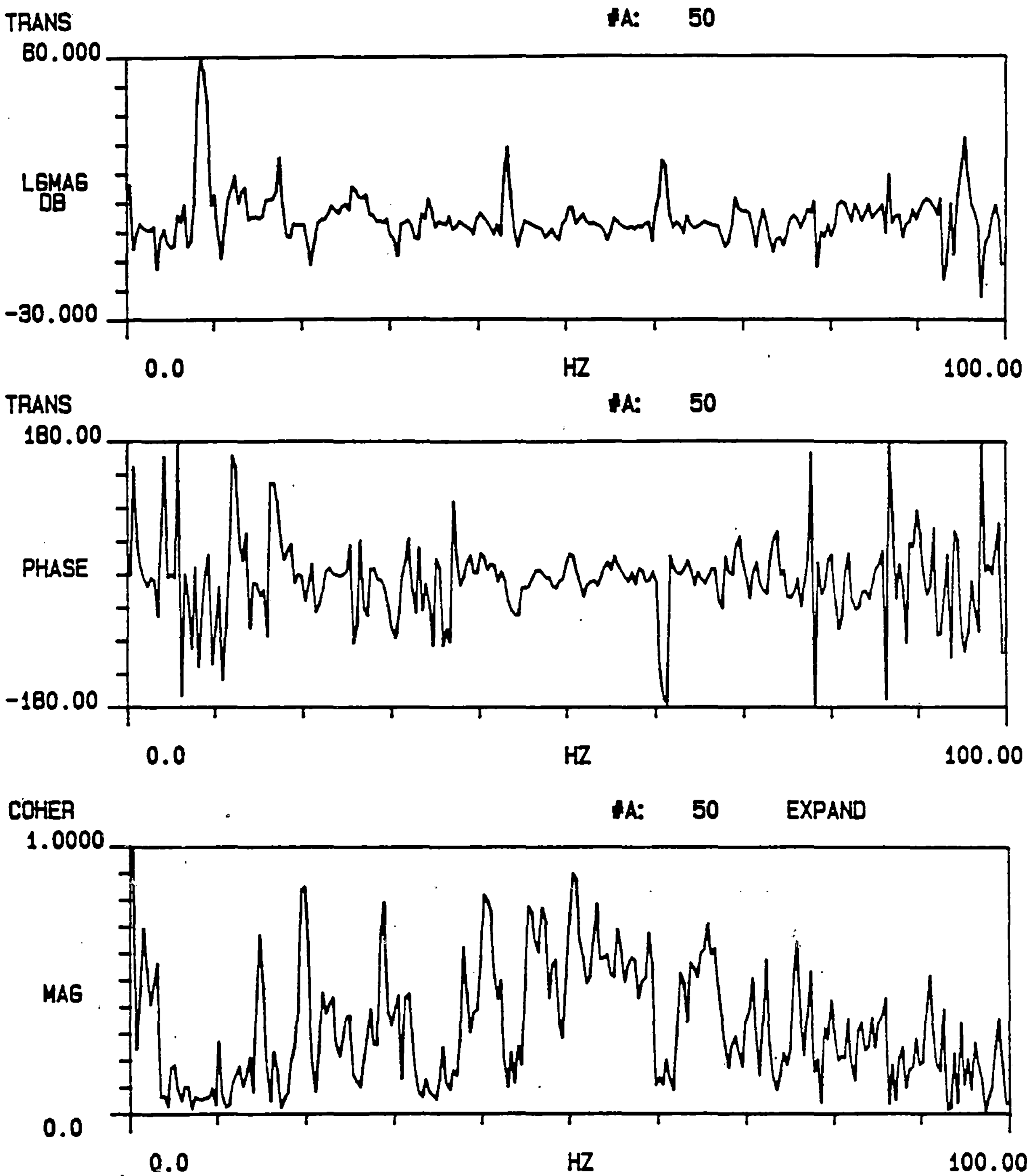

FIGURE 3.28 CAR BODY/BALLAST VERTICAL ACCELERATION TRANSFER FUNCTION AND COHERENCE

