UMTA-MA-06-0099-82-4
DOT-TSC-UMTA-82-16

Noise Test-Resilient Wheels Massachusetts Bay Transportation Authority Green Line

E.J. Rickley
M.J. Brien

Transportation Systems Center
Cambridge MA 02142

November 1982
Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation
Urban Mass Transportation Administration

Office of Technical Assistance
Office of Systems Engineering
Washington DC 20590

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTA-MA-06-0099-82-4		
4. Title and Subtitle NOISE TEST - RESILIENT WHEELS MASSACHUSETTS BAY TRANSPORTATION AUTHORITY GREEN LINE		5. Report Date November 1982 6. Performing Organization Code DTS-77
7. Author(s) E.J. Rickley, M.J. Brien		8. Performing Organization Report No. DOT-TSC-UMTA-82-16
9. Performing Organization Name and Address U.S. Department of Transportation Research and Special Programs Administration Transportation Systems Center Kendall Square Cambridge MA 02142		10. Work Unit No. (TRAIS) UM249/R2641 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Urban Mass Transportation Administration Office of Technical Assistance Office of Systems Engineering Washington DC 20590		13. Type of Report and Period Covered Final Report February-April 1982 14. Sponsoring Agency Code URT-10
15. Supplementary Notes		

16. Abstract

The purpose of this effort was to compare the noise and vibration characteristics of Sab-V resilient wheels with those of Acoustaflex (resilient) and solid-steel wheels, which are both in current use on the Green Line of the Massachusetts Bay Transportation Authority (MBTA). Noise and ground-borne vibration level measurements were made on February 9, 1982, on three rail transit vehicles operating on the Green Line. Two Boeing Light Rail Vehicles (LRV's) and one Presidential Conference Committee (PCC) car were each equipped with a different wheel set: Sab V, Acoustaflex (both resilient), and solid steel, respectively. Noise was measured inside the vehicles in the passenger seating areas and at wayside locations where ground-borne vibration was also measured. The data presented include comparative noise and vibration time histories, one-third octave and narrow band spectral analysis, and in-car statistical noise data.

17. Key Words		18. Distribution Statement	
Resilient Wheels (Acoustaflex, Sab-V) Solid-Steel Wheels Wheel Squeal Ground-borne Vibration Rapid Transit Noise		DOCUMENT IS AVAILABLE TO THE U.S. PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	80	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This document presents the results of noise and ground-borne vibration measurements made for three rail transit vehicles operating on the Green Line of the Massachusetts Bay Transportation Authority (MBTA). The purpose of the test was to assess the performance of the Sab-V resilient, the Acoustaflex resilient, and the solid-steel wheels.

The work was sponsored by the U.S. Department of Transportation, Office of Technical Assistance, Office of Systems Engineering, and performed by the Research and Special Programs Administration's Transportation Systems Center in Cambridge, Massachusetts.

Appreciation is expressed to Frank Vallely, Jeffrey Sisson, Mike Dunderdale and other MBTA personnel for support of this study. A. Richardson Goodlatte, of Energy and Environmental Engineering, Inc., provided essential liaison services.

The following members of TSC's technical staff assisted in data collection and preparation of this report: Michael Dinning, Robert Mason, Paul McGrath, Norman Rice and Arthur Ditomaso.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

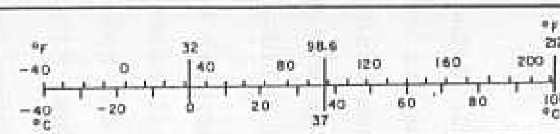


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont.)

LIST OF ILLUSTRATIONS (Cont.)

LIST OF TABLES

EXECUTIVE SUMMARY

Noise and ground-borne vibration measurements were made for three rail transit vehicles operating on the Green Line of the Massachusetts Bay Transportation Authority (MBTA) on February 9, 1982 during non-revenue service hours (1 to 5 am). The purpose of these measurements was to assess the noise and vibration performance of Sab-V resilient wheels compared with Acoustaflex (resilient) and solid-steel wheels, both in current use on the Green Line of the MBTA.

Two Boeing Light Rail Vehicles (LRV) and one Presidential Conference Committee (PCC) car were each equipped with a different wheel set: Sab-V, Acoustaflex, and solid steel, respectively. Each car was instrumented with noise measuring and recording systems. Microphones were placed inside the cars in the passenger seating areas, one over the front and one over the rear wheel trucks for each car.

Microphones were also deployed to measure wayside noise at two locations. One location was in the 72-foot radius turnaround loop at Lechmere Station, the other opposite a straight section of track midway between Northeastern University and the Museum/Ruggles stations on the Huntington Avenue branch of the Green Line. Ground-borne vibration measurements were also made at the latter site.

Statistical noise level data indicate that the high-level intrusive in-car noise (i.e., noise levels exceeded one percent of the time) was 1.5 to 3.8 dB less for the LRV equipped with Sab-V wheels than for the Acoustaflex-equipped LRV. This in-car reduction varied on the average from -2 to 10 dB when maximum levels are compared at various sections of the test track and was greatest on tightly curved portions of the test track.

Wayside noise levels for the LRV's equipped with these two types of resilient wheels showed no significant difference on straight track. On curved track, the Sab-V wheels produced levels approximately 1 dB less than the Acoustaflex wheels, when maximum passby levels were compared.

The in-car statistical data show further that the Sab-V equipped LRV was approximately 10 dB quieter than the solid-steel wheel equipped PCC car. As in the above, the reductions were greatest on tightly curved portions of the test track. Wayside passby noise levels for the Sab-V equipped LRV were as much as 14 dB quieter than for the solid-steel wheel equipped PCC car on curved track, whereas on straight track the data were similar after adjusting the levels for the slower speed of the PCC car.

One-third octave band frequency analysis of the noise data showed that each wheel set produced a somewhat different characteristic spectrum: the Sab-V wheel produced squeal noise primarily in the 630 Hz and 1600 Hz one-third octave bands; the Acoustaflex wheel generated squeal noise mostly in the 1600 Hz and 4000 Hz one-third octave bands; and the solid-steel wheel generated squeal noise chiefly in the 630 Hz and 10,000 Hz one-third octave bands.

Ground-borne vibration level measurements showed small differences in the average of the maximum acceleration levels between cars equipped with the different types of wheels tested. The Acoustaflex-equipped LRV produced acceleration levels approximately 2 dB less than the Sab-V equipped LRV in all three axes (vertical, transverse, longitudinal), whereas the solid-steel wheel equipped PCC car produced acceleration levels similar to the Acoustaflex-equipped LRV in the vertical axis, and approximately 3 dB less in the transverse and longitudinal axes. The lower values of acceleration associated with the solid-steel wheel equipped PCC car may be attributed to the slower speeds achieved during the test and to the lighter weight of the PCC car relative to the LRV's (40,000 and 67,000 pounds, respectively).

1.0 INTRODUCTION

This report presents the results of a noise and ground-borne vibration measurement program conducted on February 9, 1982, on a section of the Green Line of the Massachusetts Bay Transportation Authority (MBTA) rapid transit system. The test was conducted during non-revenue service hours (1 to 5 am) by the U.S. Department of Transportation, Transportation Systems Center (DOT/TSC) for the Urban Mass Transportation Administration (UMTA).

The objective of the test was to assess the relative effectiveness for reducing in-car and wayside noise levels and ground-borne surface vibration levels of Sab-V wheels compared with Acoustaflex and solid-steel wheels currently in use on the MBTA Green Line cars.

Three vehicles, two Boeing Light Rail Vehicles (LRV) and one Presidential Conference Committee (PCC) car, were each equipped with a different set of wheels, namely Sab-V, Acoustaflex and solid steel, respectively. The cars were instrumented with noise measuring and recording systems, with microphones placed inside the cars in the passenger seating areas, one over the front and one over the rear wheel trucks at ear level of a seated passenger.

Measurements were made of in-car noise during simulated revenue runs from Lechmere Station to Northeastern Station and return for each of the three vehicles tested. This portion of the route contains a wide variety of conditions which influence noise propagation, including subway, elevated rail, and surface rail. Microphones were also deployed to measure wayside noise at two locations along the route. One was located at the center of curvature of the turnaround loop of Lechmere Station at the end of the line; the other was located along the track midway between the Northeastern and Museum/Ruggles Stations on the Huntington Avenue branch of the Green Line, directly in front of the Boston Museum of Fine Arts.

Ground-borne vibration-level measurements were also made at the latter site where a triaxial vibration transducer for monitoring acceleration levels in three axes was secured to the concrete curb stone. The test vehicles were run back and forth past these wayside measurement stations up to six times in order to obtain statistically significant data.

2.0 EXPERIMENTAL APPROACH

2.1 GENERAL

Wheel/rail noise is generated by the interaction of wheels on steel rails and falls into three broad categories: roar, squeal, and impact. One way of reducing noise, particularly squeal, is to replace solid-steel wheels with resilient wheels. The two types of resilient wheels investigated in this study are the Acoustaflex and Sab-V wheels. A sectional diagram, Figure A.1, Appendix A, illustrates the differences between these resilient wheels and solid-steel wheels.

Currently, the MBTA uses two different vehicles for Green Line operations. One, the Presidential Conference Committee (PCC) car, is an older trolley vehicle which uses solid-steel wheels. The other is the more recent Boeing Light Rail Vehicle (LRV) and presently uses Acoustaflex wheels. The MBTA is currently considering replacement of worn Acoustaflex wheels and requested that TSC conduct measurements to evaluate the effectiveness of Sab-V wheels versus Acoustaflex and steel wheels.

2.2 TEST TRACK

The section of the Green Line between Lechmere Station, the terminus of the line, and the Northeastern station on the Huntington Avenue branch was chosen for in-car noise measurement, since it included a wide variety of conditions: elevated rail from Lechmere to North Station, subway from just beyond North Station to just beyond Symphony Station, and surface track for the remainder. It also contained several small-radius curves near the Lechmere, North Station, Boylston, and Park Street Stations, all of which frequently cause wheel squeal. A diagram of the route is shown in Figure A.2, Appendix A.

2.3 TEST VEHICLES

Three separate vehicles were instrumented with noise monitoring and recording systems: LRV Serial No. 3510, equipped with Sab-V wheels; LRV Serial No. 3419, equipped with Acoustaflex wheels; and PCC Serial No. 3270, equipped with solid-steel wheels. Two microphones were fixed at ear level of a seated passenger (four feet above the floor) and oriented with their axis perpendicular to the floor (grazing incidence). One microphone was located in a passenger seating area over the front wheel trucks, and the second over the rear wheel trucks, as shown in Figure A.3, Appendix A. The air conditioning system was shut down during the test runs.

2.4 SURFACE TEST SITES

Wayside noise measurements were made at two sites along the surface track portion of the route to ensure that noise measurements would not be affected by reverberation and echo, as they would in subway or station sections. One site was at the center of the loop at Lechmere Station, a small-radius curve of approximately 72 feet (see Figure A.4, Appendix A). The test vehicles were operated on the outside set of tracks at this location. A microphone oriented for grazing incidence at a height of five feet above the ground was placed at the center of the curve.

The other site was opposite a straight section of track on Huntington Avenue in front of the Boston Museum of Fine Arts, 41.5 feet from the center-line of the outbound track (see Figure A.5, Appendix A). A microphone was oriented for grazing incidence and placed at a height of five feet above the ground.

Ground-borne vibration level measurements were also made at the Huntington Avenue location. Accelerometers oriented to monitor vibrations in three axes were attached with epoxy cement to the concrete curb stone, 36.5 feet from the outbound track centerline (see Figure A.5, Appendix A.)

2.5 TEST PROCEDURE

Each of the three test vehicles was operated according to the following procedure:

1. Three passes each, back and forth, for a total of six events around the loop at Lechmere Station. Both, in-car and wayside noise were recorded for these events. Operating speeds were approximately 10 mph.
2. One outbound trip from Lechmere Station to Northeastern Station, recording in-car noise only. Vehicles travelled at normal operating speeds, slowing to a full stop at each station (simulating revenue operation).

3. Three passes each back and forth, for a total of six events, between the Northeastern and Museum/Ruggles Stations on Huntington Avenue. Both in-car and wayside noise, as well as ground-borne vibration, were recorded for these events. Vehicles travelled at normal operating speeds of 20 to 30 mph.

4. One return inbound trip from Northeastern to Lechmere Stations, as in 2 above.

Noise data from all microphone systems were recorded on magnetic tape. For in-car noise measurements, observers located in the operator's compartment annotated train speed onto the third track of the tape recorder in synchronism with the noise data. Speeds were read from the operator console in the LRV cars and from a hand-held doppler-radar speed gun in the PCC car.

Vibration-level recordings at the Huntington Avenue site were made in time-synchronism with wayside and in-car noise recordings at this location. The site was alerted by radio when the test car was approaching.

Details of the noise and vibration measurement system are described and illustrated in Appendix B.

3.0 MEASUREMENT DATA

3.1 SUMMARY NOISE-LEVEL DATA

Summary tabulations of the noise-level data measured at two in-car locations and both wayside locations are presented.

Tables 1 and 2 contain tabulations of statistical in-car noise-level data obtained in the passenger seating area over the front and rear wheel trucks, respectively. The data were obtained during simulated revenue runs, inbound and outbound, between the Lechmere and Northeastern Stations for each of the test trains. An inspection of the L_1 exceedence levels (noise levels exceeded one percent of the time) shows noise levels in the Sab-V equipped LRV to be 1.5 to 3.8 dB less intrusive than the Acoustaflex-equipped LRV. The PCC car with its solid-steel wheels is seen to be (using the L_1 levels as a measure of intrusiveness) 6.9 to 11.9 dB more intrusive than the Sab-V equipped vehicle.

Table 3 contains summary tabulations of maximum passby levels measured at the two wayside measuring sites. The levels reported in the Lechmere Loop consisted partly of wheel squeal noise generated while the test trains negotiated the 72-foot radius loop. The levels reported from the Huntington Avenue site were primarily "roar" noise.

The average wayside data obtained in the Lechmere Loop indicate the Sab-V equipped vehicle was 0.9 dB quieter than the Acoustaflex-equipped vehicle, and 14.1 dB quieter than the steel-wheel equipped PCC car. At the Huntington Avenue site, the average maximum passby levels show the Sab-V equipped vehicle to be 0.5 dB noisier than the Acoustaflex-equipped vehicle, and 3.2 dB noisier than the steel-wheeled PCC car. It must be noted, however, that the speed of the PCC car was on the average 4.9 mph slower. Normalizing the PCC data (using a 30 log speed ratio relationship) would increase the average passby level to 80.4 dB. Thus, the wayside passby levels on a straight section of track ("roar") for all three vehicles were within 0.5 dB of one another.

Tables 4 and 5 present in-car noise levels measured in the passenger seating areas over the front and rear wheel trucks, respectively, for the three test vehicles. The data presented from the Lechmere Loop tests are the maximum levels generated (wheel squeal), as the trains negotiated through approximately

TABLE 1. STATISTICAL IN-CAR NOISE-LEVEL DATA - PASSENGER AREA OVER FRONT WHEEL TRUCK (OUTBOUND/INBOUND)

STATISTICAL LEVEL (L_n)	LEVEL EXCEEDED n PERCENT OF TIME (L_n (dBA))		
	LRV S/N 3510 W/SAB-V WHEELS	LRV S/N 3419 W/ACOUSTAFLEX WHEELS	PCC S/N 3270 W/SOLID-STEEL WHEELS
Outbound Lechmere to Northeastern			
L_1	83.3	84.8	90.2
L_{10}	79.4	79.3	84.0
L_{50}	73.4	71.7	77.4
L_{90}	68.3	65.0	68.9
L_{99}	65.6	60.7	65.4
Inbound Northeastern to Lechmere			
L_1	83.0	84.7	92.2
L_{10}	79.8	81.0	85.9
L_{50}	74.2	74.4	76.7
L_{90}	68.9	70.3	67.0
L_{99}	66.0	68.3	65.0

TABLE 2. STATISTICAL IN-CAR NOISE-LEVEL DATA - PASSENGER AREA OVER REAR WHEEL TRUCK (OUTBOUND/INBOUND)

STATISTICAL LEVEL (L_n)	LEVEL EXCEEDED n PERCENT OF TIME (L_n(dBA))		
	LRV S/N 3510 W/SAB-V WHEELS	LRV S/N 3419 W/ACOUSTAFLEX WHEELS	PCC S/N 3270 W/SOLID-STEEL WHEELS
Outbound Lechmere to Northeastern			
L_1	82.3	86.1	92.0
L_{10}	78.6	80.4	85.9
L_{50}	71.9	73.7	79.4
L_{90}	64.7	70.2	72.0
L_{99}	60.3	68.6	68.9
Inbound Northeastern to Lechmere			
L_1	82.0	84.7	93.9
L_{10}	78.6	80.7	87.6
L_{50}	72.1	73.2	78.8
L_{90}	64.6	65.1	71.5
L_{99}	59.4	61.3	69.5

TABLE 3. SUMMARY OF WAYSIDE NOISE-LEVEL DATA - MAXIMUM PASSBY LEVELS (LECHMERE LOOP AND HUNTINGTON AVE SITES)

LOCATION - RUN NO.	LRV S/N 3510 W/SAB-V WHEELS		LRV S/N 3419 W/ACOUSTAFLEX WHEELS		PCC S/N 3270 W/SOLID-STEEL WHEELS	
	L_A MAX (dBA)	SPEED (MPH)	L_A MAX (dBA)	SPEED (MPH)	L_A MAX (dBA)	SPEED (MPH)
Lechmere Loop						
1	68.2	7	68.8	10	80.2	10
2	68.2	6	69.2	7	78.0	10
3	69.5	10	69.8	10	88.0	10
4	71.2	10	71.2	10	79.0	10
5	69.2	12	71.0	12	89.5	10
6	70.5	9	71.5	10	86.5	9
Average	69.4	9.0	70.3	9.8	83.5	9.8
Std. Dev.	1.2	2.2	1.1	1.6	5.0	0.4
Huntington Ave.						
7	80.0	27	81.8	28	80.0	23
8	82.2	25	80.0	26	78.0	24
9	83.5	30	83.5	30	77.0	22
10	80.5	30	78.5	30	76.5	23
11	80.5	28	81.5	30	78.8	24
12	80.0	28	78.8	28	77.2	23
Average	81.1	28.0	80.6	28.7	77.9	23.3
Std. Dev.	1.4	1.9	2.0	1.6	1.3	1.0

TABLE 4. SUMMARY OF MAXIMUM IN-CAR NOISE-LEVEL DATA - PASSENGER AREA OVER FRONT WHEEL TRUCK (LECHMERE LOOP AND HUNTINGTON AVE SITES)

LOCATION - RUN NO.	LRV S/N 3510 W/SAB-V WHEELS		LRV S/N 3419 W/ACOUSTAFLEX WHEELS		PCC S/N 3270 W/SOLID-STEEL WHEELS	
	L_A MAX (dBA)	SPEED (MPH)	L_A MAX (dBA)	SPEED (MPH)	L_A MAX (dBA)	SPEED (MPH)
Lechmere Loop						
1	70.5	7	74.8	10	-	-
2	72.2	6	76.0	7	No Data	
3	70.5	10	80.0	10	-	-
4	73.0	10	81.2	10	-	-
5	70.0	12	74.0	12	-	-
6	72.5	9	79.0	10	88.2	9
Average	71.3	9.0	77.5	9.8	88.2	9.0
Std. Dev.	1.4	2.2	3.0	1.6	-	-
Huntington Ave.						
7	77.0	27	79.5	28	81.8	23
8	79.5	25	77.2	26	81.0	24
9	76.5	30	81.0	30	81.0	22
10	77.0	30	77.8	30	82.0	23
11	77.5	28	80.5	30	80.5	25
12	79.5	28	79.0	28	78.0	23
Average	77.8	28.0	79.1	28.7	80.7	23.3
Std. Dev.	1.3	1.9	1.5	1.6	1.4	1.0

TABLE 5. SUMMARY OF MAXIMUM IN-CAR NOISE-LEVEL DATA - PASSENGER AREA OVER REAR WHEEL TRUCK (LECHMERE LOOP AND HUNTINGTON AVE SITES)

LOCATION - RUN NO.	LRV S/N 3510 W/SAB-V WHEELS		LRV S/N 3419 W/ACOUSTAFLEX WHEELS		PCC S/N 3270 W/SOLID-STEEL WHEELS	
	L_A MAX (dBA)	SPEED (MPH)	L_AMAX (dBA)	SPEED (MPH)	L_A MAX (dBA)	SPEED (MPH)
Lechmere Loop						
1	73.8	7	79.0	10	-	-
2	68.0	6	75.5	7	-	-
3	71.8	10	78.2	10	No Data	
4	69.0	10	75.0	10	-	-
5	76.0	12	77.2	12	-	-
6	71.2	9	76.0	10	88.0	9
Average	71.4	9.0	76.8	9.8	88.0	9
Std. Dev.	2.7	2.2	1.6	1.6	-	-
Huntington Ave.						
7	76.5	27	78.2	28	82.8	23
8	78.5	25	76.5	26	81.0	24
9	77.5	30	81.8	30	80.0	22
10	77.0	30	77.0	30	81.5	23
11	77.0	28	81.2	30	78.2	25
12	78.0	28	78.2	28	80.5	23
Average	77.4	28.0	78.8	28.7	80.6	23.3
Std. Dev.	0.7	1.9	2.2	1.6	1.5	1.0

150 degrees of the turnaround loop. In general, the maximum in-car levels coincided with the measured wayside levels (see Table 3). At this site, only one event was recorded in-car for the PCC car. The average data (Tables 4 and 5) show that the Sab-V equipped LRV produced maximum in-car A-weighted noise levels that were 6.2 to 5.4 dB quieter than the Acoustaflex-equipped LRV and 16.9 to 16.6 dB quieter than the steel-wheeled PCC car (in-car in the passenger seating area over front/rear wheels, respectively).

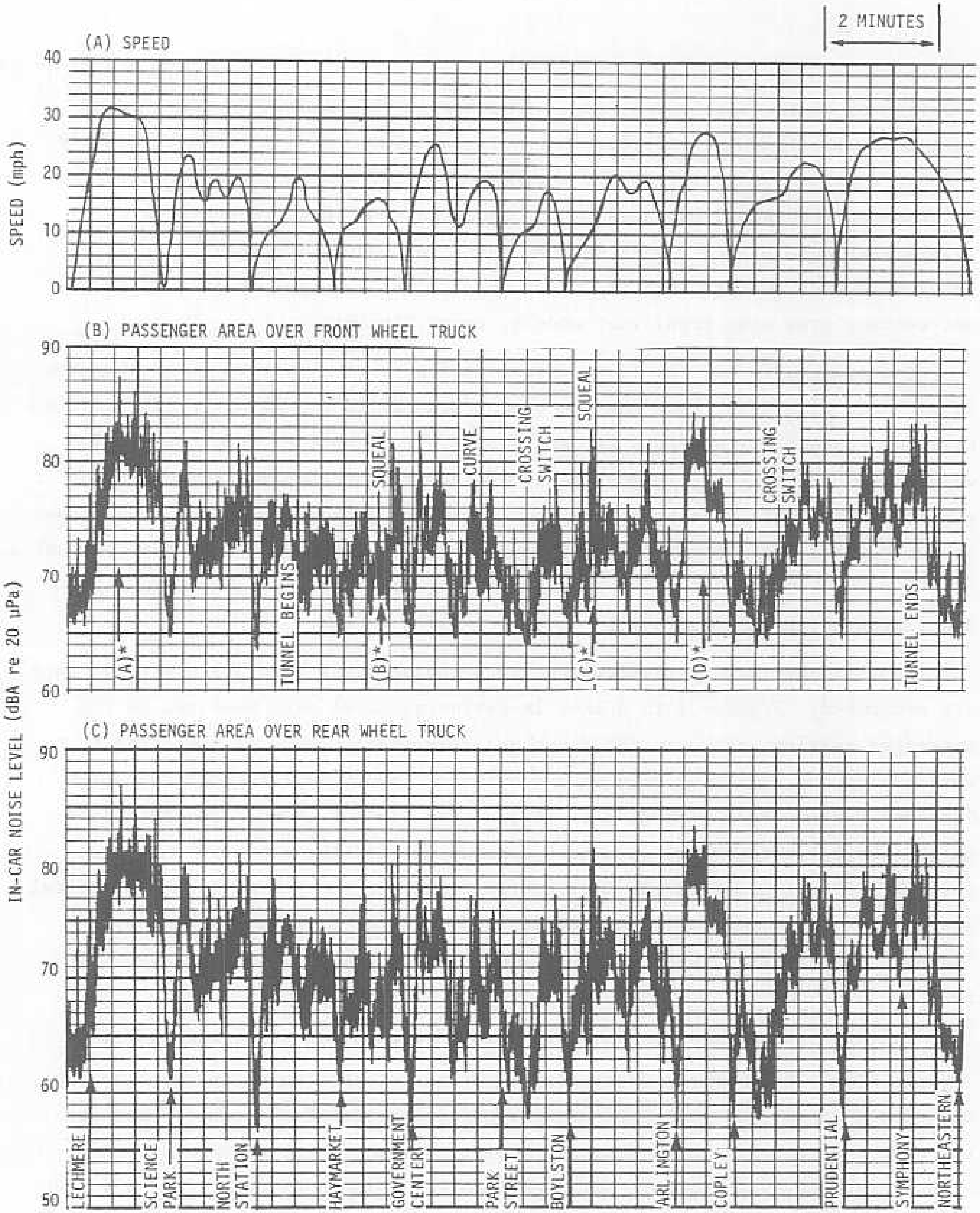
The average in-car levels measured, during passby opposite the Huntington Avenue measuring site, show the Sab-V equipped LRV to be 1.3 to 1.4 dB quieter than the Acoustaflex-equipped LRV and 2.9 to 3.2 dB quieter than the steel-wheeled PCC car. Again, it must be noted that the average speed of the PCC car was 5 mph less than that of the LRV's. Normalizing the in-car levels for speed as above, would make the PCC car approximately 5 dB noisier in-car than the LRV's.

3.2 NOISE LEVEL TIME HISTORIES

In this section, representative in-car noise-level time-history recordings are presented. Figures 1 to 3 show in-car noise-level data measured in the passenger seating area over the front and rear wheel trucks of the three test cars during the simulated revenue run outbound from Lechmere to Northeastern Stations (noise level histories of inbound run are not shown). Superimposed on the charts is the speed information obtained from the operator's console for the LRV cars and from the Doppler radar gun for the PCC car. A statistical analysis of these data over the periods shown in the time histories (approximately 14-15 minutes) was performed and is tabulated in Tables 1 and 2 (see Section 3.1).

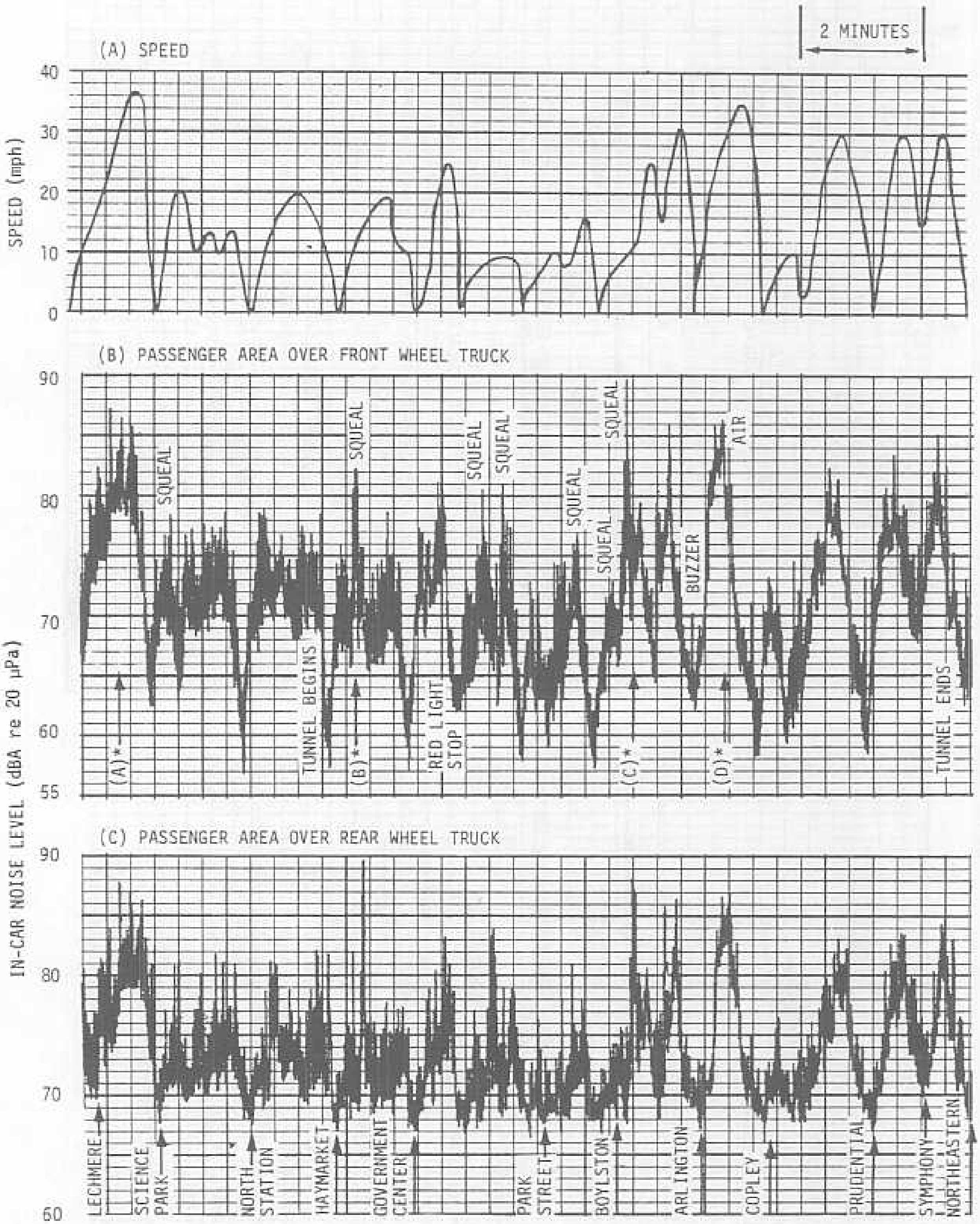
Various points are identified in Figures 1 to 3 and are lettered (A) through (D). These points correspond to events of particular interest during the simulated revenue run, most notably wheel squeal. Each point represents the center of a four-second analysis period over which the average one-third octave frequency spectrum was obtained from the noise data (see Figures 4 - 6 in Section 3.3).

An inspection of Figures 1 to 3 shows, for individual high level events occurring over various portions of the test track, that the Sab-V equipped vehicle generated levels which varied by +2 to -10 dB from the levels generated



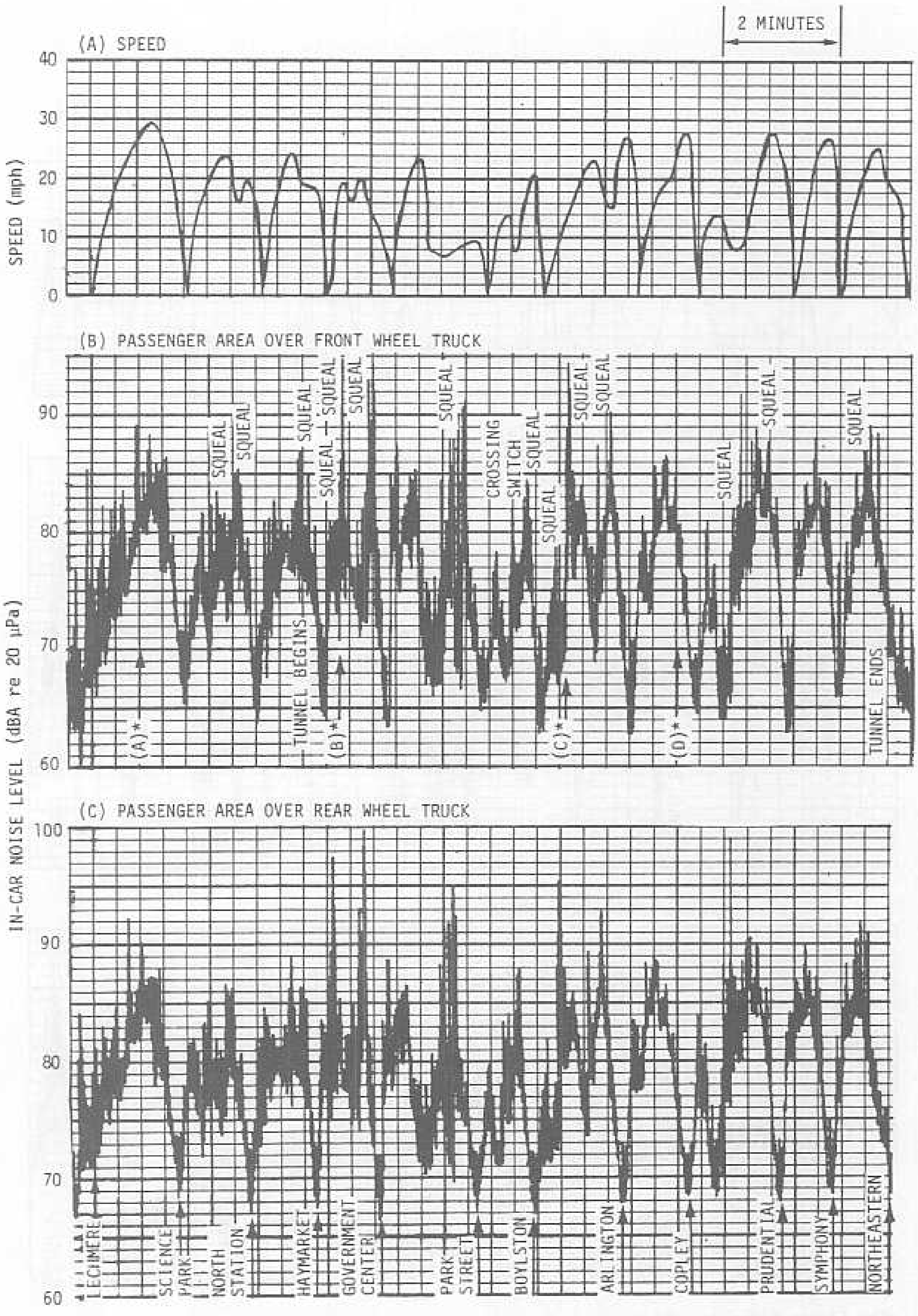
*See Figure 4 for one-third octave frequency spectra.
See Figure C.1 for narrow band frequency spectra.

Figure 1. In-Car Noise-Level Time History Data - Lechmere to Northeastern (Outbound). LRV S/N 3510 w/Sab-V Wheels



*See Figure 5 for one-third octave frequency spectra.
See Figure C.2 for narrow band frequency spectra.

Figure 2. In-Car Noise-Level Time History Data - Lechmere to Northeastern (Outbound). LRV S/N 3419 w/Acoustaflex Wheels



*See Figure 6 for one-third octave frequency spectra.
See Figure C.3 for narrow band frequency spectra.

Figure 3. In-Car Noise-Level Time History Data - Lechmere to Northeastern (Outbound). PCC S/N 3270 w/Solid-Steel Wheels

by the Acoustaflex-equipped LRV at the same location. Levels inside the steel-wheel PCC car were 2 to 16 dB greater. These differences are seen to be greatest on tightly curved sections of the test track, where maximum levels are strongly influenced by wheel squeal, e.g., between Haymarket and Government Center Stations and between Boylston and Huntington Avenue Stations. A small difference is seen between the high level noise data measured at the front vs. the rear of the train. The rear of the train was 0 to 1.8 dB noisier (see L_1 levels Tables 1 and 2). The differences noted in the low levels (ambient, primarily when the train comes to a stop) between the front and rear in-car measurement areas is attributed to on-board equipment. For example, in the case of the LRV Serial No. 3419, a noisy inverter at the rear of the train can be seen in Figure 2 to raise the low level ambient by approximately 7 dB over that measured at the front measuring location. A difference of approximately 5 dB is similarly noted in LRV Serial No. 3510, while for the PCC car the ambient level at the front of the train is approximately 3 dB noisier than the area at the rear of the train.

Figures 7 through 12 contain representative time-history recordings of the noise data recorded at the wayside and simultaneously in-car over the front wheel truck for each of the test cars both at the Lechmere Loop and Huntington Avenue measurement sites. Speed data along with the appropriate explanatory notations are included. A four-second time period is identified for the one-third octave analysis (see Section 3.3).

3.3 NOISE LEVEL FREQUENCY SPECTRA

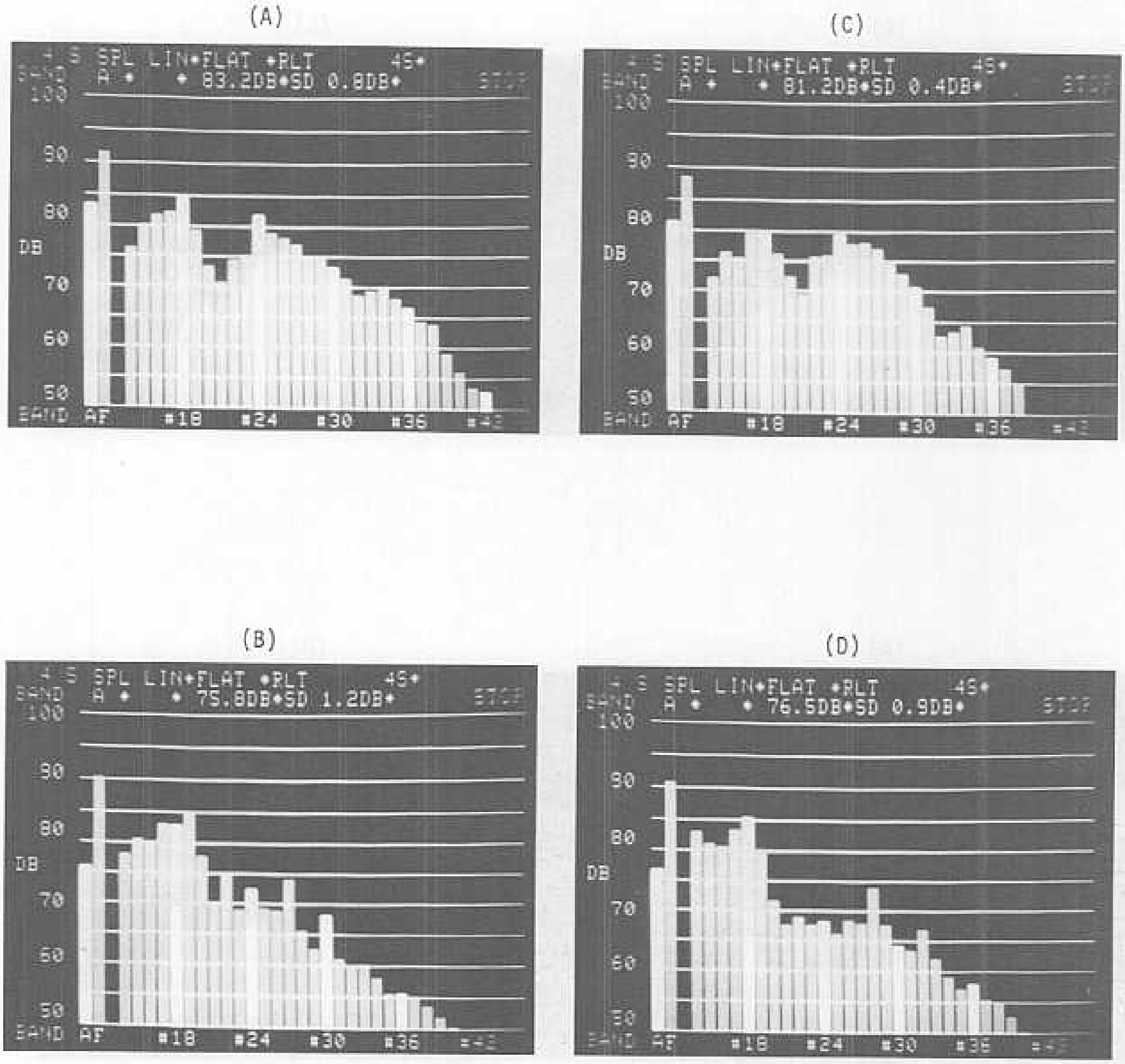
One-third octave-band frequency spectra of selected representative portions of the measured noise data are presented. The noise data chosen for spectral analysis are identified on the graphic-level time-history recordings of Section 3.2. In general, four seconds of data, encompassing a selected event, were averaged to produce a one-third octave frequency spectrum. The band number conversion tables and explanation of the information on the spectral photograph are shown in Appendix B. A one-half second time period centered around the maximum level that occurred within the four-second period identified above was chosen for narrow band analysis in order to show the fine detail of the noise spectrum. These spectra are presented in Appendix C.

Figures 4 through 6 contain one-third octave frequency spectra of four in-car noise events selected during the simulated revenue runs for each of the test vehicles. The locations on the test track are approximately the same for each vehicle. These are identified on the graphic histories of Figures 1 to 3 as: point (A), an elevated straight section between Lechmere and Science Park Stations; point (B), a curved section in the tunnel between Haymarket and Government Stations; point (C), a curve in tunnel between Boylston and Arlington Stations; and point (D), a straight section in the tunnel between Arlington and Copley Stations.

The spectra obtained at point (A) show typical in-car roar noise resulting from surface operations on the three test trains (Figures 4 to 6). Small, but recognizable, differences are observed. In particular, the Sab-V equipped LRV exhibits peaks in the 63 Hz and 250 Hz one-third octave bands, the Acoustaflex-equipped LRV displays somewhat broader peaks centering in the 50 Hz and 315 Hz one-third octave bands, and the solid steel-equipped PCC car exhibits a single peak in the 40 Hz one-third octave band. The spectra obtained at point (D) show typical in-car roar noise resulting from in-tunnel operations for the three test trains. Similar characteristics to the outside spectra can be seen except that, in general, an amplification in noise level in the vicinity of the 250 Hz one-third octave band is observed. This is the result of tunnel resonances on the roar spectra. See narrow band spectra, Appendix C, to obtain the fine detail of spectral characteristics.

A comparison of spectra showing squeal noise at points (B) and (C) reveals prominent differences between the three wheels tested. It can be seen (from Figures 4 to 6) that for both the Sab-V wheel and solid-steel wheel, the greater squeal noise levels occur in the vicinity of the 630 Hz third-octave band. However, for the Acoustaflex wheel, the largest third-octave noise levels lie in the 1600 Hz band. It can also be seen that additional one-third octave squeal is generated near the 1600 Hz band for the Sab-V wheel, near the 4000 Hz band for the Acoustaflex wheel, and near the 10,000 Hz band for the solid-steel wheel.

Figures 7 to 9 contain one-third octave frequency spectra and noise level time histories of the noise data recorded at the Lechmere site, showing both in-car and wayside noise for each of the test vehicles. These figures point out several characteristics. A comparison of wayside noise from one vehicle to the

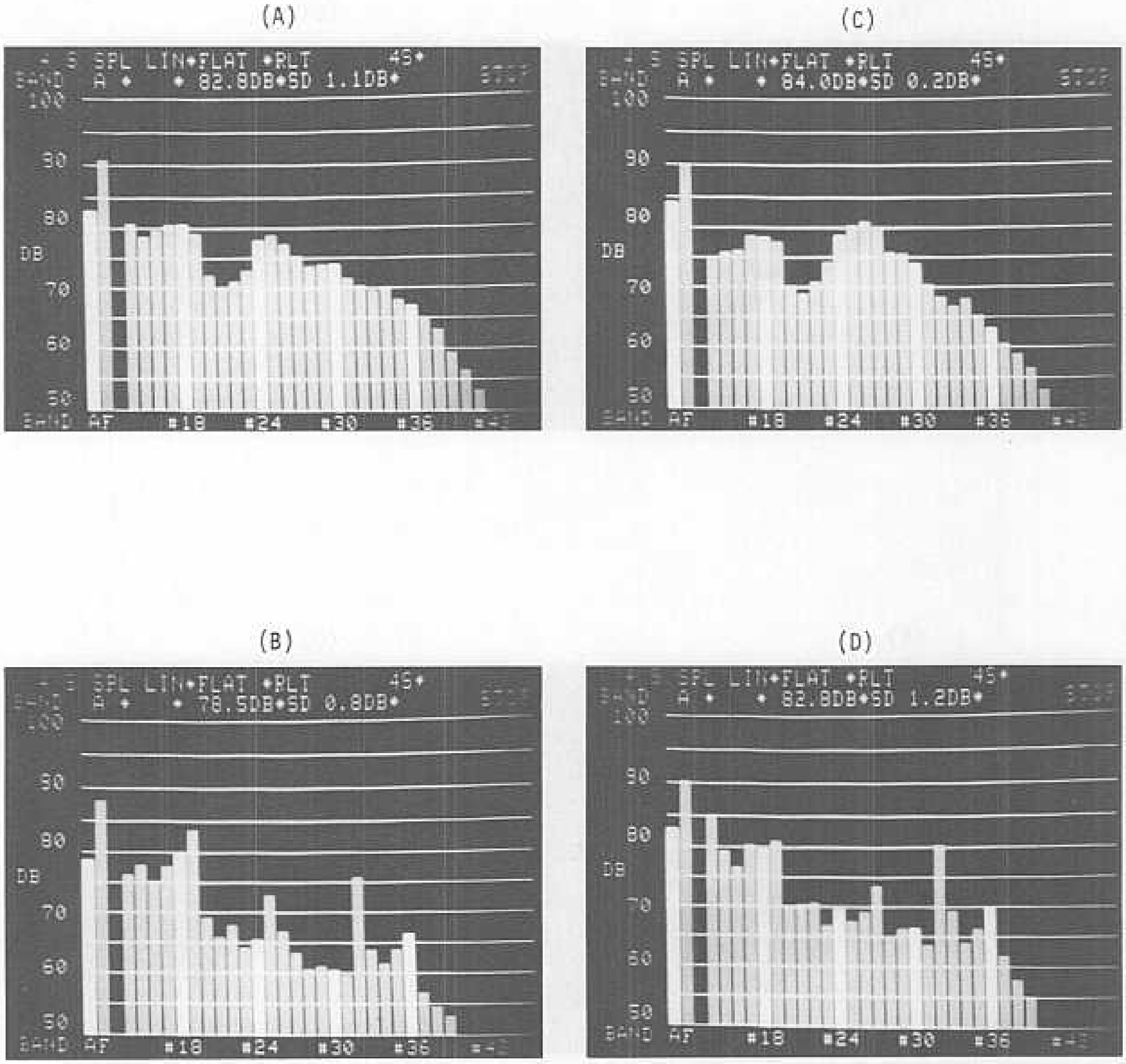


INTEGRATION PERIOD: 4 seconds

SEE FIGURE 1 FOR TIME HISTORY OF IN-CAR NOISE.

SEE TABLE B.1 FOR BAND NUMBER CONVERSION.