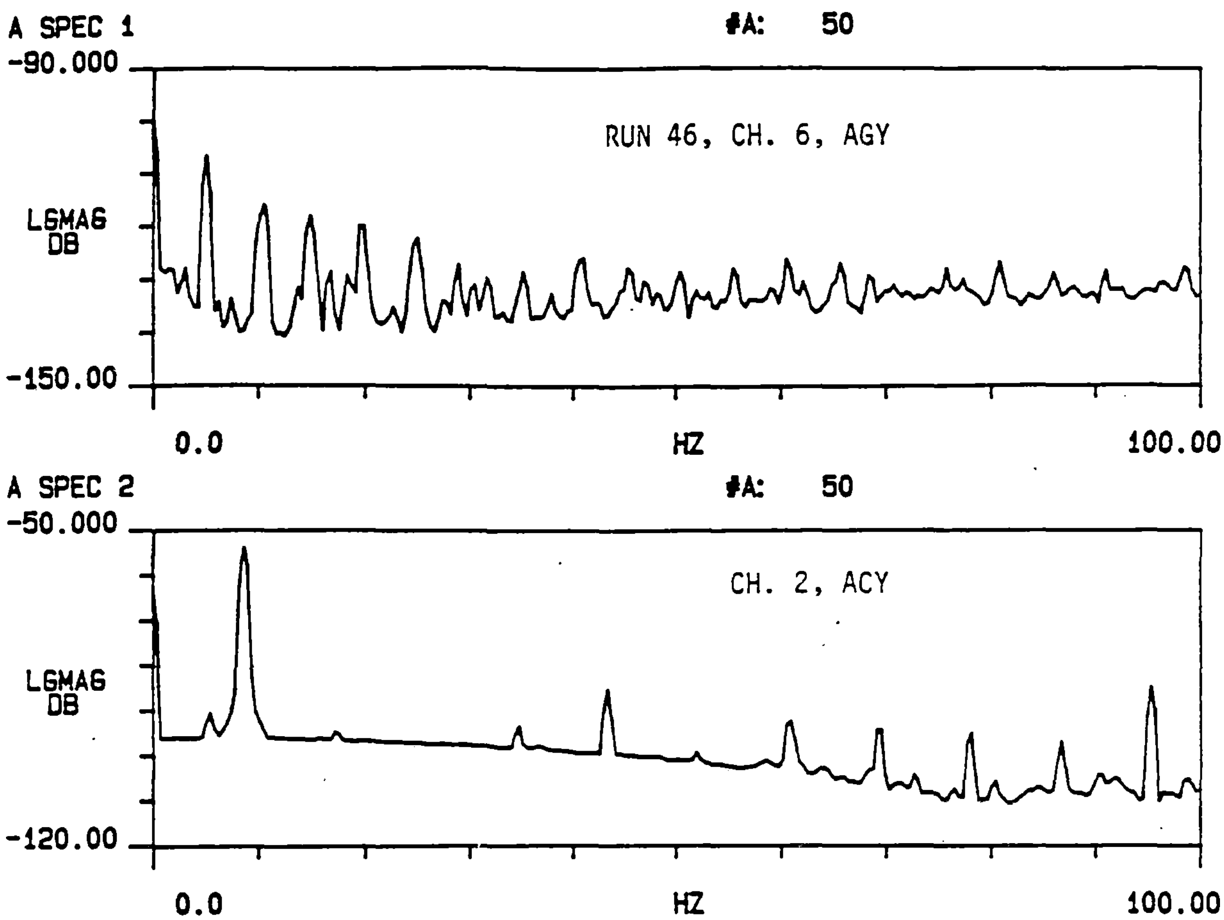

FIGURE 3.29 BALLAST AND CAR BODY LATERAL ACCELERATION AUTO SPECTRA OVER 0-100 HZ BANDWIDTH (HP 5420A)