Figure 4. One-Third Octave Frequency Spectra of In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3510 w/Sab-V Wheels

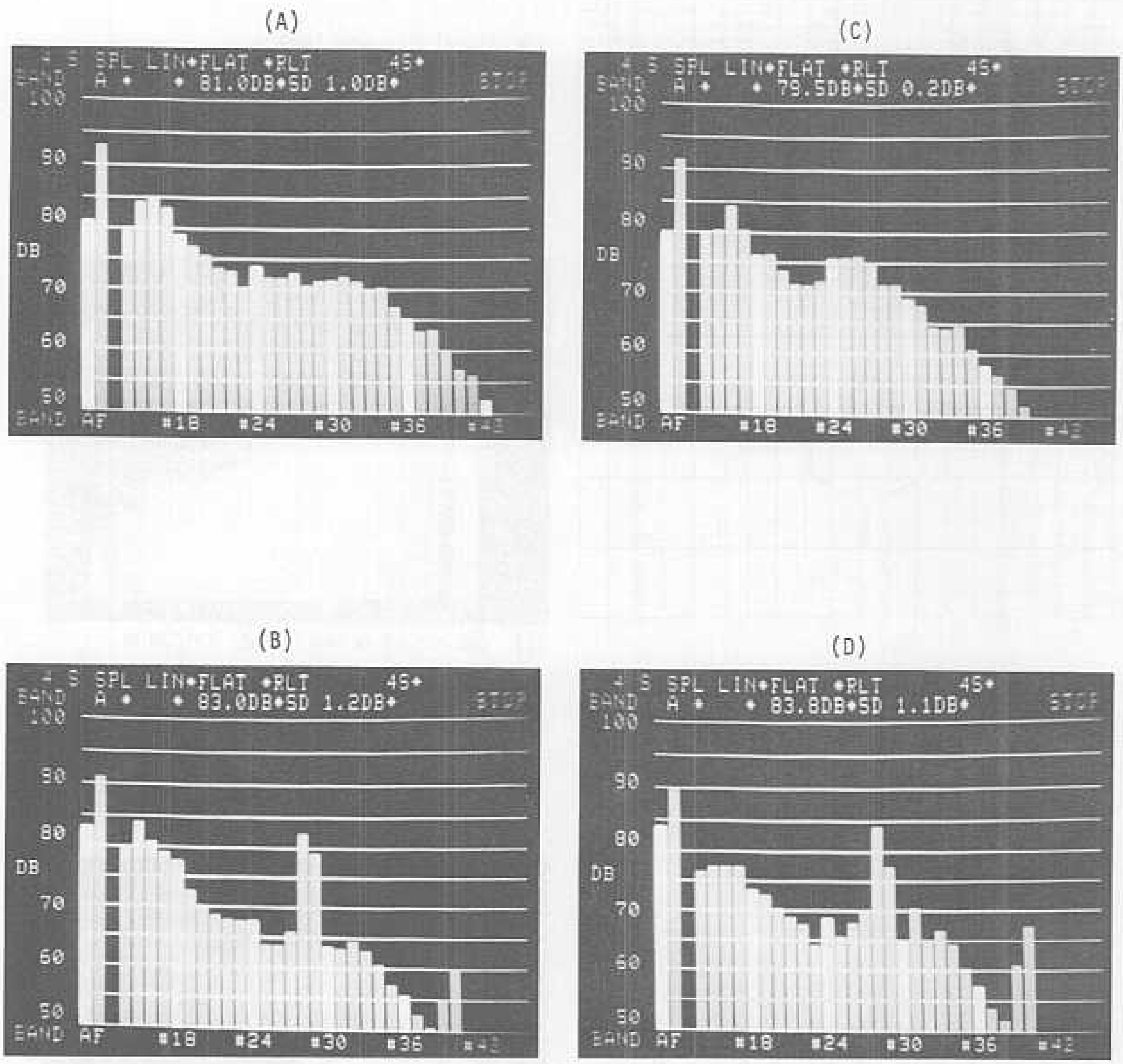


INTEGRATION PERIOD: 4 seconds

SEE FIGURE 2 FOR TIME HISTORY OF IN-CAR NOISE.

SEE TABLE B.1 FOR BAND NUMBER CONVERSION.

Figure 5. One-Third Octave Frequency Spectra of In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3419 w/Acoustaflex Wheels



INTEGRATION PERIOD: 4 seconds

SEE FIGURE 3 FOR TIME HISTORY OF IN-CAR NOISE.

SEE TABLE B.1 FOR BAND NUMBER CONVERSION.

Figure 6. One-Third Octave Frequency Spectra of In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). PCC S/N 3270 w/Solid-Steel Wheels

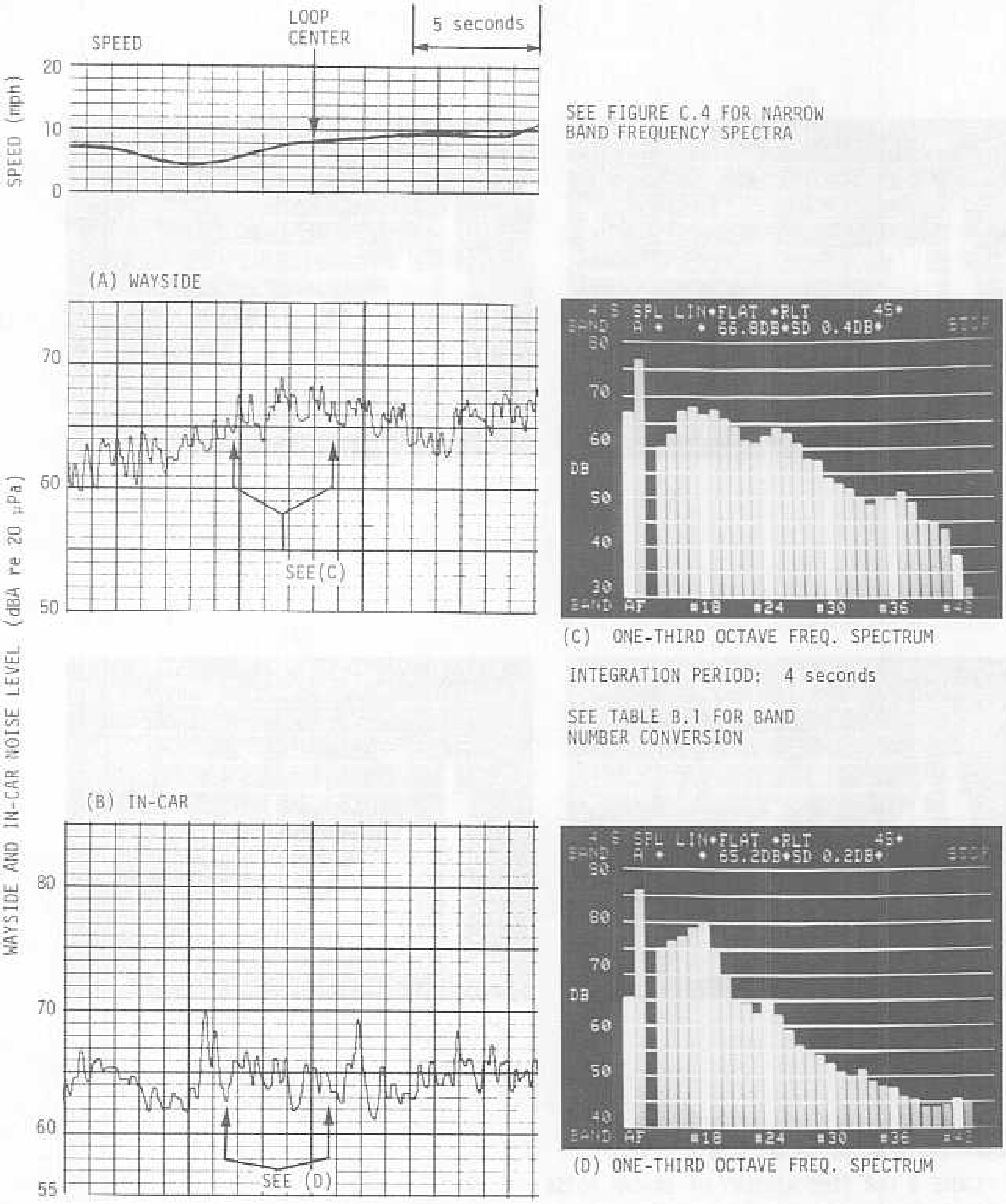


Figure 7. Coincident Wayside and In-Car (over Front Wheel Truck) Noise-Level Data with One-Third Octave Frequency Spectra - Lechmere Loop Run No. S5. LRV S/N 3510 w/Sab-V Wheels

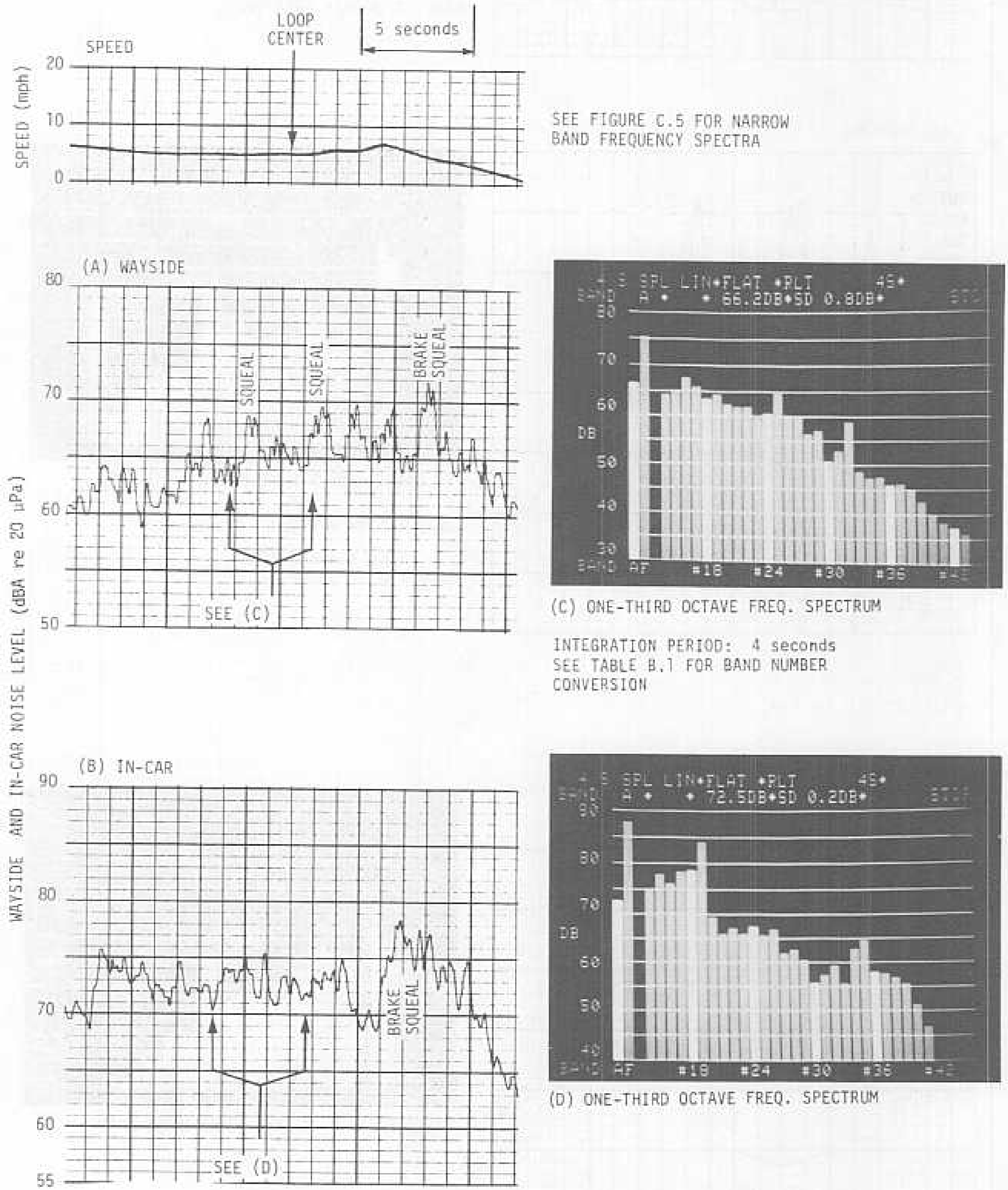


Figure 8. Coincident Wayside and In-Car (over Front Wheel Truck) Noise-Level Data with One-Third Octave Frequency Spectra - Lechmere Loop Run No. A1. LRV S/N 3419 w/Acoustaflex Wheels

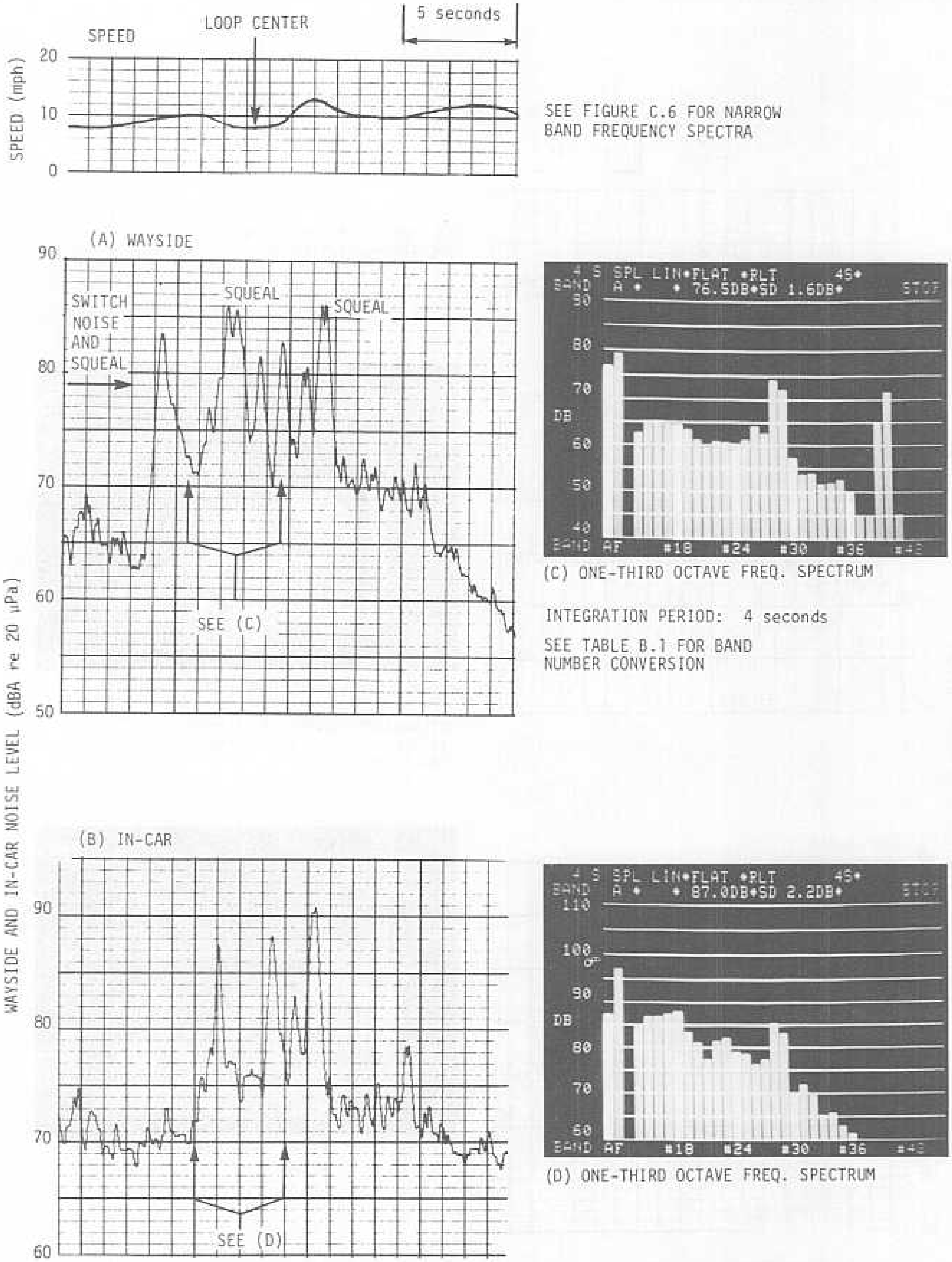


Figure 9. Coincident Wayside and In-Car (over Front Wheel Truck) Noise-Level Data with One-Third Octave Frequency Spectra - Lechmere Loop Run No. P6. PCC S/N 3270 w/Solid-Steel Wheels

other shows: no prominent wheel squeal frequencies for the Sab-V equipped LRV, some discrete frequency peaks for the Acoustaflex-equipped LRV in the 315 Hz and 1600 Hz third-octave bands, and strong peaks for the solid steel-equipped PCC car in the 630 Hz and 10 kHz third-octave bands. In-car noise data show similar characteristics except that the squeal frequencies are not as prominent. This is particularly noticeable in Figure 9, where there is a very large reduction in the 10 kHz one-third octave band when comparing in-car to wayside noise. The in-car noise reduction at higher frequencies can be attributed to the transmission loss through the vehicle body.

Figures 10 to 12 contain one-third octave frequency spectra of "roar" noise measurement at the Huntington Avenue site, showing both in-car and wayside noise. It can be seen from the Figures that the three test vehicles have different spectral characteristics. This is most noticeable in the wayside noise spectrum which shows a broad peak centered around 250 Hz with a noise shelf extending out to high frequencies for the Sab-V equipped LRV. The spectrum for the Acoustaflex-equipped LRV has a similar broad peak which gradually rolls off at high frequencies. The wayside spectra for the solid-steel-equipped PCC car shows a predominantly flat spectrum to 1000 Hz and a gradual rolloff beyond.

3.4 VIBRATION DATA

In this section, summary data, time history recordings, and one-third octave-band frequency spectra of ground-borne vibration measurements are presented. Table 6 contains a summary of the maximum acceleration levels measured for all passbys for each test vehicle at the Huntington Avenue measurement site. It can be seen from the average of the maximum levels shown in Table 6 that there are small differences between cars equipped with the different wheels tested. The Acoustaflex-equipped LRV produced acceleration levels approximately 2 dB less than the Sab-V equipped LRV in all three axes (vertical, transverse, and longitudinal), whereas the solid-steel wheel equipped PCC car produced acceleration levels similar to the Acoustaflex-equipped LRV in the vertical axis, and approximately 3 dB less in the transverse and longitudinal axes. The lower values of acceleration level associated with the solid-steel-wheel equipped PCC car may be attributed to slower speeds during the test and to the lighter weight of the PCC car compared to the LRV cars (40,000 and 67,000 pounds, respectively).

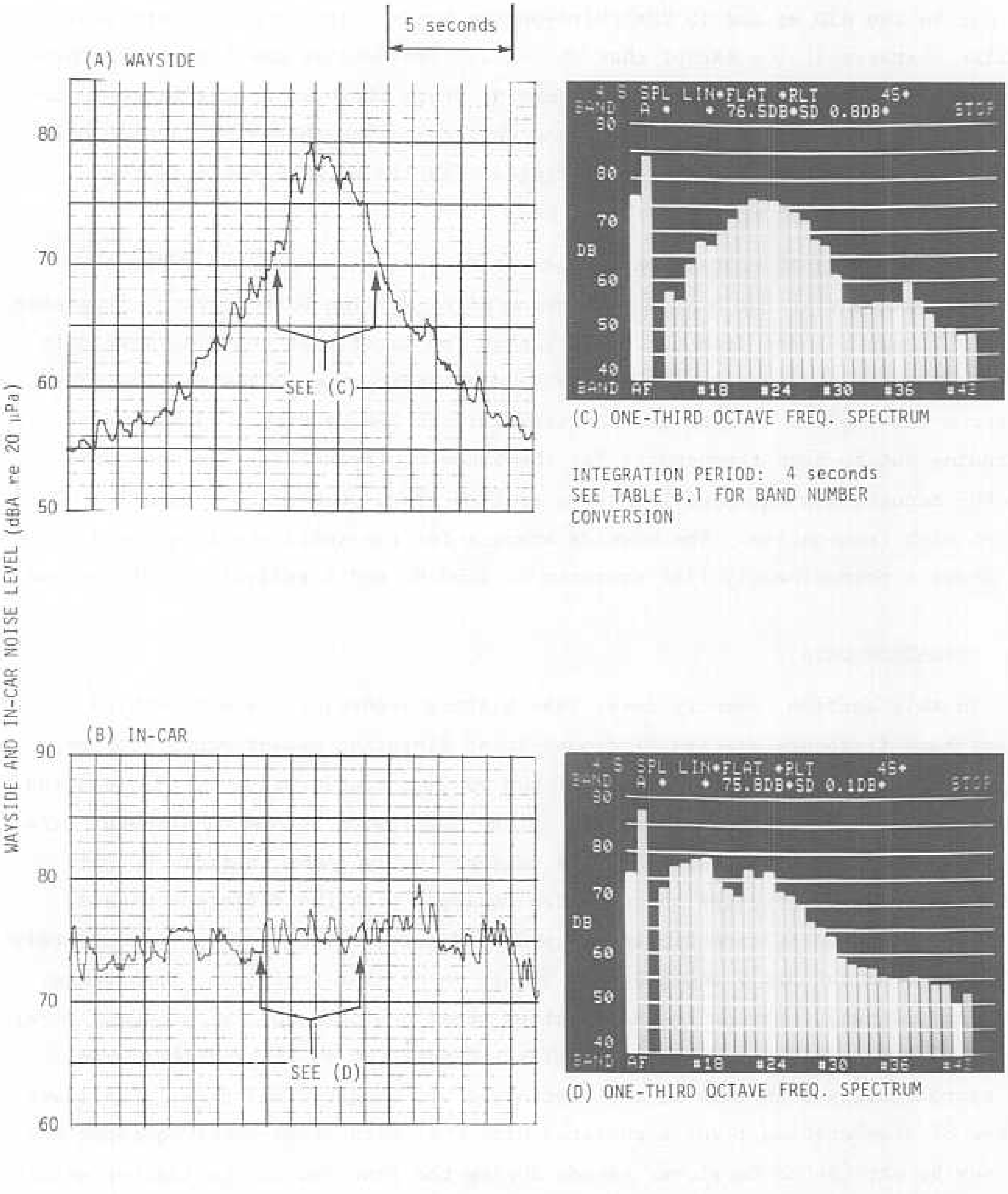


Figure 10. Coincident Wayside and In-Car (over Front Wheel Truck) Noise-Level Data with One-Third Octave Frequency Spectra - Huntington Avenue Run No. S7. LRV S/N 3510 w/Sab-V Wheels. Speed: 30 mph

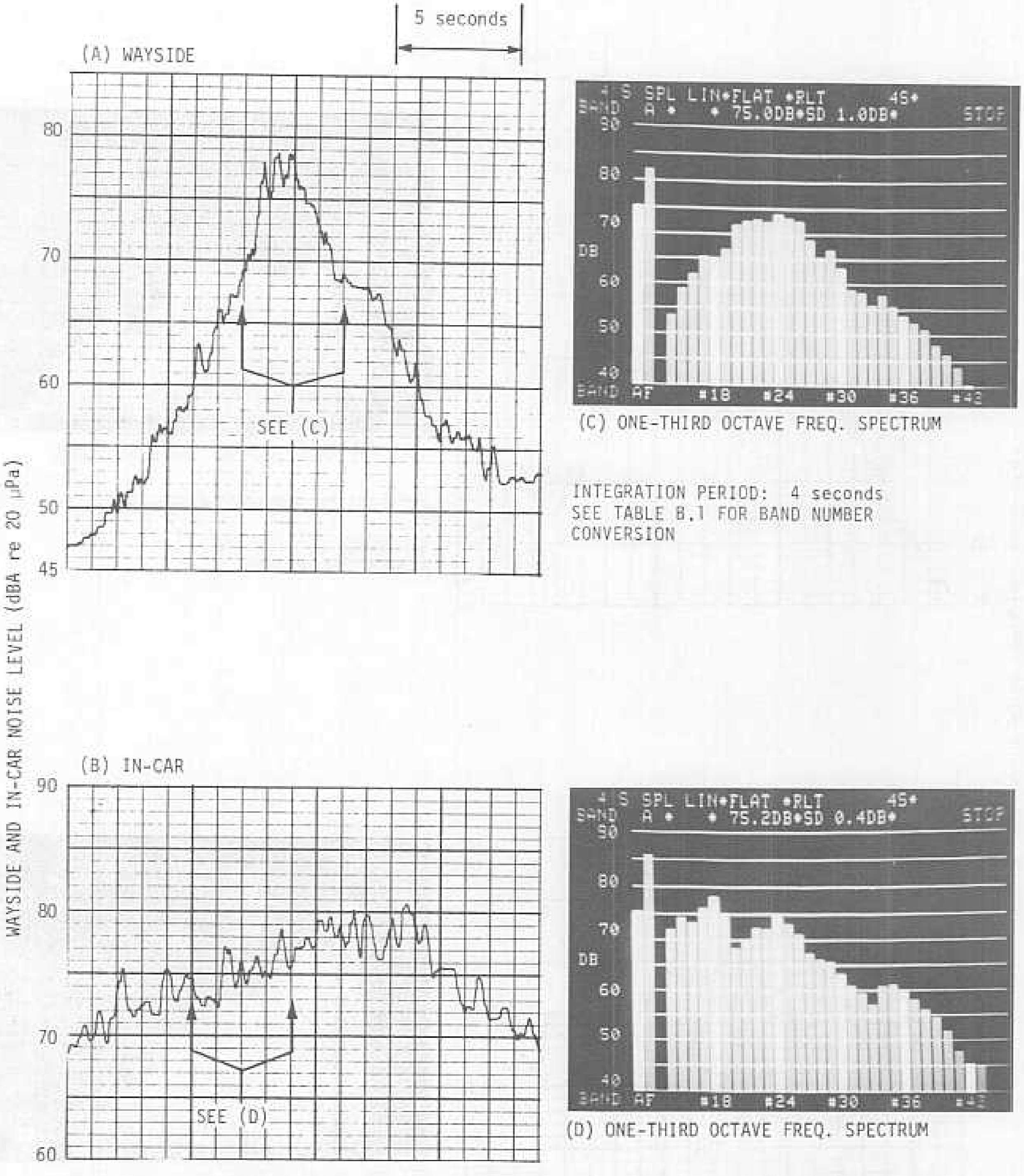


Figure 11. Coincident Wayside and In-Car (over Front Wheel Truck) Noise-Level Data with One-Third Octave Frequency Spectra - Huntington Avenue Run A12. LRV S/N 3419 w/Acoustaflex Wheels. Speed: 20 mph

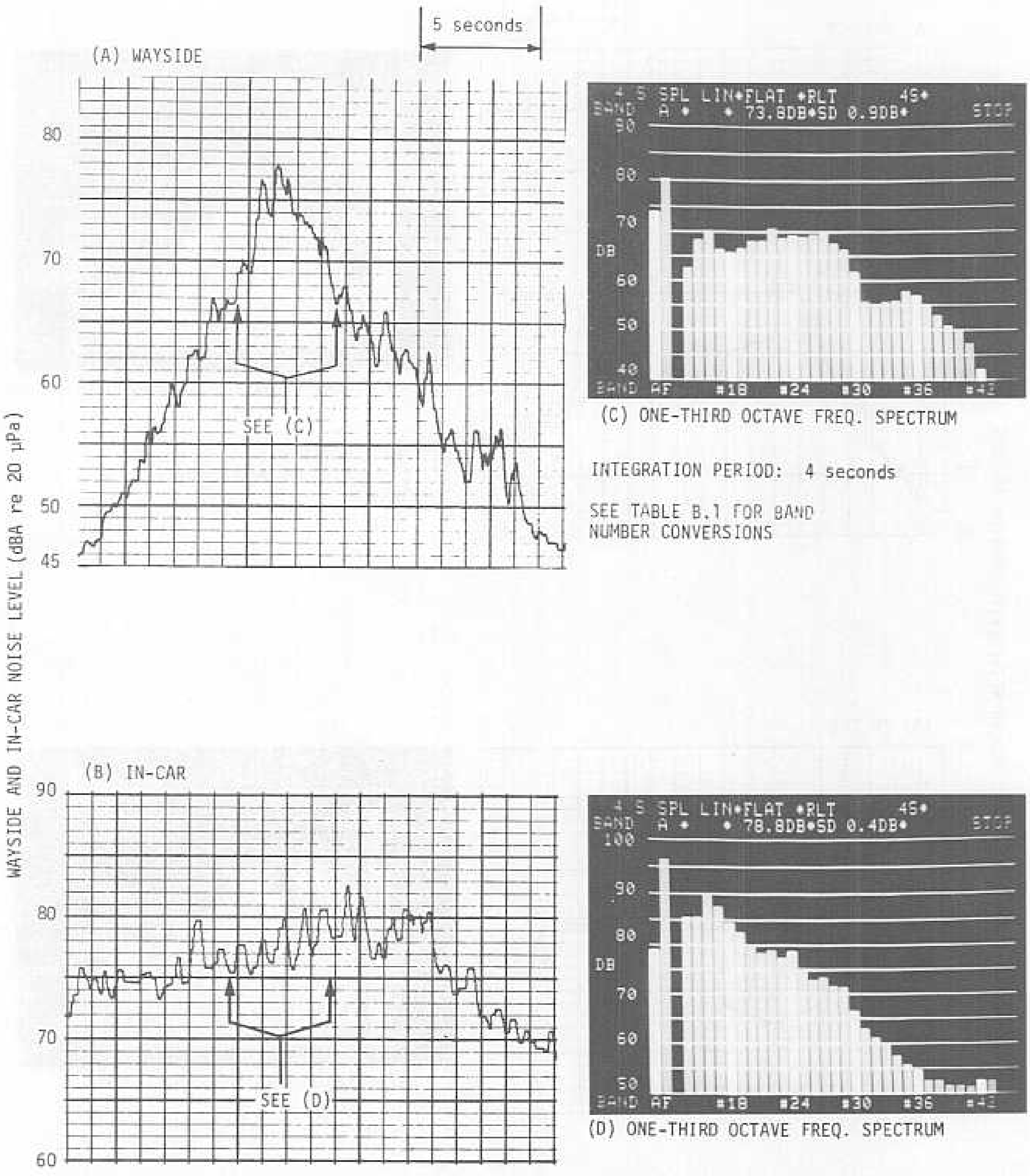


Figure 12 - Coincident Wayside and In-Car (over Front Wheel Truck) Noise-Level Data with One-Third Octave Frequency Spectra - Huntington Avenue Run No. P8. PCC S/N 3270 w/Solid-Steel Wheels. Speed: 24 mph

TABLE 6. SUMMARY OF GROUND-BORNE VIBRATION-LEVEL DATA FOR MAXIMUM ACCELERATION LEVELS AT HUNTINGTON AVE. SITE

RUN NO.	ACCELERATION LEVEL (dB)*			SPEED (MPH)
	VERTICAL	TRANSVERSE	LONGITUDINAL	
LRV S/N 3510 w/Sab-V Wheels				
S7	76.0	66.5	65.2	30
S8	74.8	66.2	67.8	30
S9	75.2	65.4	66.4	30
S10	75.0	65.6	64.2	30
S11	75.6	66.4	67.2	24
S12	77.2	66.5	64.0	24
Average	75.6	66.0	65.9	28
LRV S/N 3419 w/Acoustaflex Wheels				
A7	73.6	63.6	64.4	28
A8	72.8	62.2	62.0	30
A9	73.4	64.6	62.4	30
A10	74.8	63.4	64.8	30
A11	73.8	64.6	63.4	26
A12	73.9	64.8	64.0	26
Average	73.7	63.9	63.6	27
PCC S/N 3270 w/Solid-Steel Wheels				
P7	74.8	62.6	60.8	17
P8	73.8	61.8	59.8	24
P9	74.0	60.8	61.2	24
P10	73.8	61.2	59.0	24
P11	73.6	61.8	61.8	20
P12	74.0	61.2	59.4	20
Average	74.2	61.8	60.7	22

*dB re 1 micro-g RMS

Figures 13 to 15 present ground-borne vibration time histories and one-third octave band spectra of triaxial acceleration levels for selected runs at the Huntington Avenue site. Each figure presents data for a specific test car on a particular run, as indicated. A close inspection of the time histories shows small individual peaks within the overall envelope of each passby. Figures 13 and 14 show a pattern of three peaks which roughly correspond to the passage of the three wheel trucks on the LRVs (corresponding to a speed of approximately 25 mph and a wheel-truck separation distance of approximately 35 feet). Similarly, in Figure 15, two peaks dominate, which correspond to the passage of the two wheel-trucks of the PCC car.

Figures 13 and 14 for the two LRV cars equipped with resilient wheels are very similar, with maximum levels lying in the 50 Hz and 63 Hz one-third octave bands. Figures 15 for the PCC car equipped with solid-steel wheels is slightly different, with a sharper peak in the 50 Hz one-third octave band.

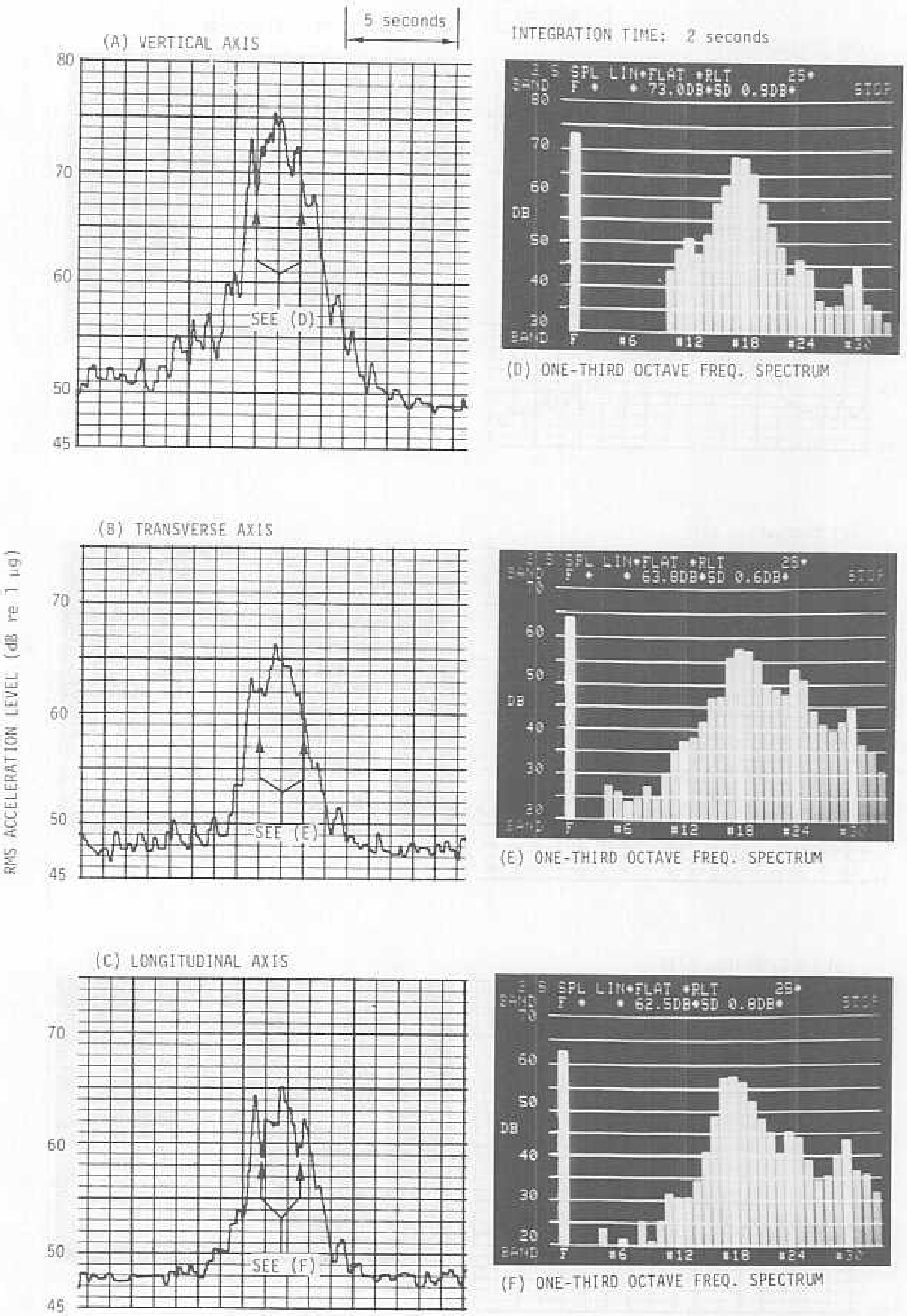


Figure 13. Ground-Borne Vibration Data with One-Third Octave Frequency Spectra - Huntington Avenue Run No. S7. LRV S/N 3510 w/Sab-V Wheels. Operating Speed: 30 mph

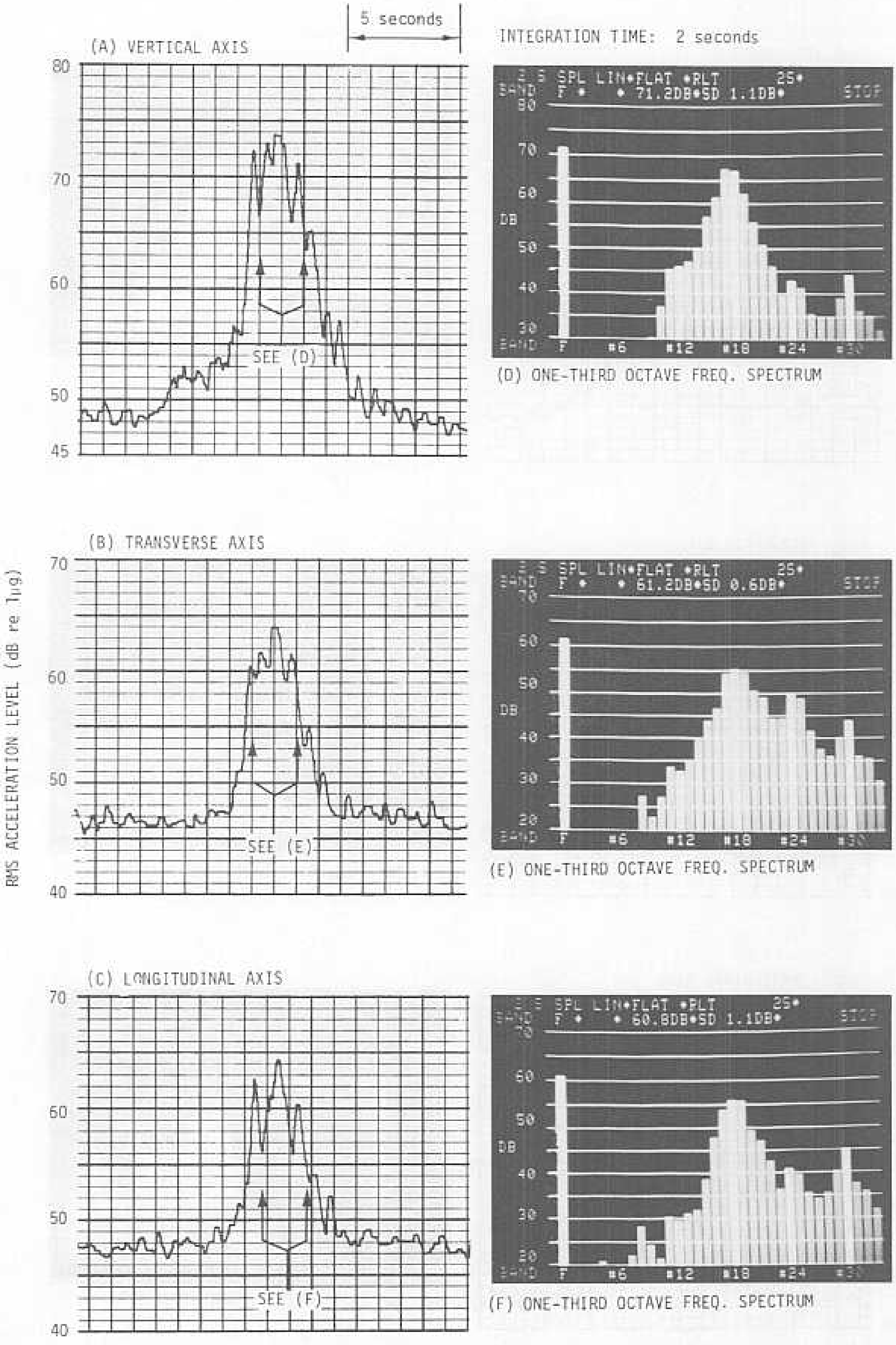


Figure 14. Ground-Borne Vibration Data with One-Third Octave Frequency Spectra - Huntington Avenue Run No. A12. LRV S/N 3419 w/Acoustaflex Wheels. Operating Speed: 20 mph

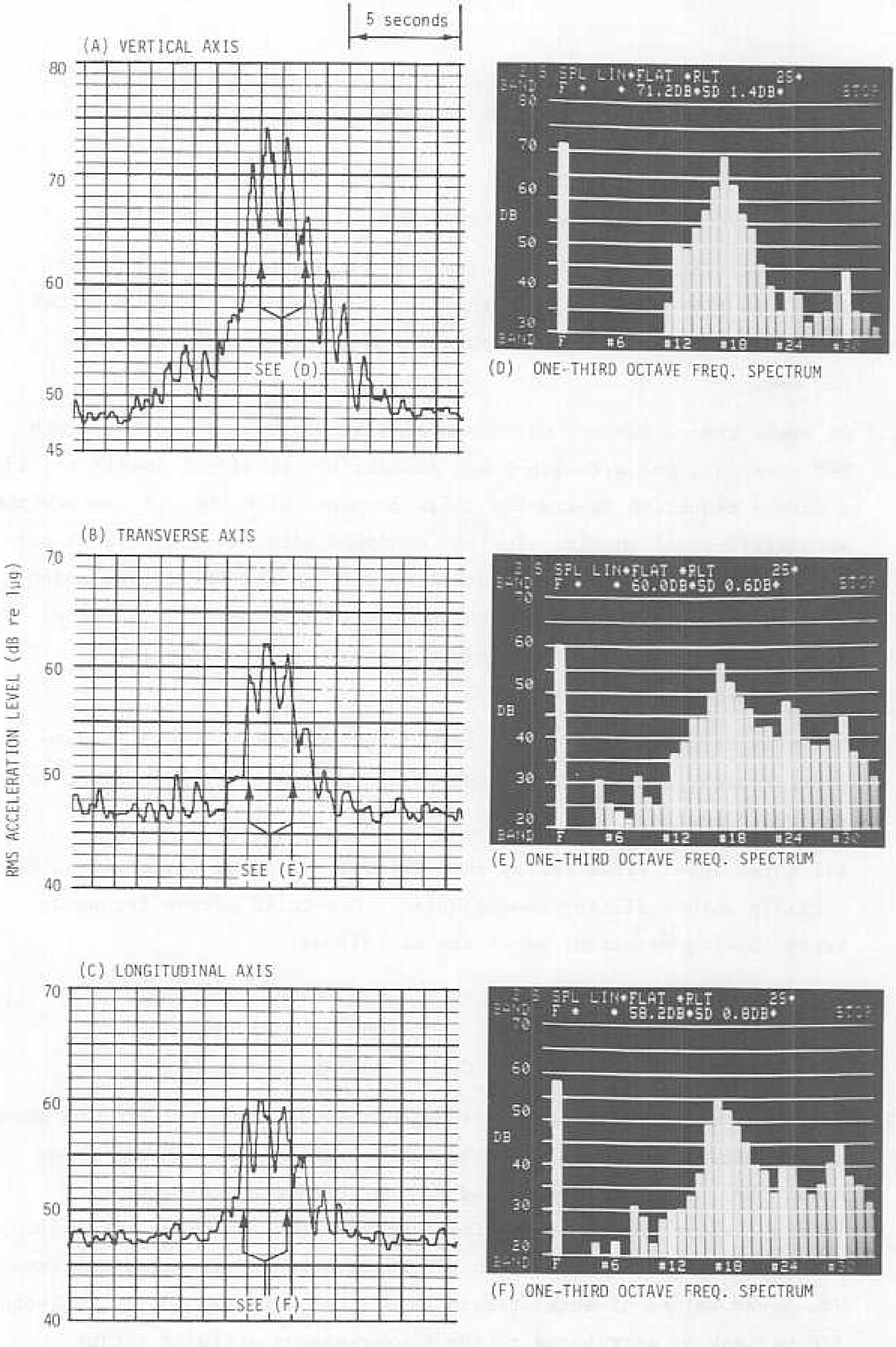


Figure 15. Ground-Borne Vibration Data with One-Third Octave Frequency Spectra - Huntington Avenue Run No. P8. PCC S/N 3270 w/Solid-Steel Wheels. Operating Speed: 24 mph

4.0 CONCLUSIONS

From the analysis of the measurements, the following is concluded:

1. High level intrusive in-car noise for the LRV equipped with Sab-V wheels is 1.5 to 3.8 dB less than for the Acoustaflex-equipped LRV, and approximately 10 dB less than for the solid-steel-equipped PCC car.

2. On small radius curves, where squeal noise is most prevalent, both LRV cars equipped with Sab-V and Acoustaflex resilient wheels provide a marked reduction in wayside noise compared with the PCC car equipped with solid-steel wheels. The LRV equipped with Sab-V wheels is marginally quieter than the Acoustaflex-equipped car (by approximately 1 dB) and much quieter than the solid steel-equipped PCC car (by approximately 14 dB), when maximum passby wayside noise levels are compared at the Lechmere loop.

3. On straight track, all wheels (resilient and solid steel) produce approximately equivalent wayside noise levels (after adjustment for speed differences).

4. All three wheel types tested show distinct spectral differences, especially when radiating squeal noise. One-third octave frequency bands showing prominent peaks are as follows:

Sab-V-equipped LRV	630 Hz, and 1600 Hz
Acoustaflex-equipped LRV	1600 Hz, and 4000 Hz
Solid-steel-equipped PCC Car	630 Hz, and 10 kHz

5. The Acoustaflex-equipped LRV produced ground-borne acceleration levels approximately 2 dB less than the Sab-V-equipped LRV, in all three axes. The solid-steel-equipped PCC car produced acceleration levels similar to the Acoustaflex-equipped LRV in the vertical axis, and approximately 3 dB less in the transverse and longitudinal axes. The lower values of acceleration associated with the solid-steel-equipped PCC car may be attributed to the slower speeds achieved during the test and to the lesser weight of the PCC car relative to the LRV's (40,000 and 67,000 pounds, respectively).