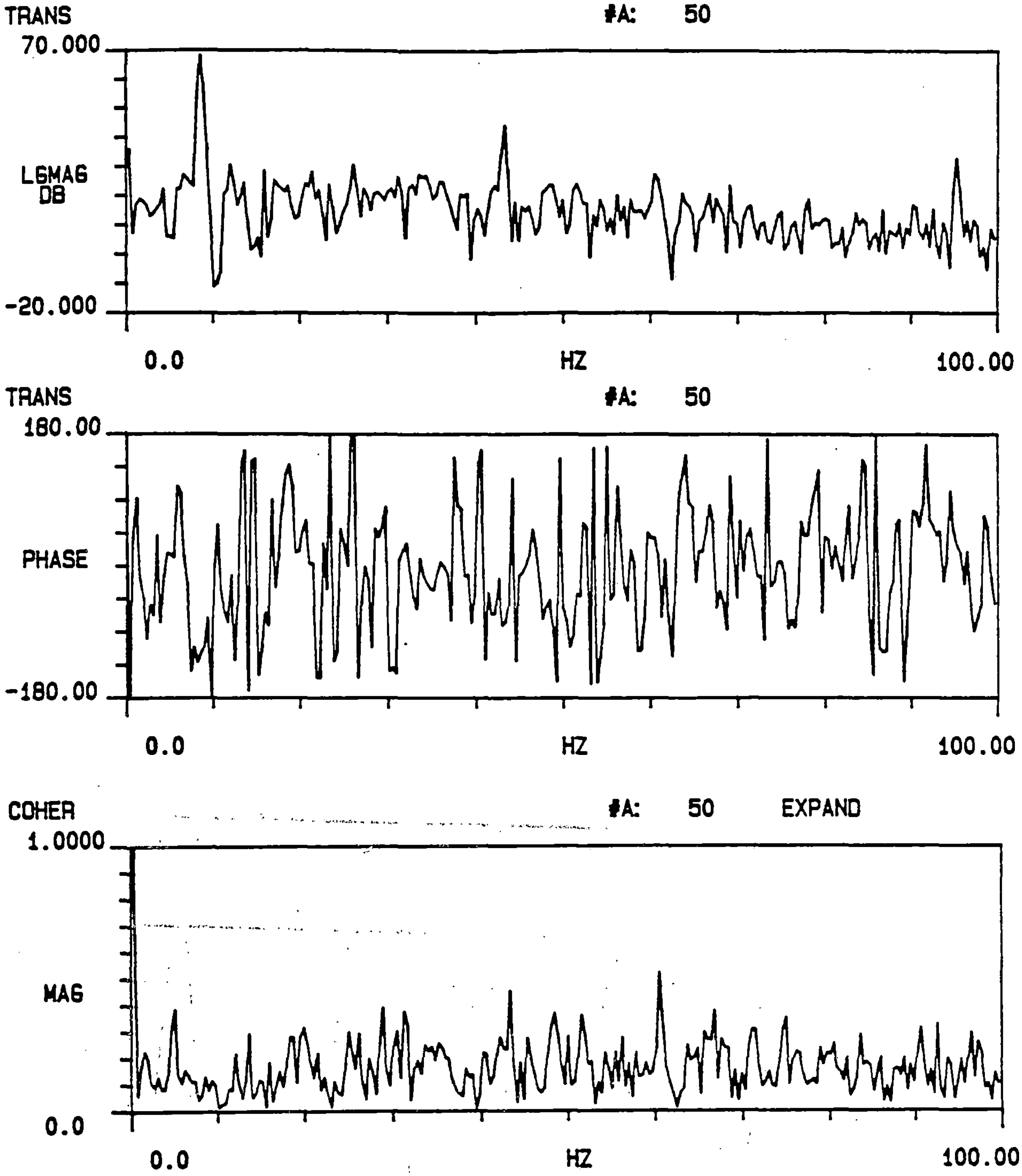

FIGURE 3.30 CAR BODY/BALLAST LATERAL ACCELERATION TRANSFER FUNCTION AND COHERENCE

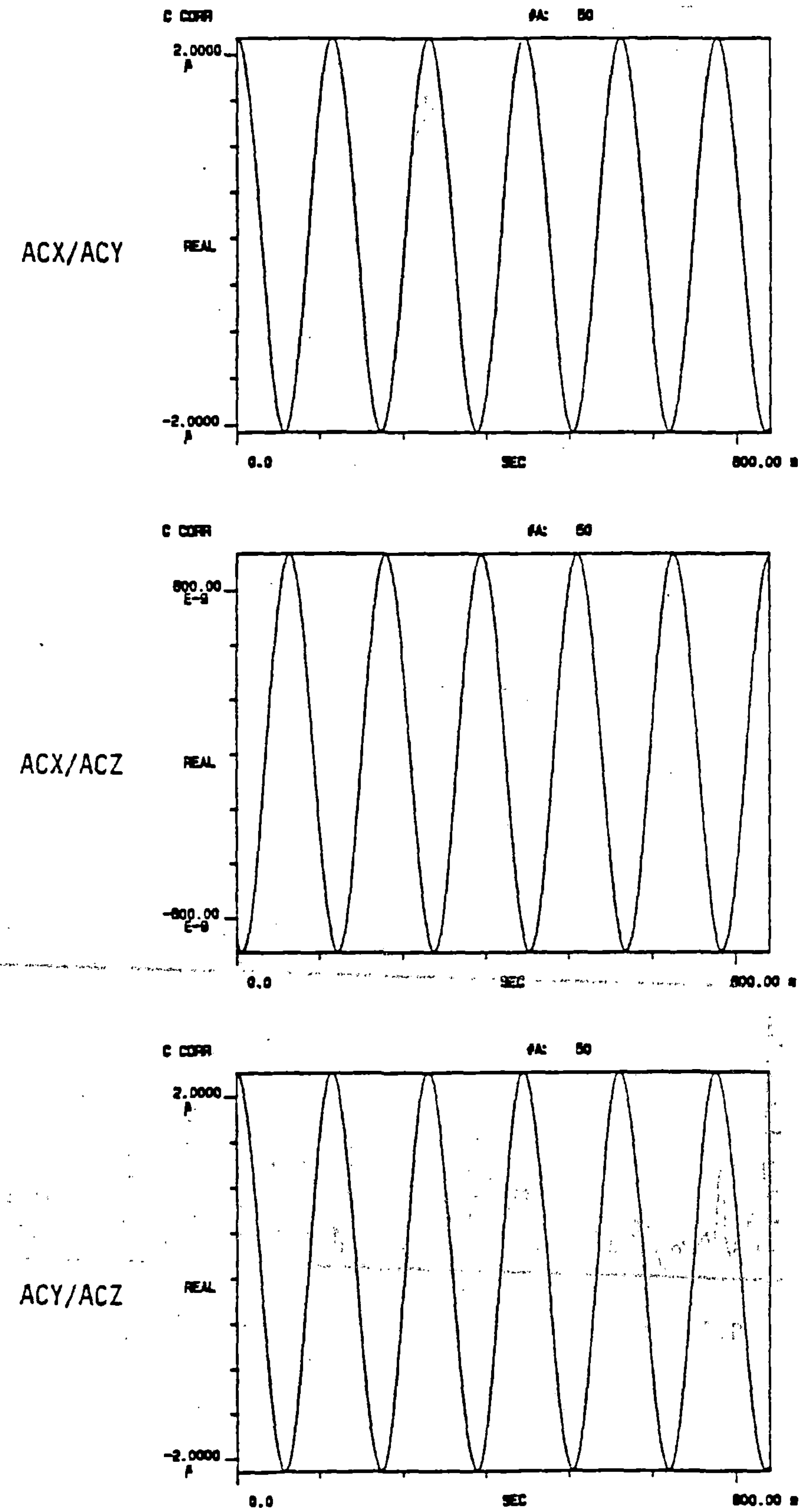

FIGURE 3.31 CROSS-CORRELATION FUNCTION FOR CAR BODY ACCELERATIONS, RUN 46, U30C LOCOMOTIVE

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- Wind-induced vibration levels were not as significant as expected, in spite of wind gusts during the first run segment that exceeded 50 mph (at least one gust of 73 mph was recorded). Transient acceleration events in the oscillograph time histories do not seem to be directly associated with the recorded wind speed. However, test personnel "felt" the wind-induced vibrations while sitting on the edge of the car.

- Locomotive engine type and running speed have a significant influence on the acceleration levels as various structural and rigid-body resonances are excited by engine-induced vibrations. In Notch 8, the higher-speed 4-cycle engine of the GE U30C locomotive has a firing frequency near 8.5 Hz and a running frequency near 17 Hz, with strong harmonic content. This excites a car body spectral peak at 8.6 Hz with a vector peak amplitude of about 0.004 g. The 2-cycle EMD GP9 locomotive tends to excite this peak in Notch 4, around 500 rpm, since the fundamental firing and running frequencies are the same.

- Low coherence between ground (track ballast) and car body accelerations indicates that vibration transmission occurs primarily through the bunched couplers and draft gear or (possibly) acoustically, rather than through the wheels from the track. Separation of the locomotive from the car reduces the ground vibration levels.

- Train pass-by on an adjacent track resulted in acceleration levels up to 0.021 g rms measured on the car. One car in the passing consist had a severe wheel flat which generated vertical car body accelerations up to 0.43 g peak at 57 Hz, for a 45 mph pass-by train speed. This type of event is not that rare: about 1 out of every 1000 passing wheelsets will produce this level of response.