APPENDIX A

WHEEL TYPES AND MEASUREMENT LOCATIONS

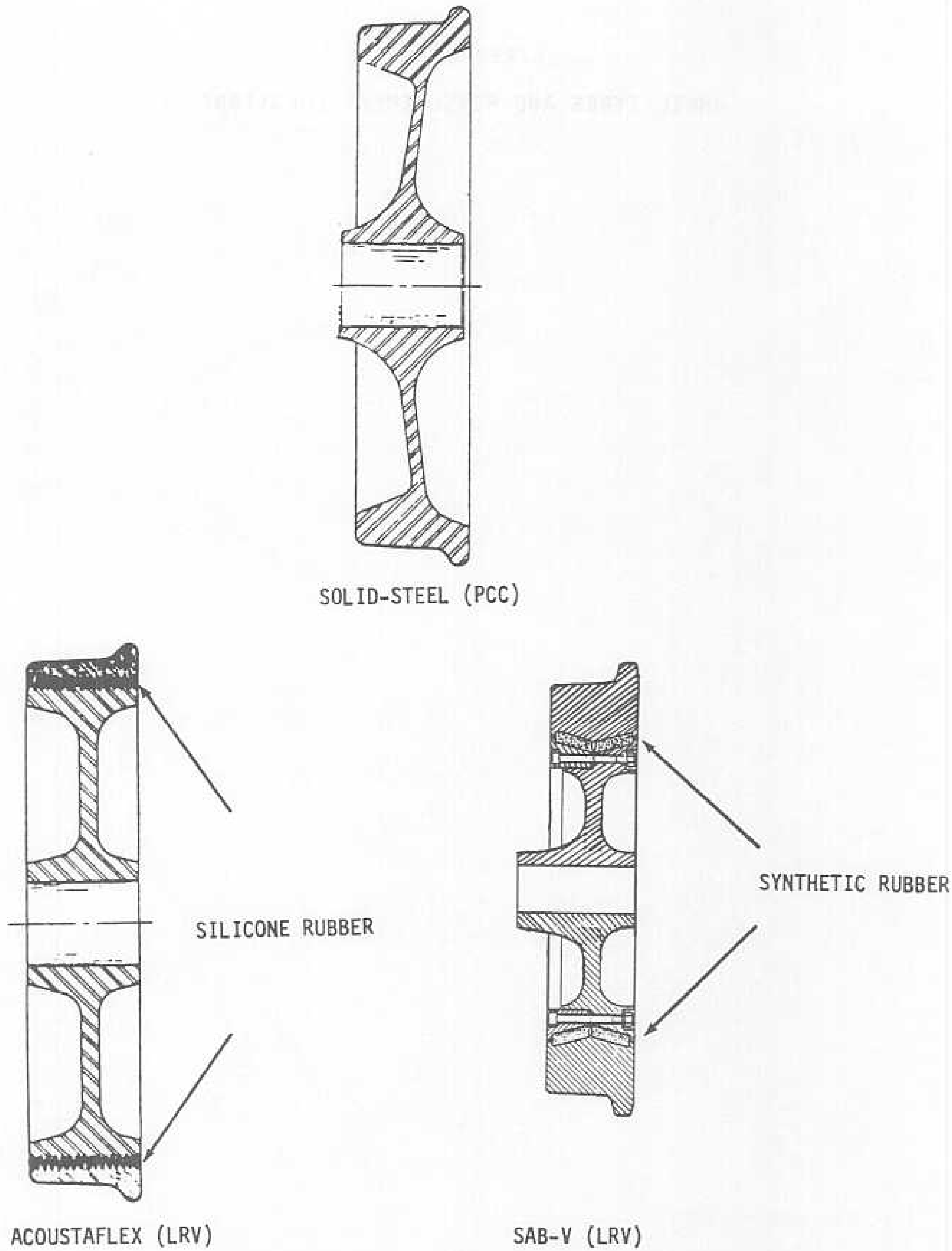
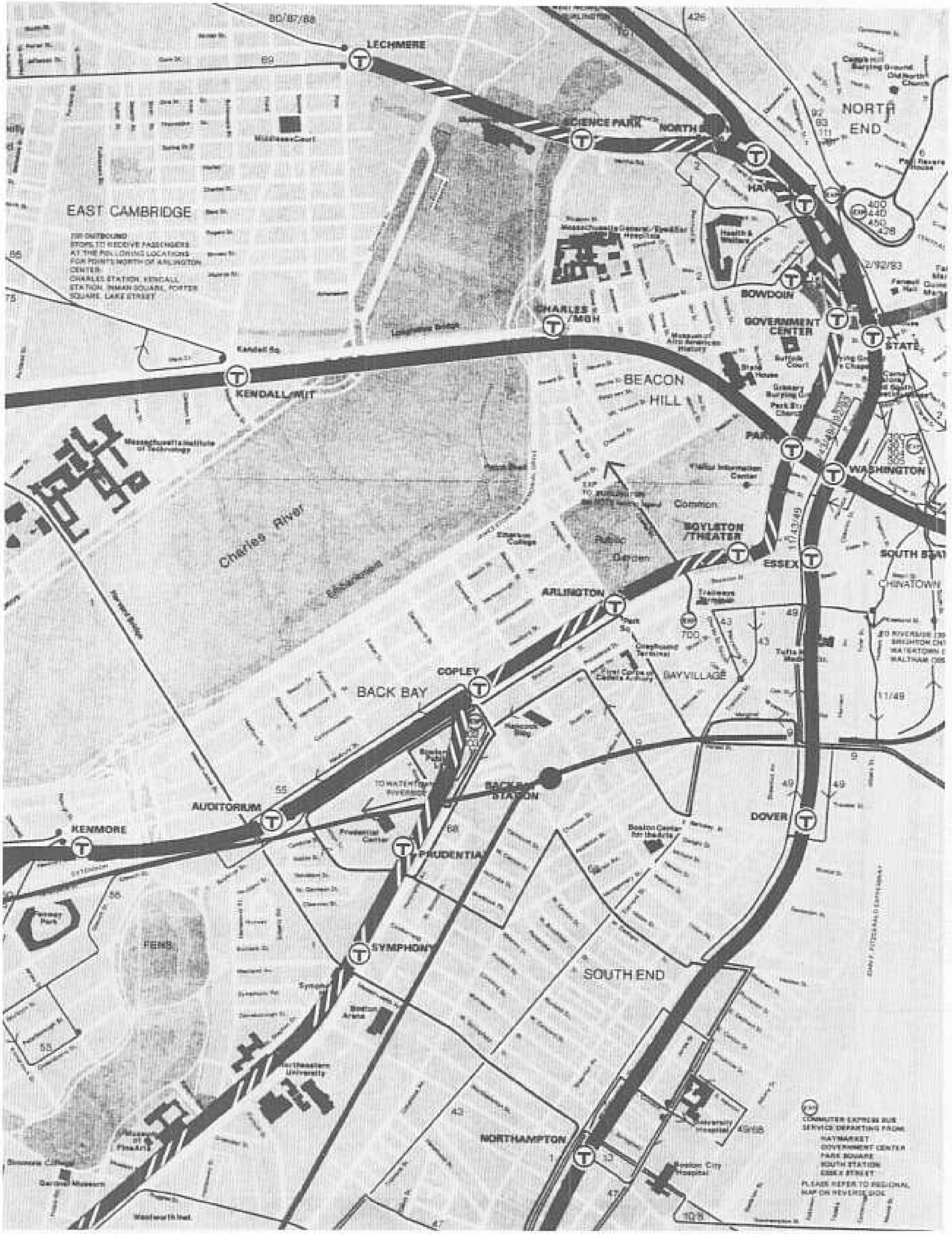
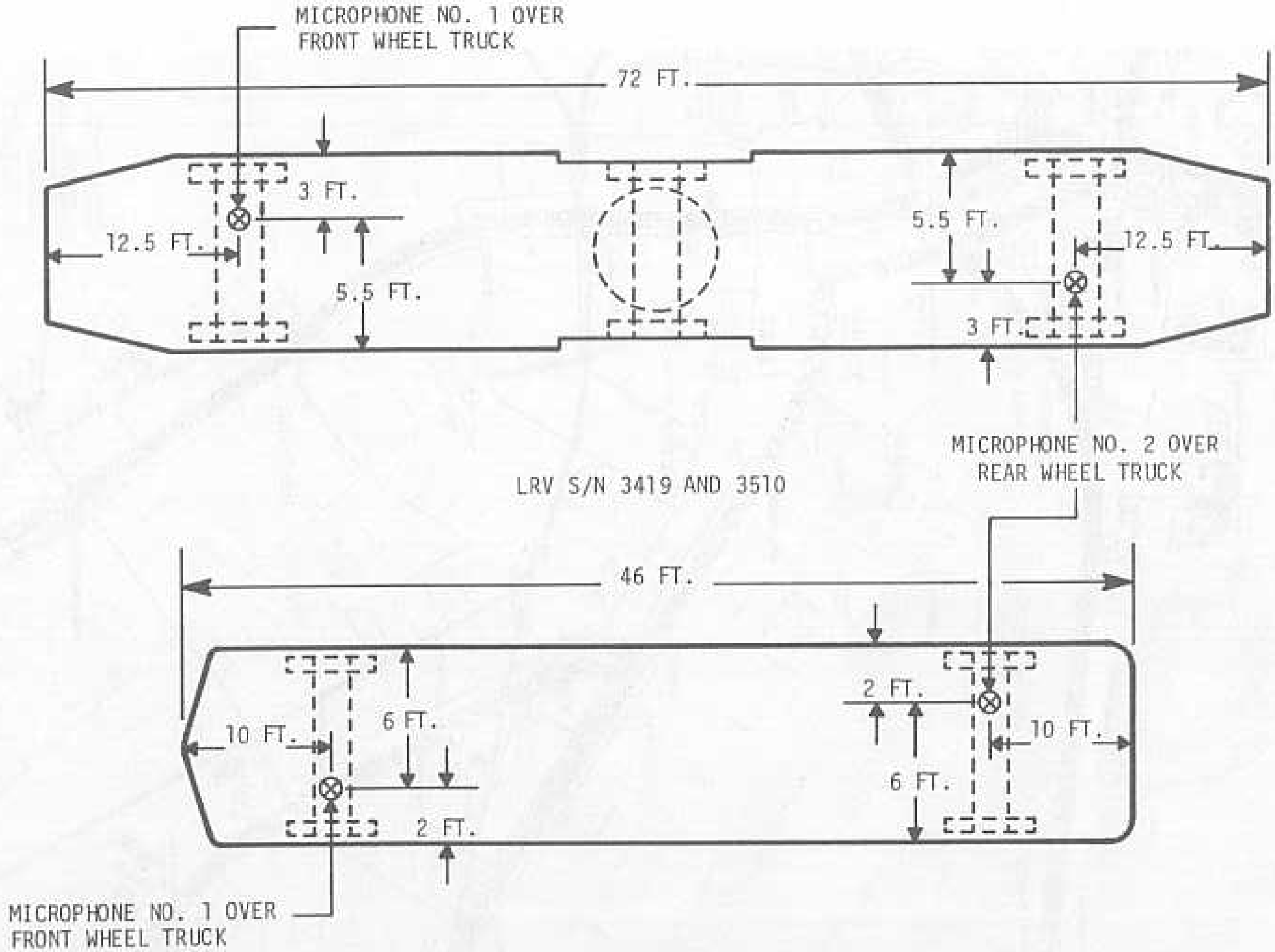


Figure A.1 Cross Sectional Diagram of the Three Wheel Types Used in Test



- Test Section of the MBTA Greenline

Figure A.2 Map of Test Section of MBTA Green Line



⊗ MICROPHONE LOCATED 4 FT. ABOVE THE FLOOR.

(NOT TO SCALE.)

Figure A.3 In-Car Microphone Locations

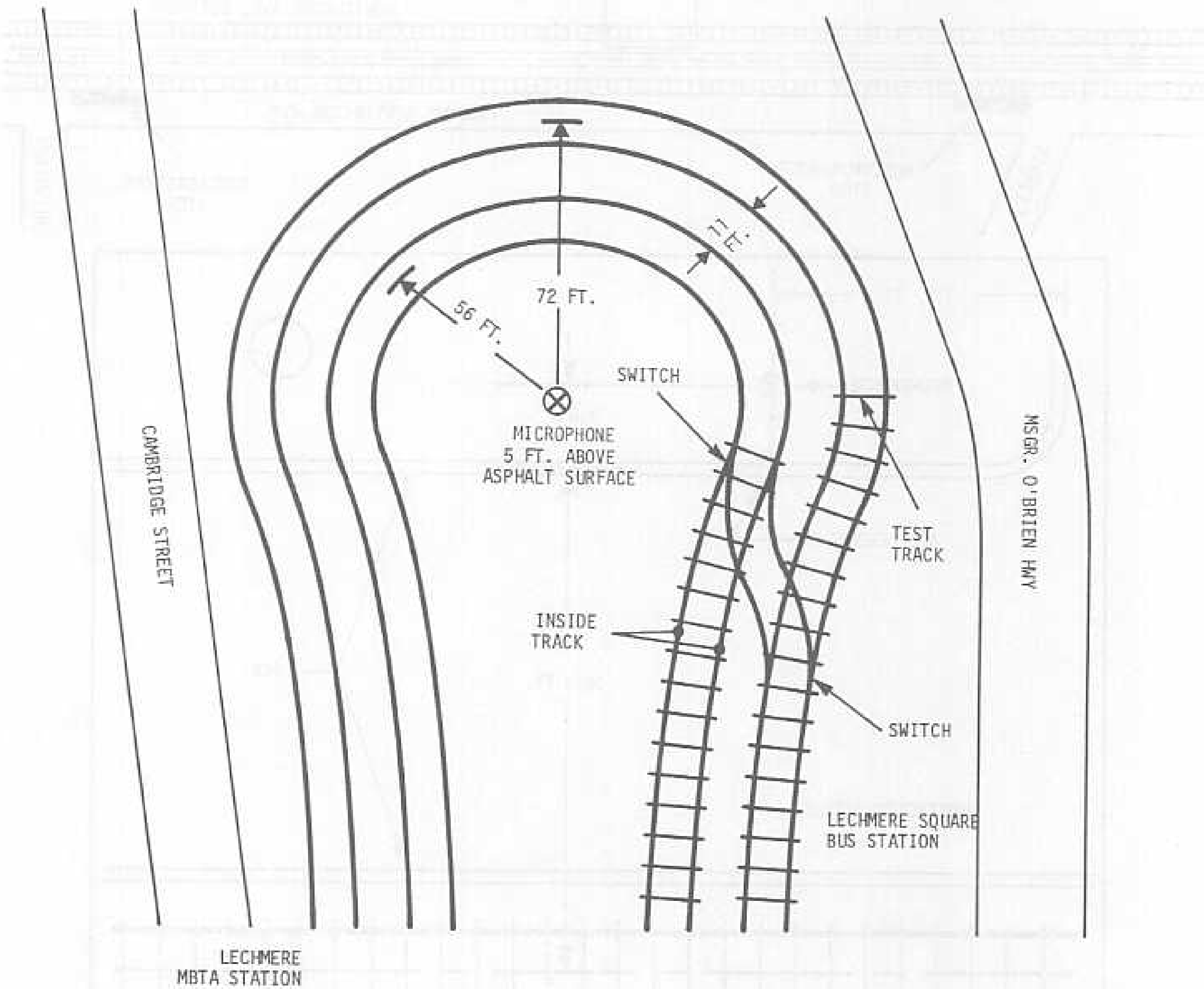


Figure A.4 Map of Lechmere Loop Measurement Site

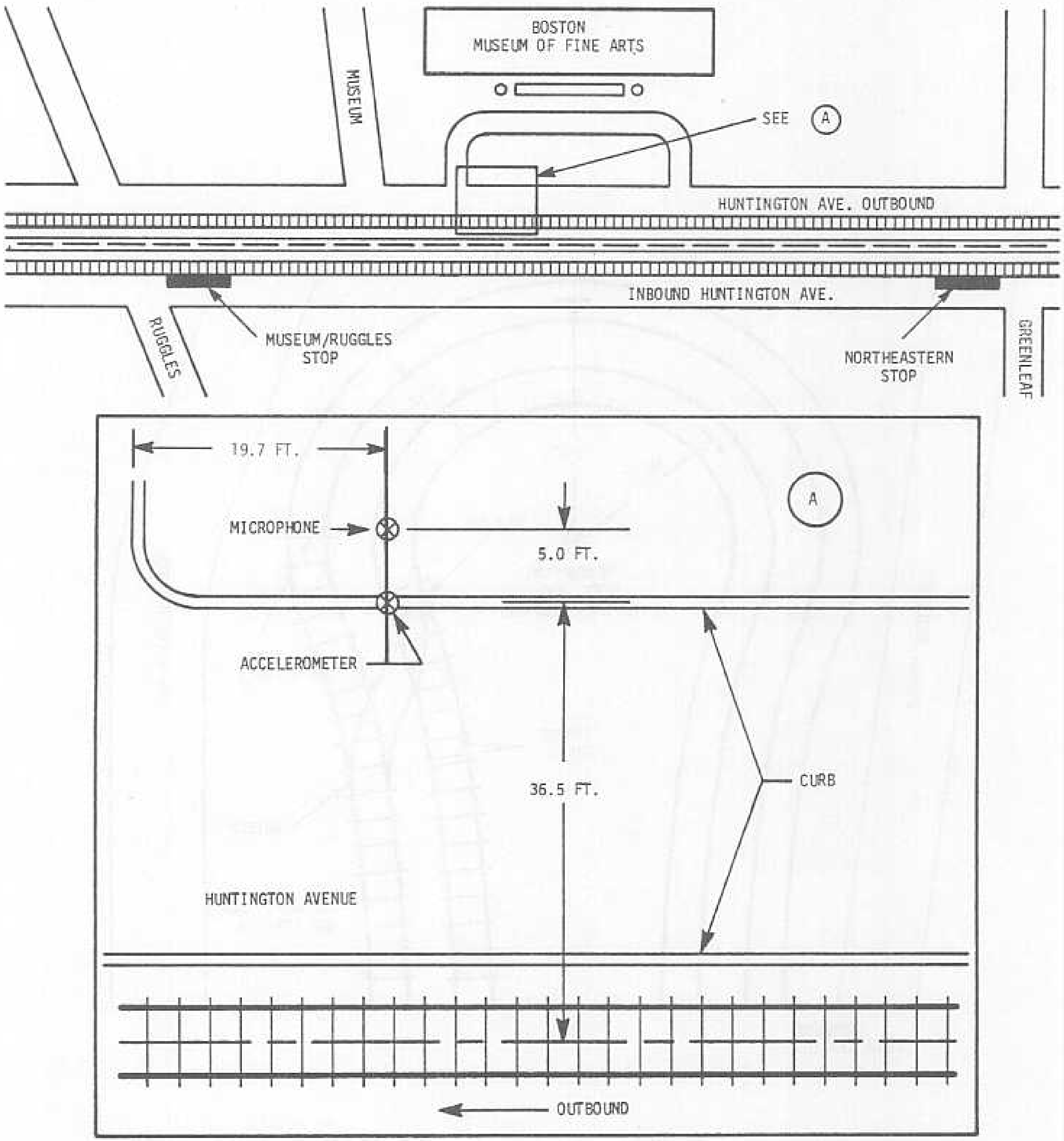


Figure A.5 Map of Huntington Avenue Measurement Site

APPENDIX B

NOISE AND VIBRATION MEASUREMENT AND DATA REDUCTION SYSTEMS

B.1 NOISE MEASUREMENT SYSTEM

Figure B.1 depicts the noise-data-gathering system used. The system frequency response was 15 Hz to 19 kHz.

A two-channel (two microphones) system was used in-car, with microphones placed in the passenger seating area at a height of four-feet above the floor, one over the front wheel truck, the other over the rear wheel truck.

Similar single-channel systems were used at the two wayside measuring sites where the microphones were placed at a height of five feet. See Figures A.3 to A.5 for exact microphone placement.

A calibration signal of 1000 Hz at a level of 114 dB re 20 microPascal was fed into the system and recorded on tape before and after each test series to provide a reference level for the data analysis instrumentation and to detect any system instability. A passive microphone simulator was substituted for the microphone to determine the minimum discernable signal (Noise Floor) of the system. This signal was also preserved on tape.

The cue track of the recorder was used for verbal annotations by the system operator. Pertinent remarks relative to train location and operational characteristics were annotated as well as time marks to be used to synchronize data between channels and recording systems, where applicable. In addition, speed information was read from the operator's console and the radar gun and annotated on cue track in synchronism with the measured noise data.

B.2 VIBRATION MEASUREMENT SYSTEM

Figure B.2 depicts the three-channel vibration-data-gathering system used. The system frequency response was 3 to 1250 Hz.

Three accelerometers were mounted on a one-inch brass cube in a triaxial arrangement, insulated from one another. The cube was attached to a curb-stone with epoxy adhesive to measure ground vibration levels in three axes. See Figure A.5 for exact accelerometer placement.

A dynamic calibration was performed on each accelerometer system in the laboratory using a 100 Hz, 1 g Vibration Calibrator. The dynamic calibration was subsequently transferred in the laboratory to an electrical calibration, using the electrical output of a microphone calibration and the insert voltage

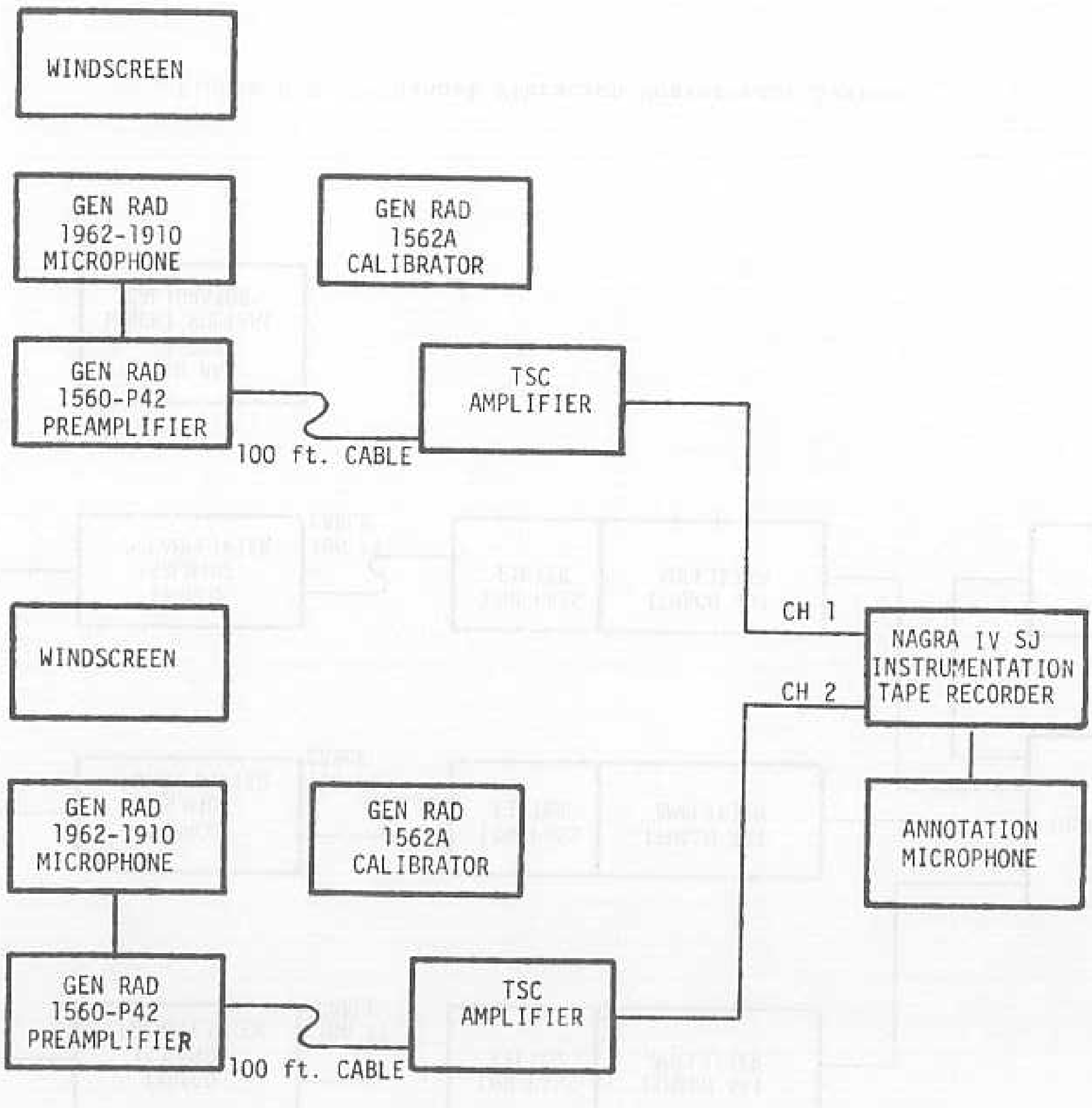


Figure B.1 2-Channel Acoustic Measurement System

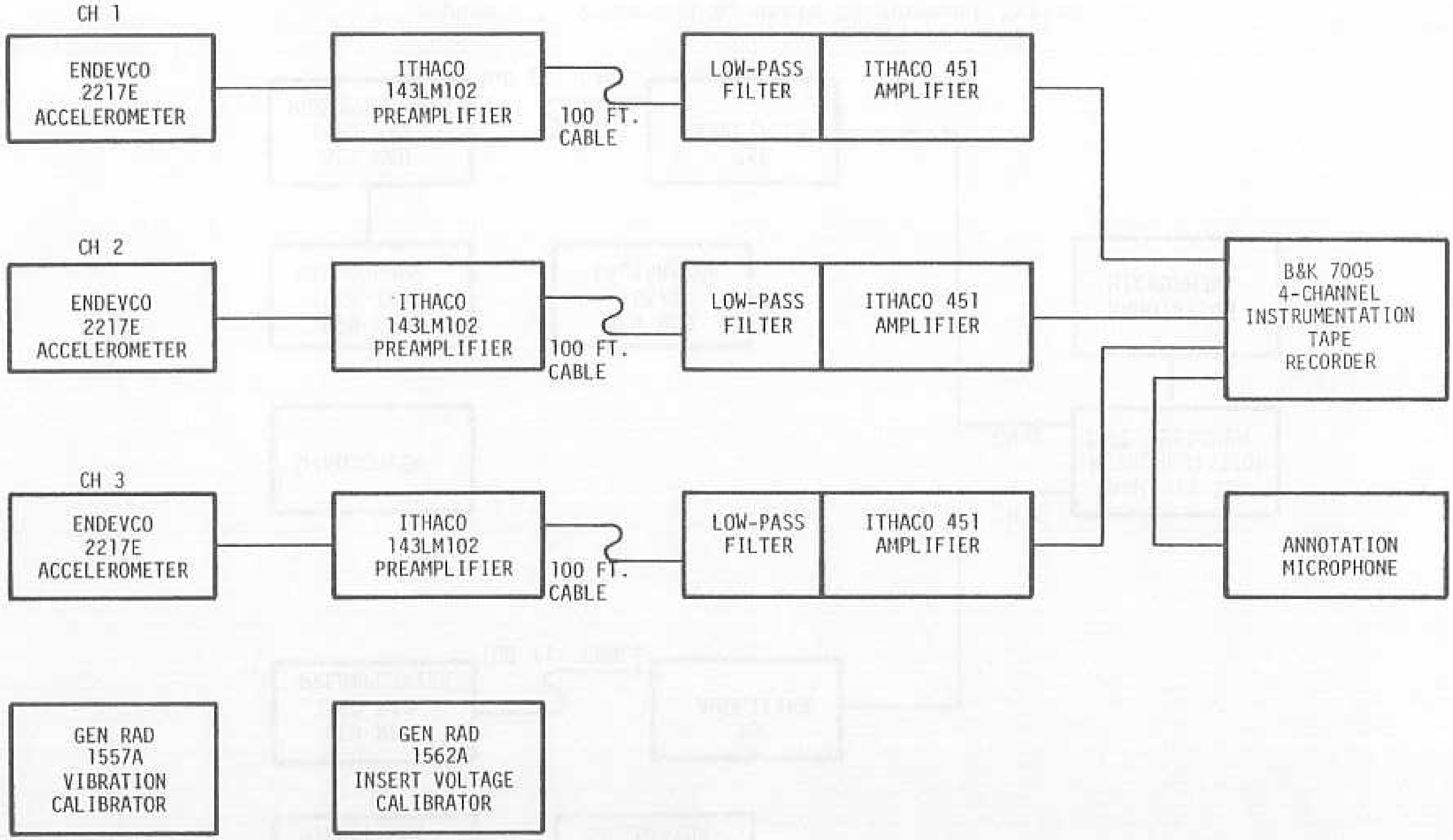


Figure B.2 3-Channel Vibration Measurement System technique. The insert calibration signal was fed into each system and recorded on tape before and after each test series to provide a reference level for the data analysis instrumentation and to detect any system instability. The accelerometer was replaced with a short-circuit to determine the minimum discernable signal (Noise Floor) for the measuring system. This signal was also preserved on tape.

A fourth channel of the recorder was used for voice annotations by the system operator. Pertinent remarks relative to operational parameters and observations were annotated, as well as time marks to synchronize the recorded vibration data with the noise data measuring systems.

B.3 NOISE AND VIBRATION DATA ANALYSIS

B.3.1 Noise Data Reduction

The configuration of the noise-data analysis system is shown in Figure B.3. The calibration signals and noise data are reproduced and fed simultaneously into the GEN RAD 1523 Graphic Level Recorder and into either the GEN RAD 1995 Real Time Analyzer or into the Nicolet Scientific Model O-FFT 400A Fast Fourier Transform Analysis System; necessary gain and full scale adjustments are made.

The Graphic Level Recorder adjusted for a writing speed to simulate "fast" sound level meter response (0.1 second averaging time) produced a chart of "A"-weighted noise level vs. time (time history) of the recorded data. Maximum noise levels were obtained from these recordings and tabulated.

Statistical information on continuous data (in-car noise data during simulated revenue runs over a 14-15 minute period) were obtained by programming the GEN RAD 1995 Real Time Analyser to linearly average the data in 1/8-second increments. The digitized "A"-weighted levels computed by the 1995 were fed, eight per second, to the Data General Nova 2 computer which sorted and counted the number of samples at each noise level. At the end of the prescribed analysis time (14-15 minutes), the statistical data, in the form of exceedence levels (noise levels exceeded n percent of the time, L_n), were provided by the computer.

Special selected events were analyzed in detail for their one-third octave-band and narrow-band frequency spectra. The data selected for analysis are

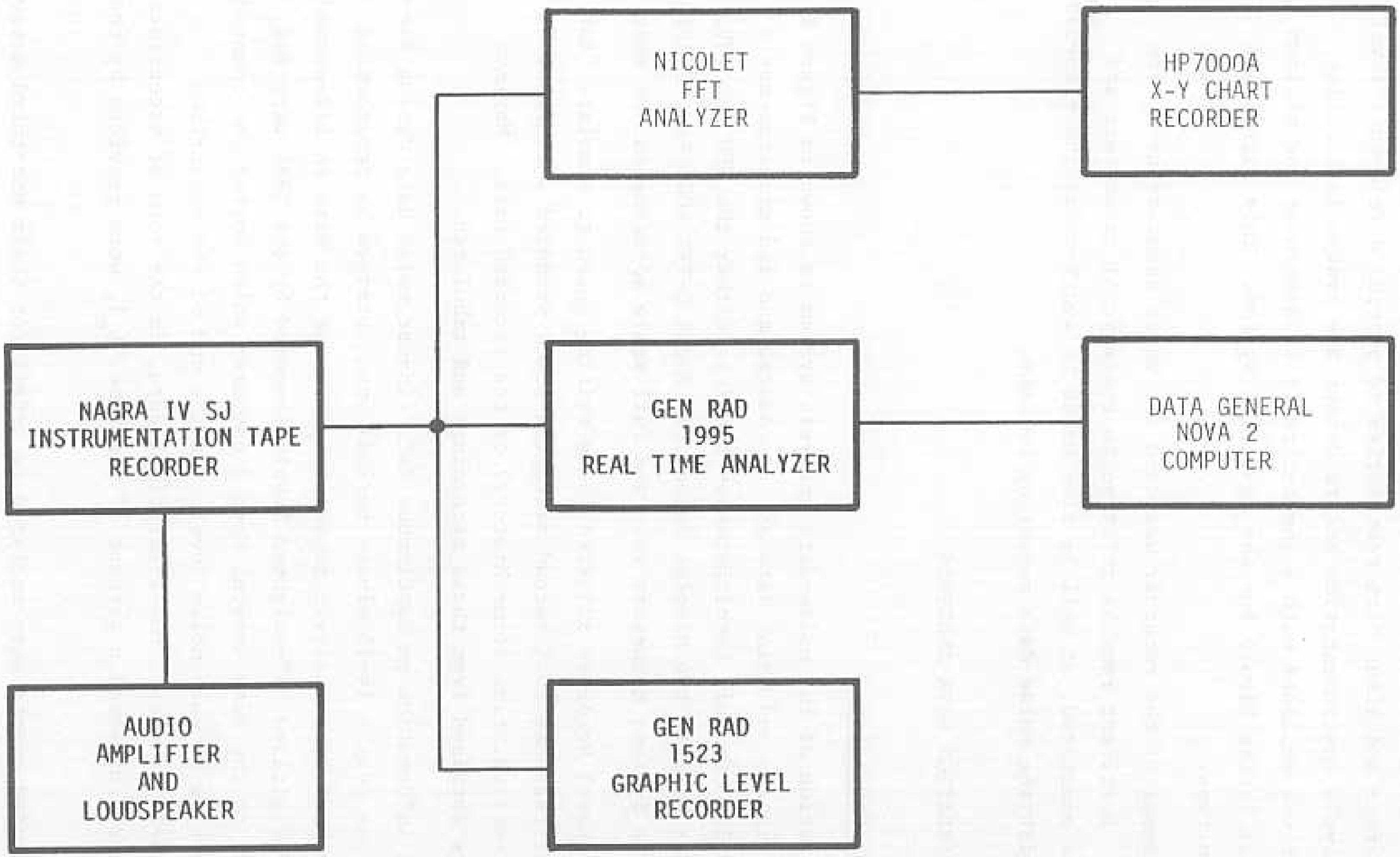


Figure B.3 Acoustic Analysis System

identified on the graphic level histories presented. The GEN RAD 1995 was programmed to linearly average the data over a four-second time period around the specific occurrence identified and display on its video monitor in graphical format the noise levels as a function of one-third octave frequency bands (25 Hz to 20 kHz). Reproductions of the spectral display are provided in this report.

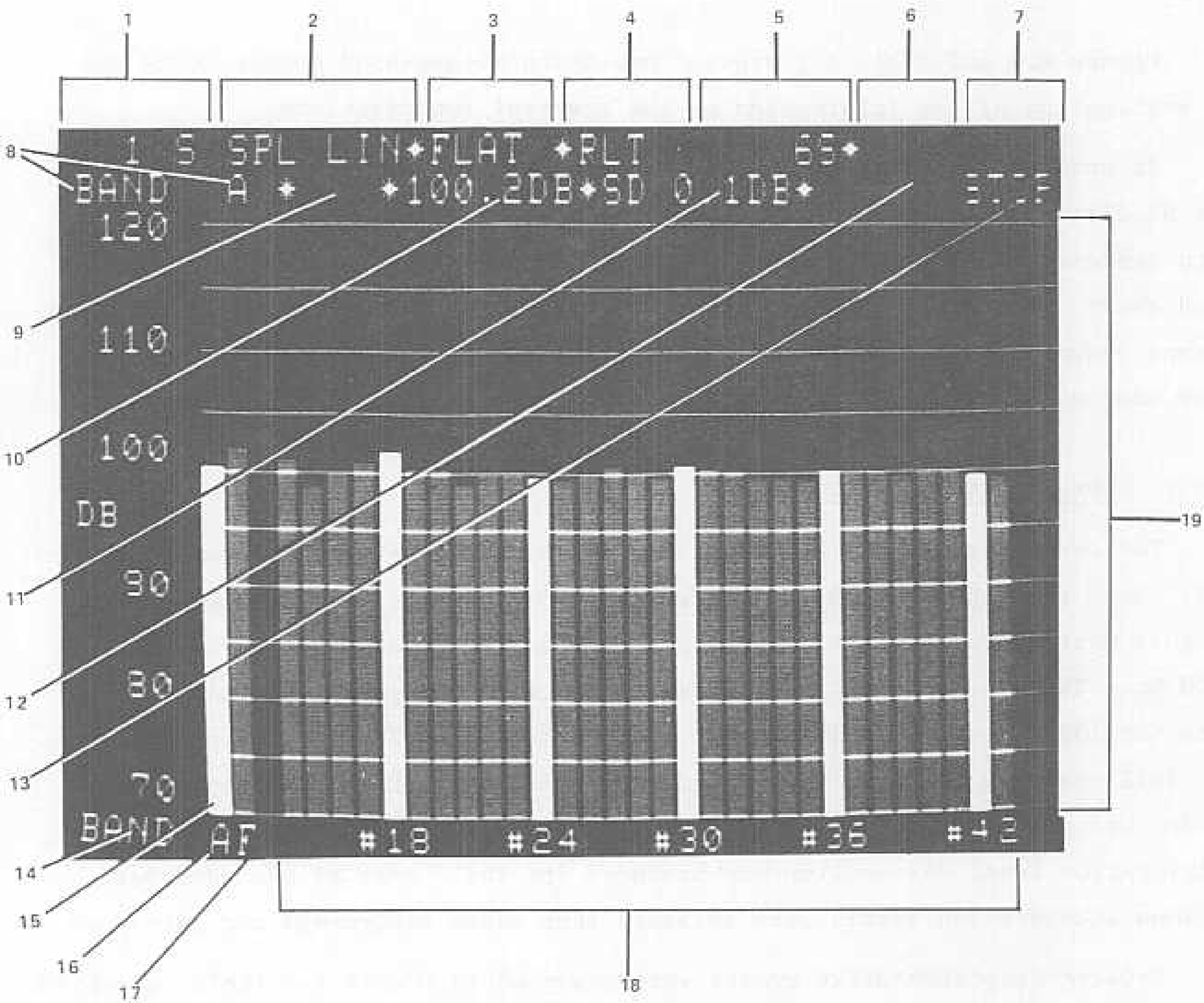
Figure B.4 and Table B.1 present one-third octave-band number codes and an explanation of the information on the spectral reproductions.

In order to show the fine details of the noise spectra for these events, the Nicolet 400A was programmed to analyze a one-half second period of noise data centered around the maximum level within the four-second period identified above. The rms noise level data vs. frequency are presented over the frequency range of 0.4 to 20 kHz and in expanded format (40 to 2000 Hz) on the same single page.

B.3.2 Vibration Data Reduction

The configuration of the vibration data analysis system is shown in Figure B.5. Note that the GEN RAD 1995 described above was utilized in the same way in this system, except that one-third octave analysis covered the range 2.5 to 2000 Hz. The vibration data and insert vibration calibration signal were fed into the 1523 Graphic Level Recorder and the 1995 Real Time Analyzer, and gain and full scale adjustments were made. The writing speed of the graphic recorder was set moderately fast (0.1 second averaging time) and a chart of RMS acceleration level versus time was produced for the 3 axes of recorded data. Maximum acceleration levels were obtained from these recordings and tabulated.

Selected representative events were analyzed in detail for their one-third octave frequency spectra. The data selected for analysis were for a two-second period around the peak acceleration levels which occurred during the passby of the test vehicle. The same period was selected for all three data channels. The GEN RAD 1995 was programmed to linearly average the data over the 2-second time period and display on its video monitor in graphical format the acceleration level versus one-third octave frequency bands (2.5 to 2000 Hz). Reproductions of the spectral display are presented in this report (see explanation of information on spectral reproductions in Figure B.4 and Table B.1).



(See Table B.1 for description of Ref. Numbers)

Figure B.4 Display and Status Information

TABLE B.1 DISPLAY AND STATUS INFORMATION

Fig. B.4 Ref.	Description	Specific Fig. B.4 Reading
1	Integration time	4S
2	Integration mode	SPL LIN
3	Frequency response	FLAT
4	Spectrum status	RLT
5	Elapsed time	4S
6	OVLD (overload indication)	–
7	BATT (low-battery indication)	–
8	Band selected by cursor when in level/freq mode	BAND A
9	Period selected by cursor when in level/time mode	–
10	Level of band occupied by cursor	100.2DB
11	Standard deviation of band occupied by cursor	SD 0.1DB
12	NOTE 1 through NOTE 8 (special notes flagged)	–
13	Operating status	STOP
14	"BAND" in level/freq mode or "PERIOD" in level/time mode	BAND
15	Intensified bar indicating cursor position	BAND A
16	Bar graph representing A-preweighted results when in level/freq mode	A
17	Bar graph representing flat-response results when in level/freq mode	F
18	Band identities of bar graphs when in level/freq mode, or period identities of bar graphs when in level/time mode	BANDS 14 through 43
19	Displayed 50-dB range, determined by preselected FULL SCALE-dB pushbutton	70 to 120 dB

BAND NUMBER VERSUS 1/3-OCTAVE CENTER FREQUENCIES

(Low-Frequency Option)

Band Number	Center Frequency (Hz)	Band Number	Center Frequency (Hz)	Band Number	Center Frequency (Hz)	Band Number	Center Frequency (kHz)
4	2.5	14	25	*24	250	34	2.5
5	3.15	*15	31.5	25	315	35	3.15
*6	4	16	40	26	400	*36	4
7	5	17	50	*27	500	37	5
8	6.3	*18	63	28	630	38	6.3
*9	8	19	80	29	800	*39	8
10	10	20	100	*30	1000	40	10
11	12.5	*21	125	31	1250	41	12.5
*12	16	22	160	32	1600	*42	16
13	20	23	200	*33	2000	43	20

*Denotes full-octave band and center frequency.

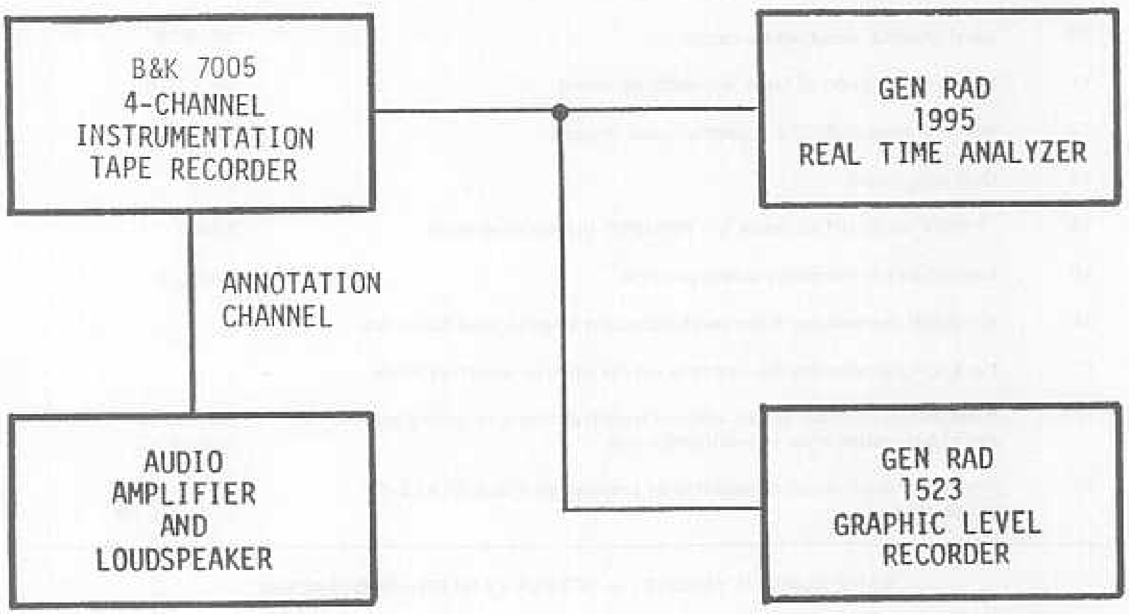


Figure B.5 Vibration Analysis System

APPENDIX C

NARROW BAND FREQUENCY SPECTRA

This appendix contains detailed narrow band frequency spectra for most of the events in which one-third octave frequency spectra were obtained in Section 3.3. A one-half second period of noise data was analyzed as identified in the graphic time-history plots of Section 3.3. The noise level vs. frequency data are provided over the frequency range 0.4 to 20 kHz and in expanded format (40 to 2000 Hz) in Figures C.1 through C.6.

SEE FIGURE 1(B), POINT (A), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

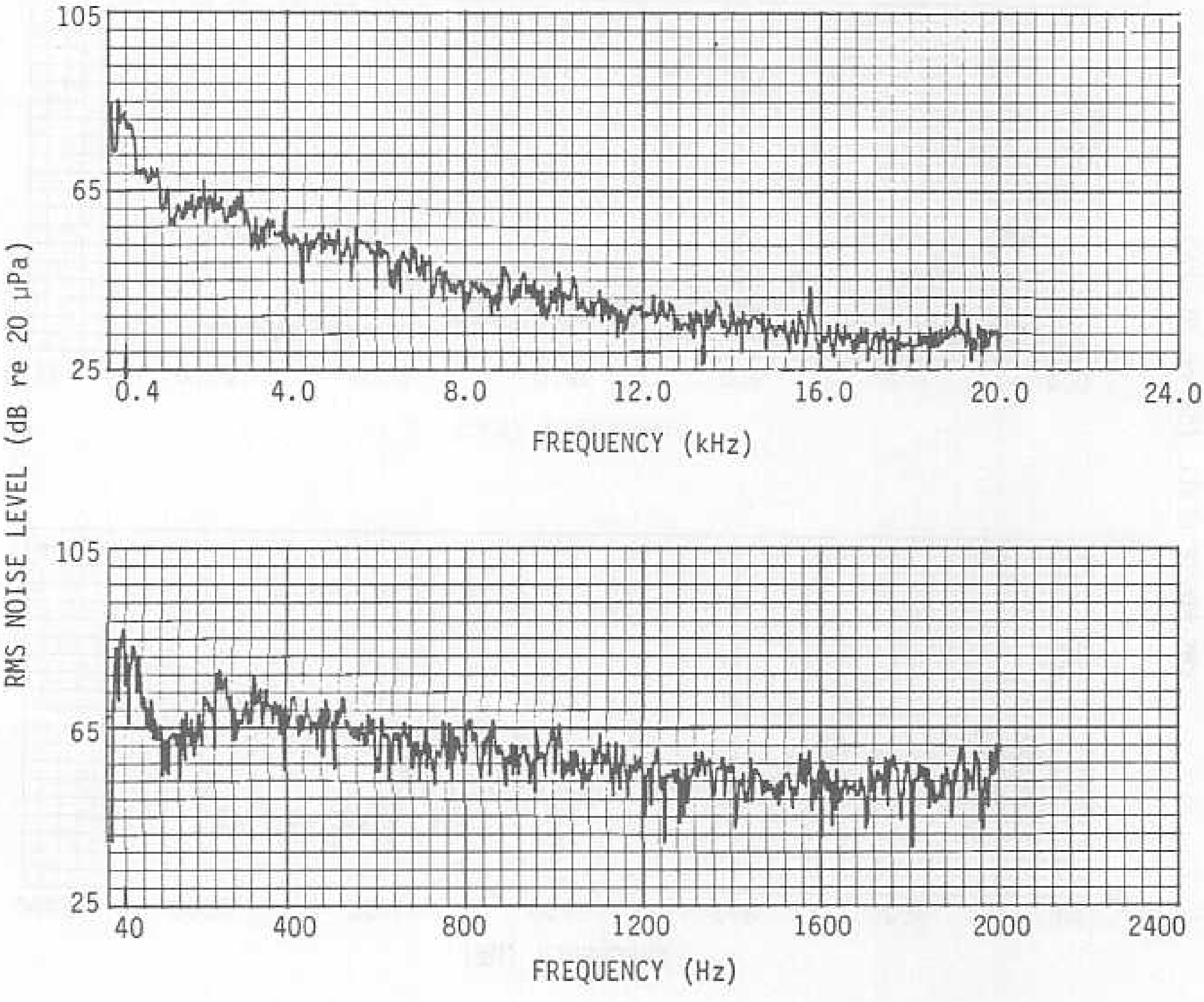


Figure C.1(a) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3510 w/Sab-V Wheels

SEE FIGURE 1(B), POINT (B), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

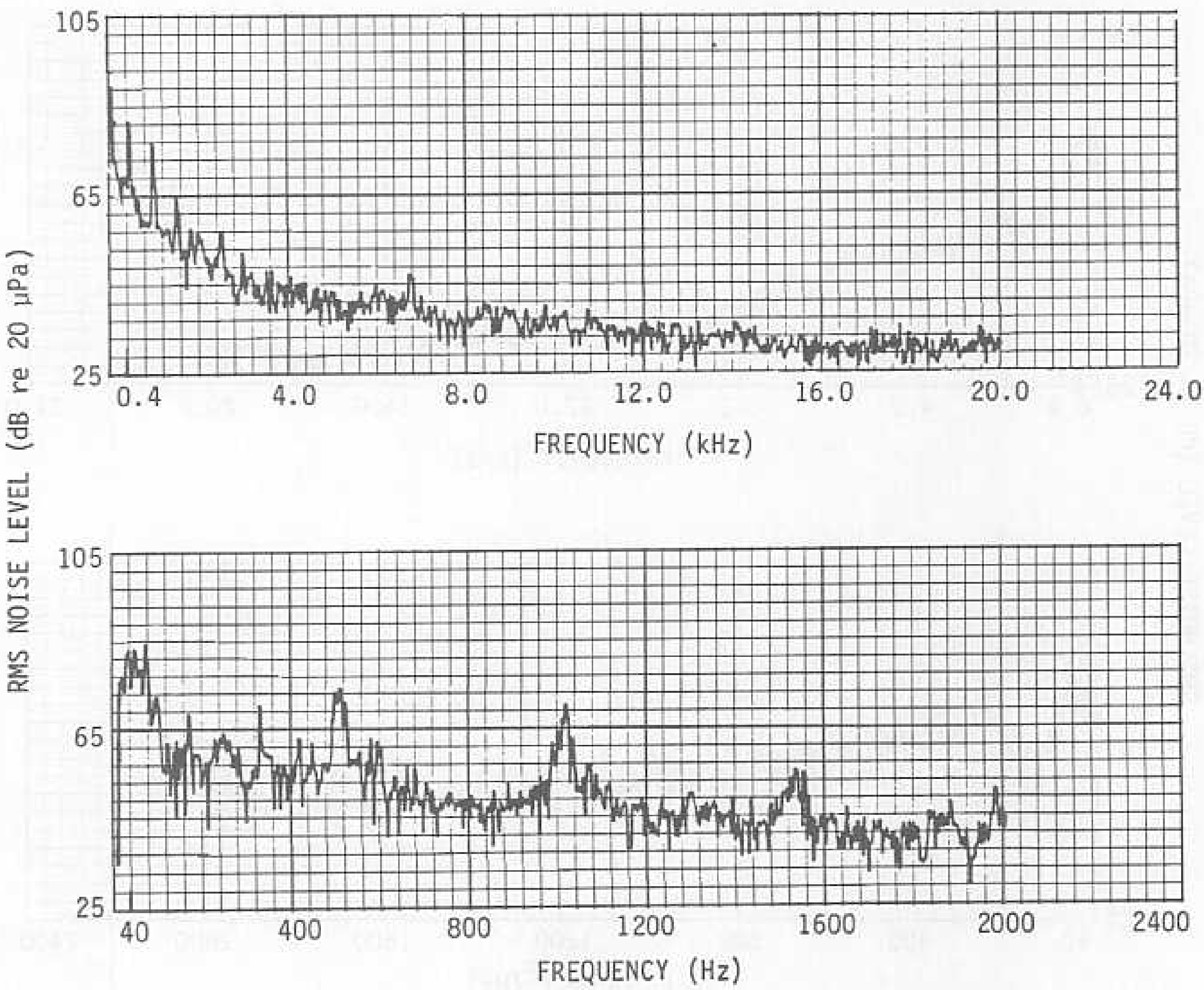


Figure C.1(b) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3510 w/Sab-V Wheels

SEE FIGURE 1(B), POINT (C), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

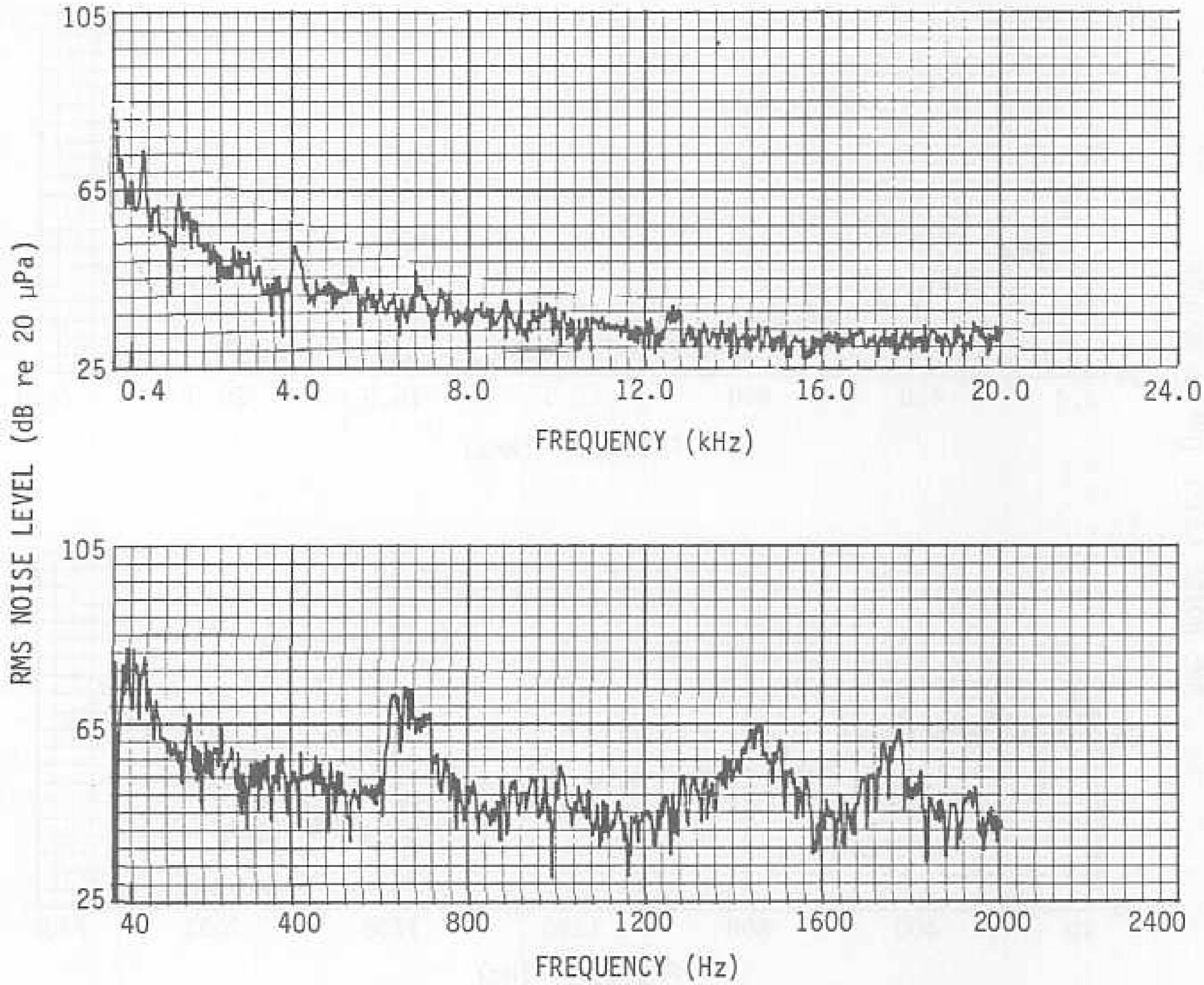


Figure C.1(c) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3510 w/Sab-V Wheels

SEE FIGURE 1(B), POINT (D), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

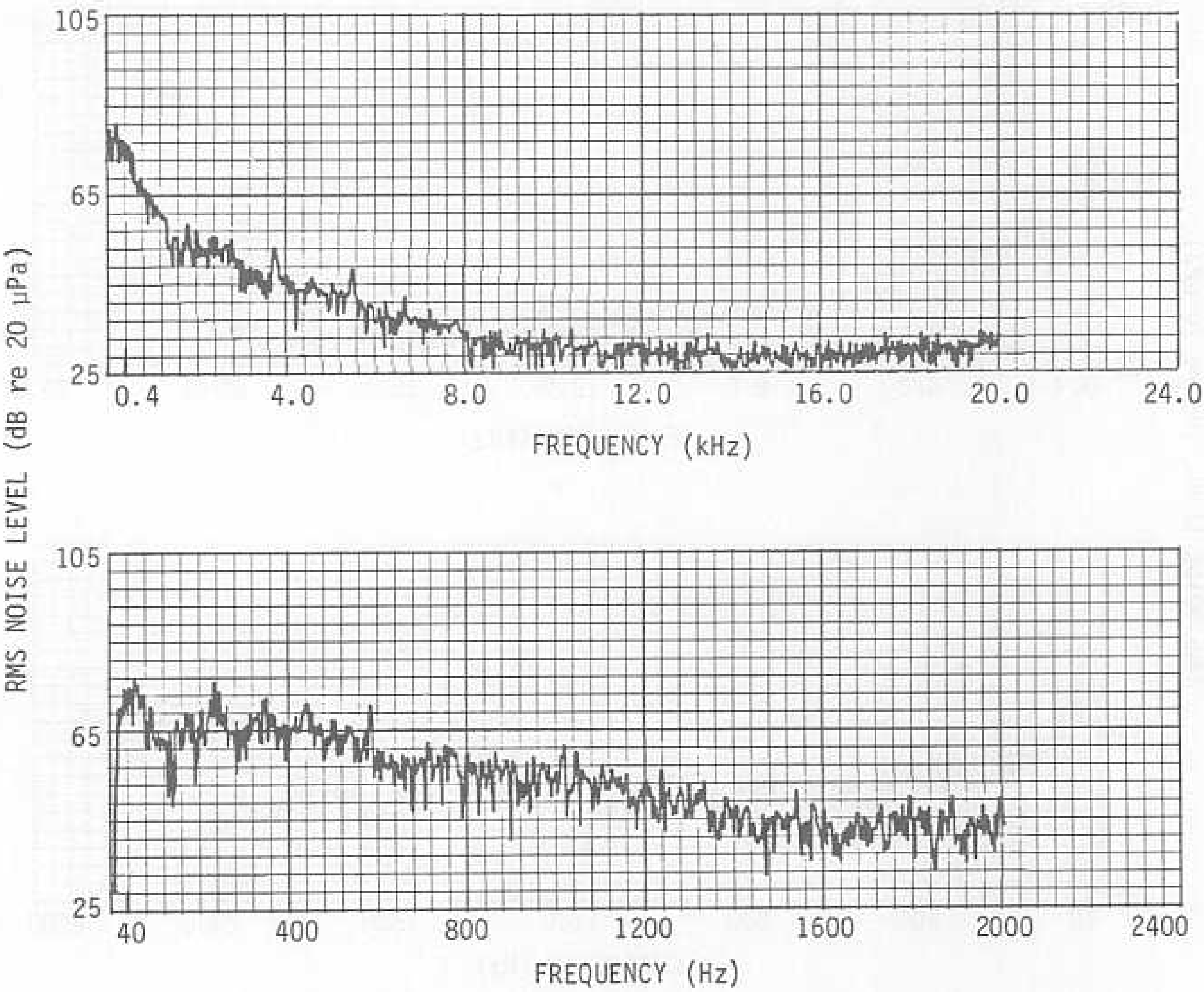


Figure C.1(d) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3510 w/Sab-V Wheels

SEE FIGURE 2(B), POINT (A), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

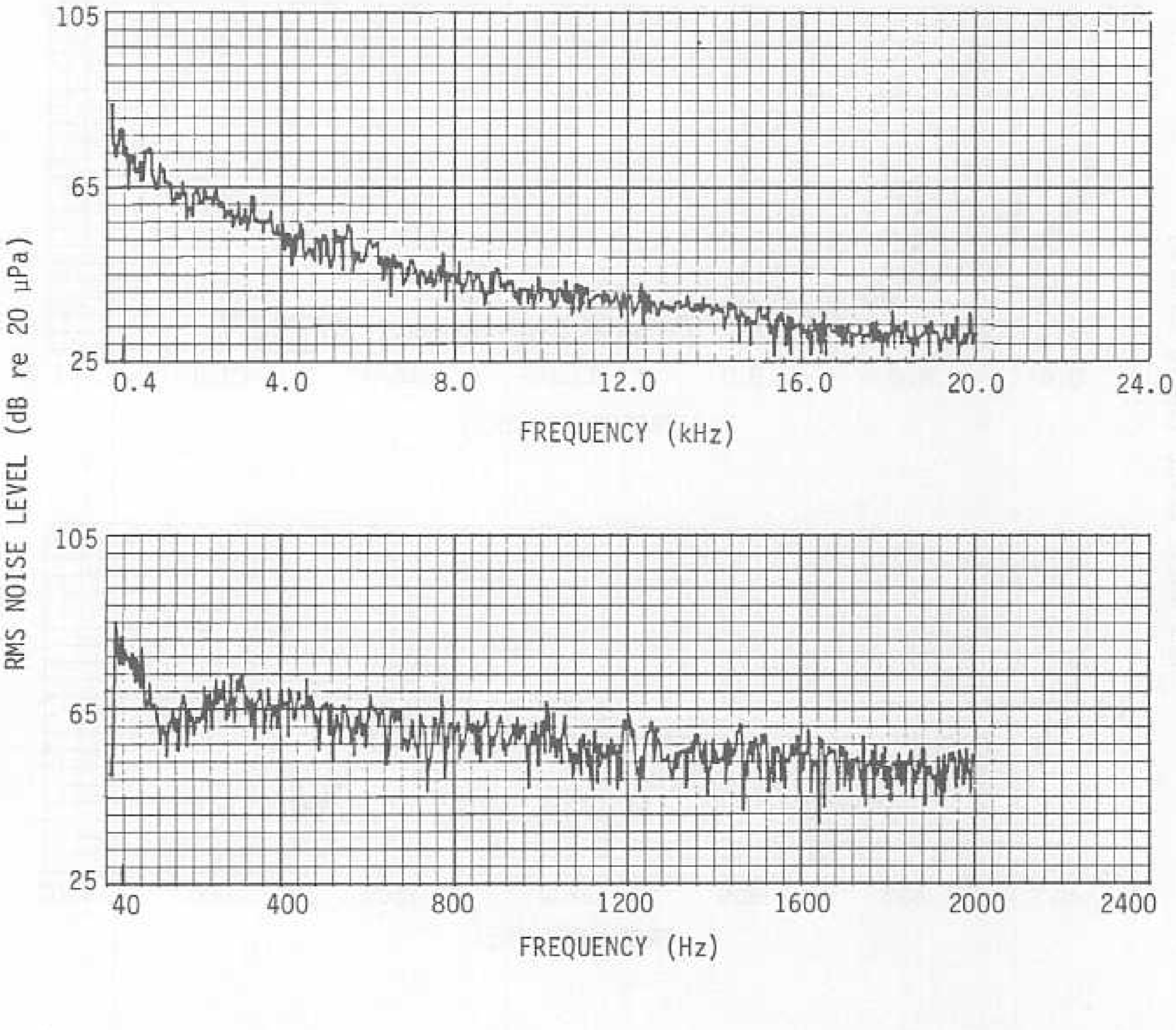


Figure C.2(a) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3419 w/Acoustaflex Wheels

SEE FIGURE 2(B), POINT (B), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

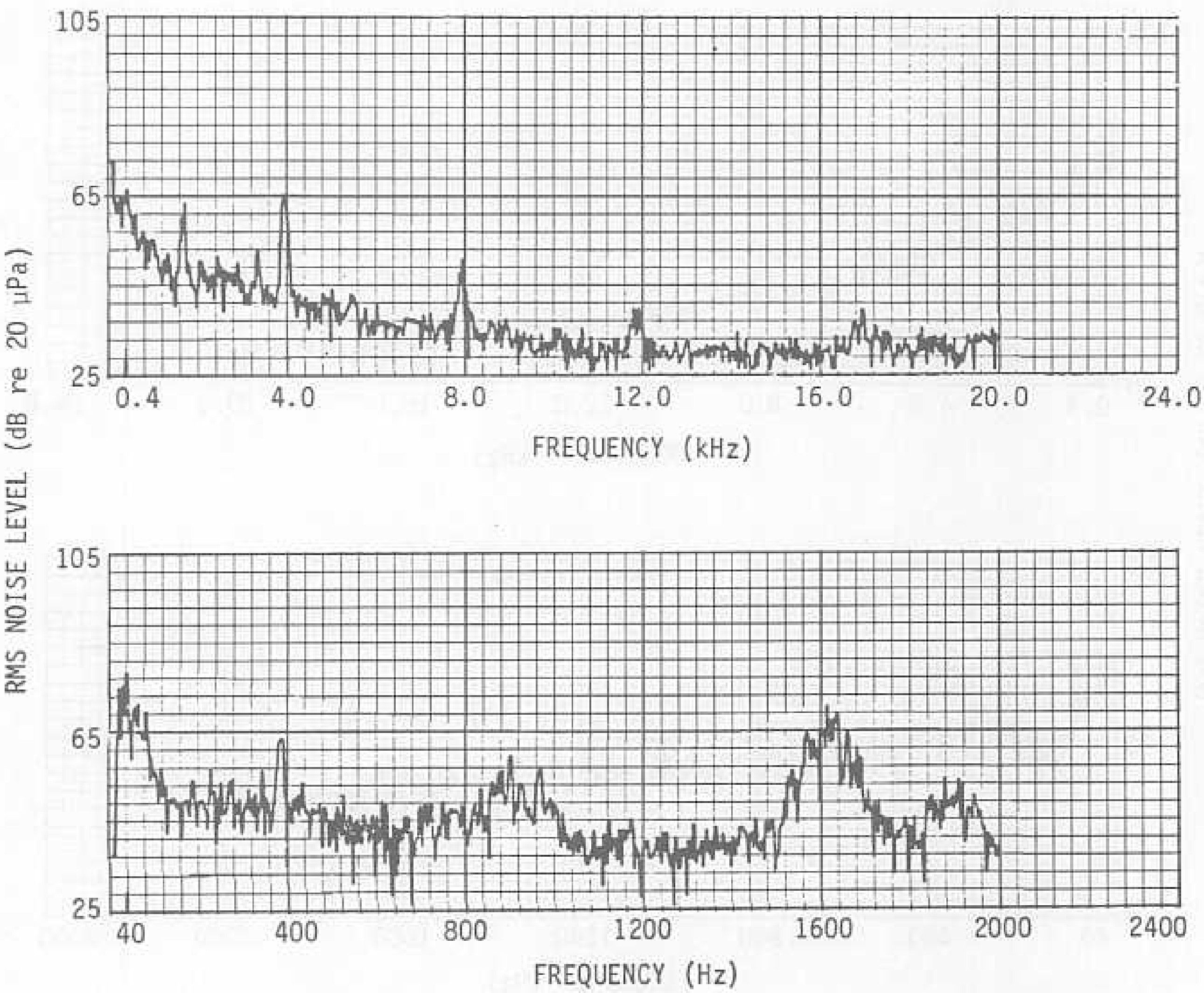


Figure C.2(b) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3419 w/Acoustaflex Wheels

SEE FIGURE 2(B), POINT (C), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

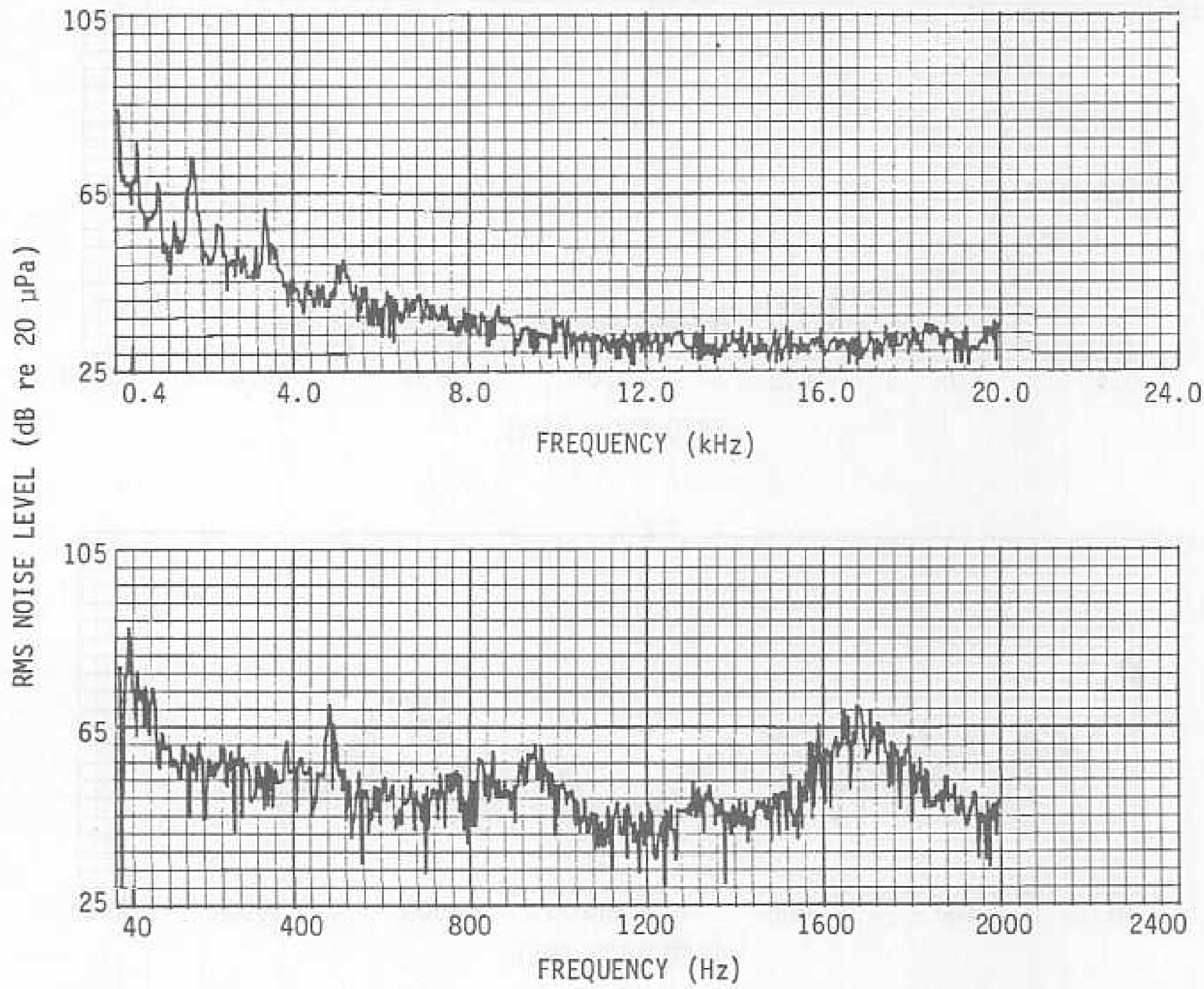


Figure C.2(c) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3419 w/Acoustaflex Wheels

SEE FIGURE 2(B), POINT (D), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

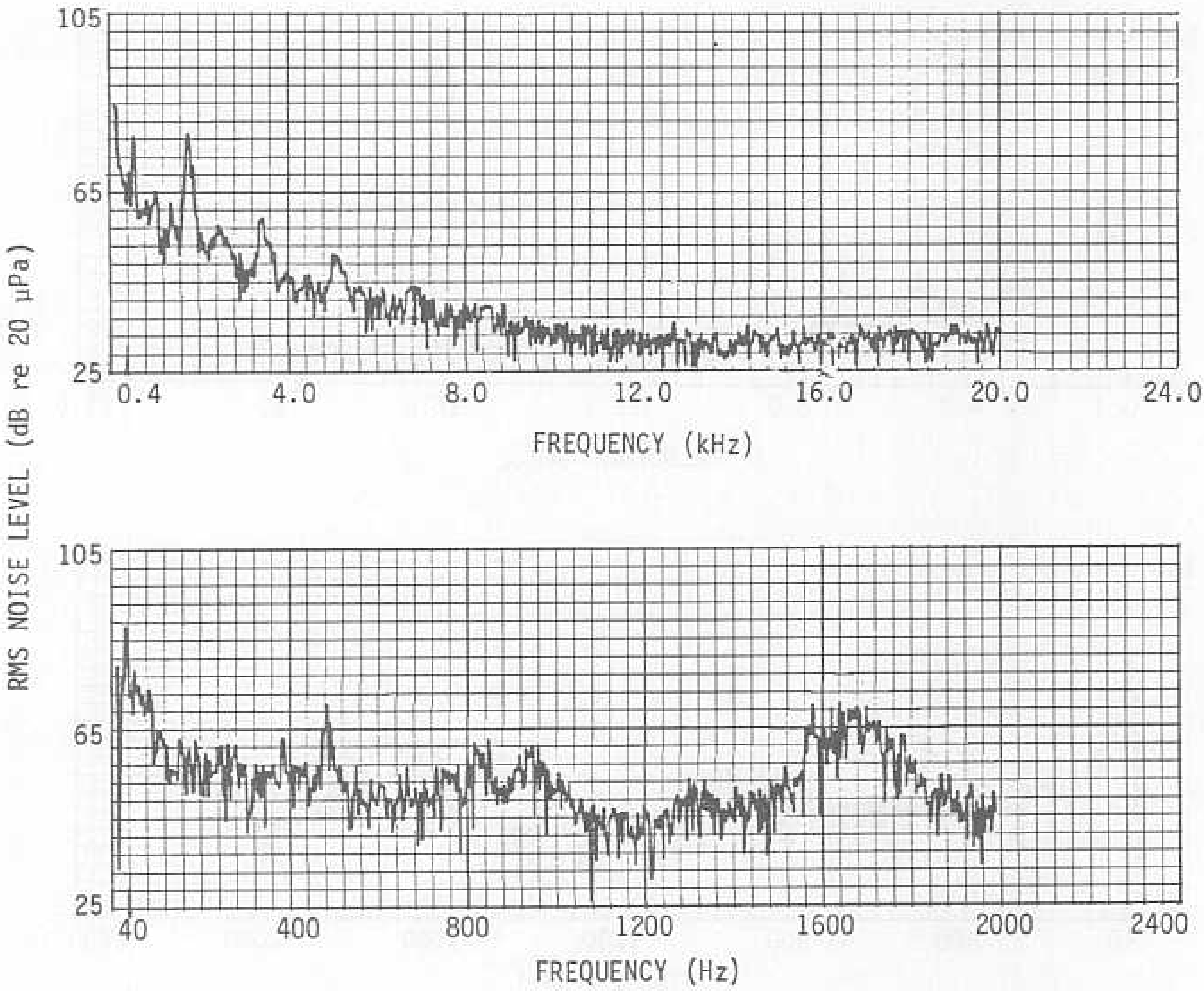


Figure C.2(d) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). LRV S/N 3419 w/Acoustaflex Wheels

SEE FIGURE 3(B), POINT (A), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

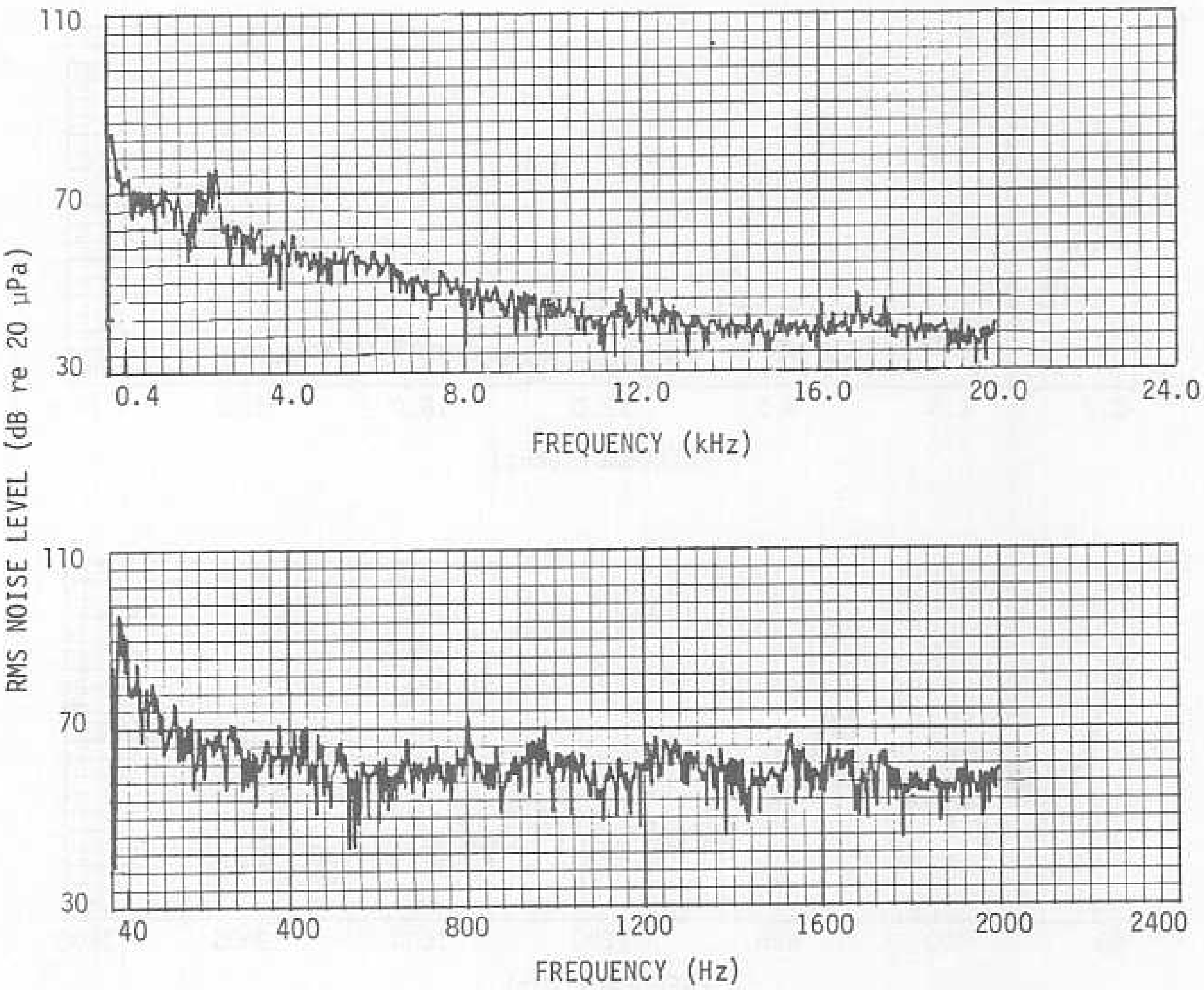


Figure C.3(a) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). PCC S/N 3270 w/Solid-Steel Wheels

SEE FIGURE 3(B), POINT (B), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

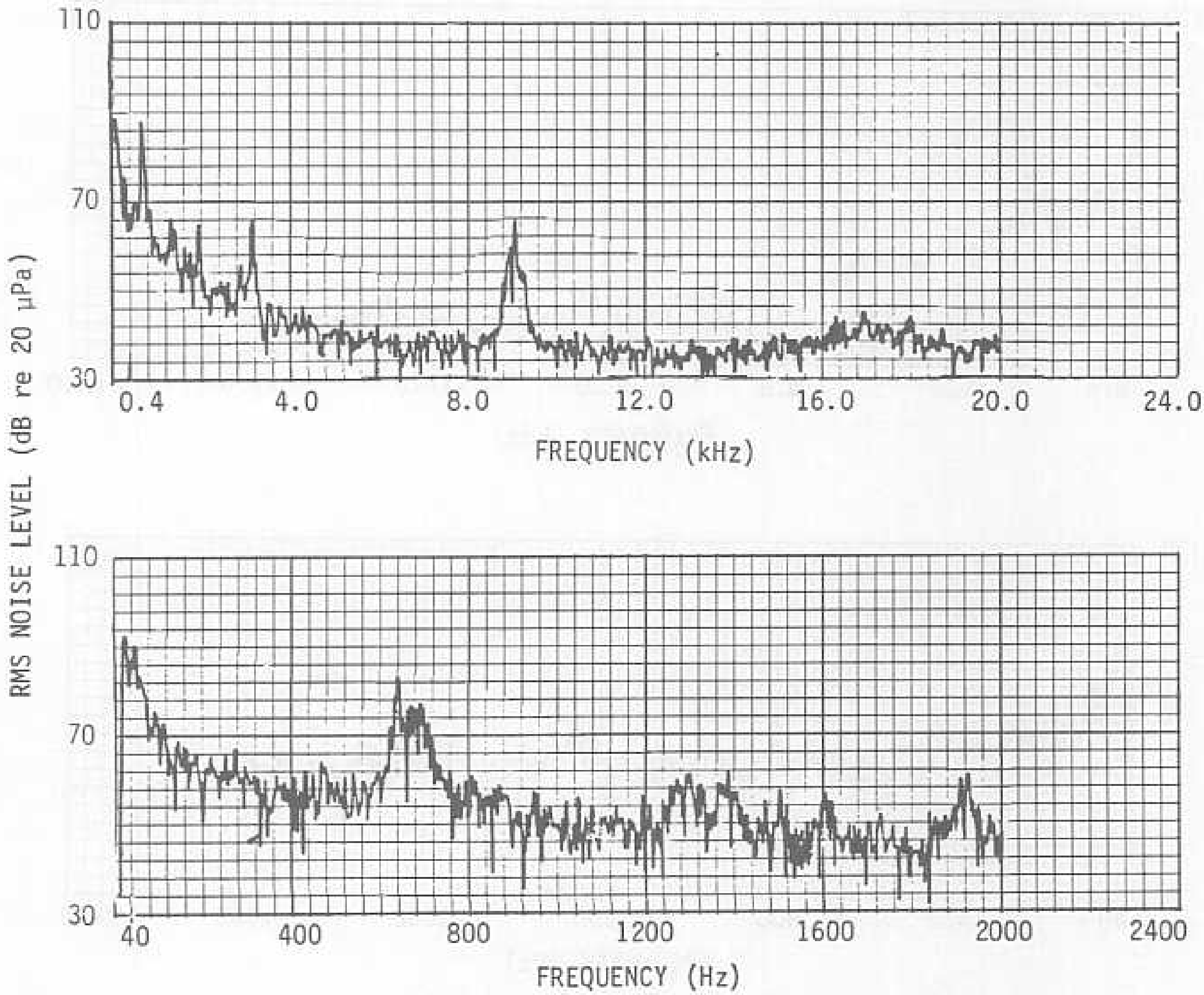


Figure C.3(b) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). PCC S/N 3270 w/Solid-Steel Wheels

SEE FIGURE 3(B), POINT (C), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

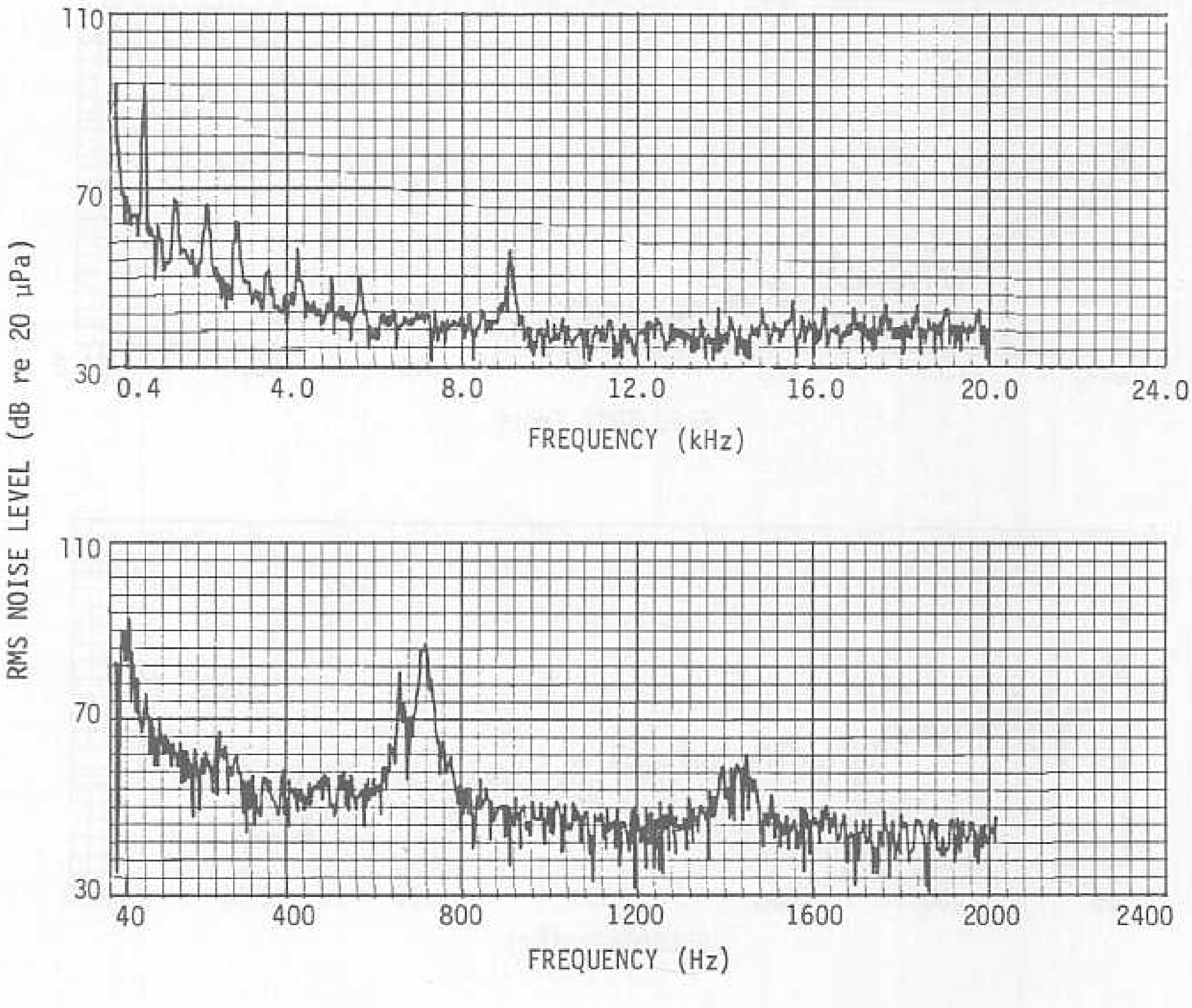


Figure C.3(c) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). PCC S/N 3270 w/Solid-Steel Wheels

SEE FIGURE 3(B), POINT (D), FOR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

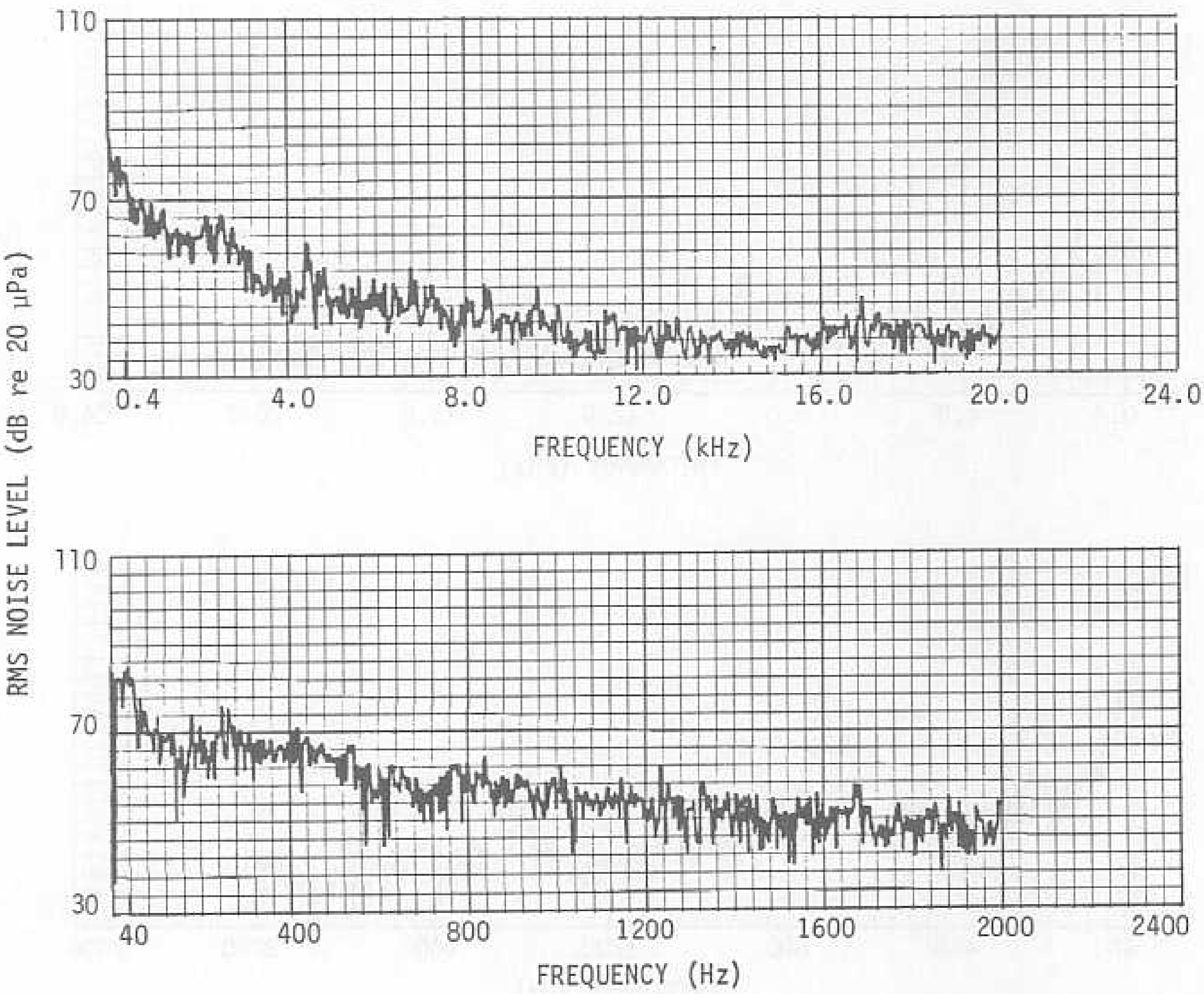


Figure C.3(d) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere to Northeastern (Outbound). PCC S/N 3270 w/Solid-Steel Wheels

SEE FIGURE 7(A) FOR WAYSIDE NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

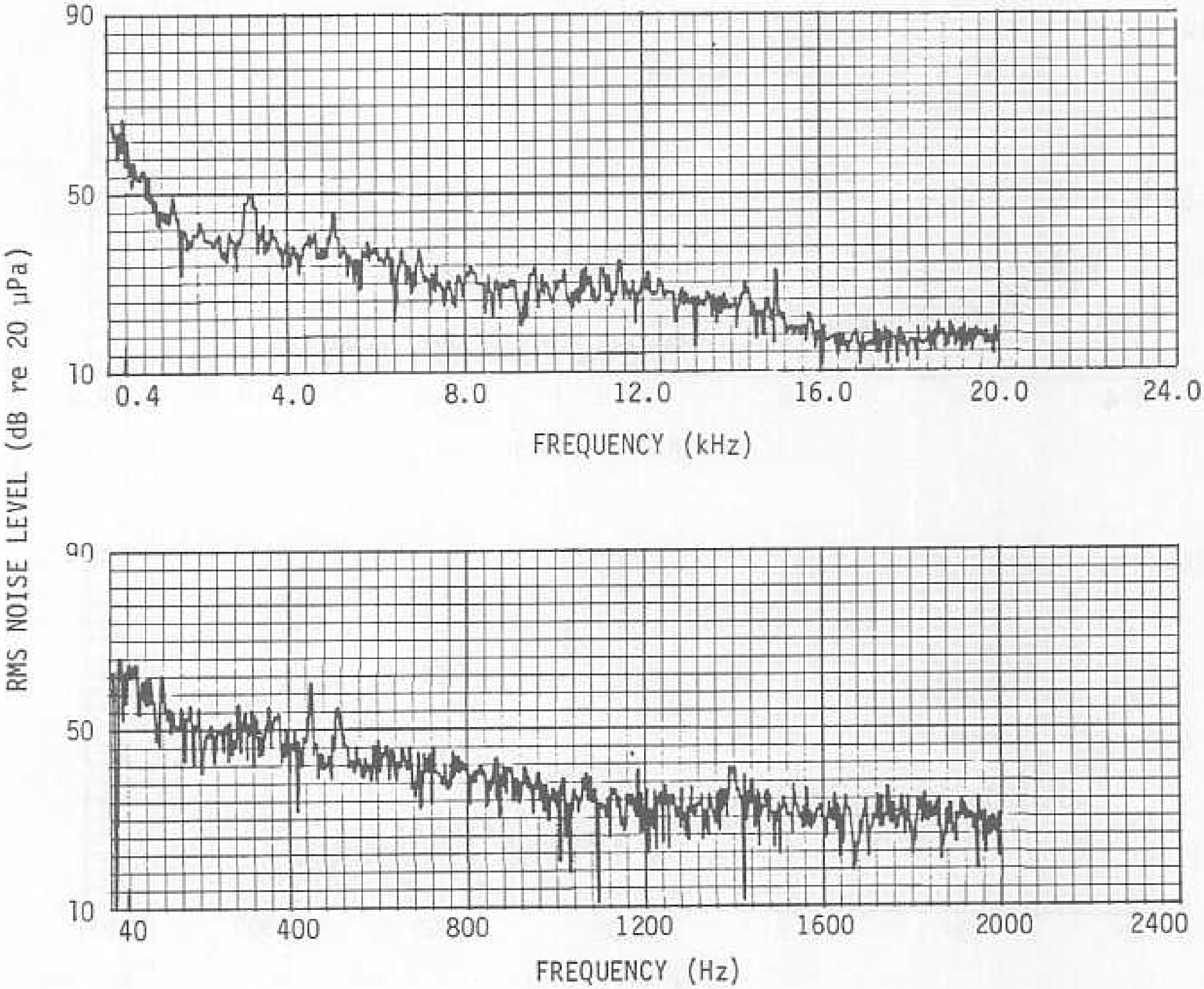


Figure C.4(a) Narrow Band Frequency Spectrum. Wayside Noise-Level Data - Lechmere Loop Run No. S5. LRV S/N 3510 w/Sab-V Wheels

SEE FIGURE 7(B) FOR IN-CAR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

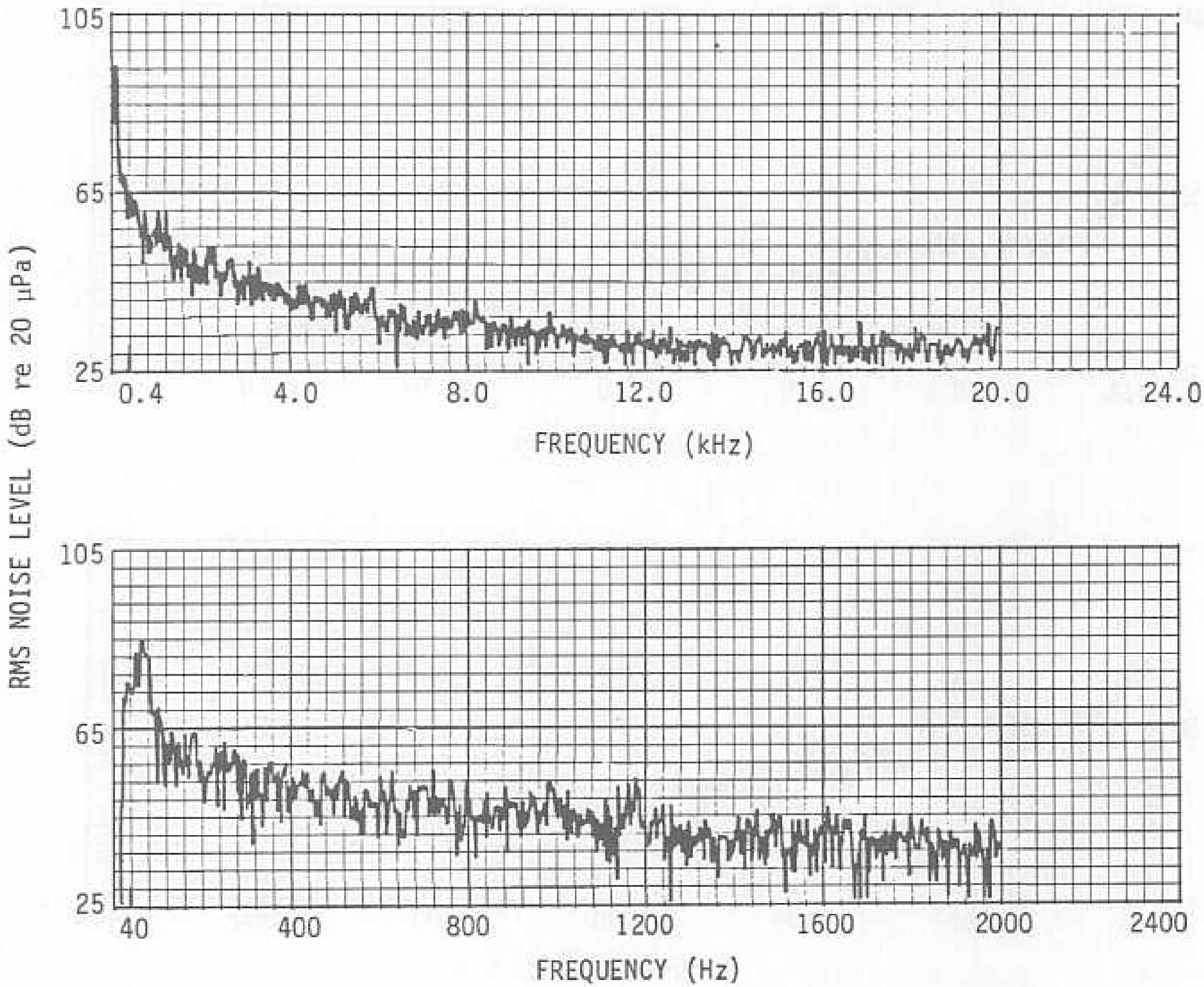


Figure C.4(b) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere Loop Run No. S5. LRV S/N 3510 w/Sab-V Wheels

SEE FIGURE 8(A) FOR WAYSIDE NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