correlation analysis is based on about one-fourth of the run segment that the MASSCOMP analysis used. These analysis results indicate that the data for this run does not represent a stationary random process.

4.0 SUMMARY AND CONCLUSIONS

A series of tests were conducted at the Transportation Test Center near Pueblo, Colorado to establish environmental vibration levels to assist in the Rail Garrison missile guidance system design. These tests utilized a heavily-loaded 8-axle flat car to simulate the missile launch car, plus combinations of other loaded cars to approximate the weight and geometry of other Rail Garrison train cars. Although a modern 3800-hp locomotive was desired for the tests, none was available at the Test Center at the time. Therefore tests were conducted with both the available 2-cycle EMD GP9 and 4-cycle GE U30C locomotives.

Background vibration levels were established at the test site both with and without the a.c. power generator in operation. With the generator off, vibration levels on the car fell below 70 micro-g's rms (all but one channel value below 30 micro-g's). With the generator on, all values were still below 200 micro-g's rms, although spectral peaks at 30 Hz (the generator firing frequency) and 60 Hz (the generator running speed) were observed in some channels. PSDs of these background vibrations showed a "floor" of about 1E-13 g^2/Hz with spectral peaks of 5E-11 g^2/Hz or less.

A variety of test conditions was run, and rms acceleration levels in the 0 to 200+ frequency bandwidth were determined. Specific runs where higher rms values were noted were then examined further by power spectral density (PSD) analysis. A "worst-case" run was chosen to generate examples of transfer function and cross-correlation analysis.

From the test results, the following specific conclusions can be made: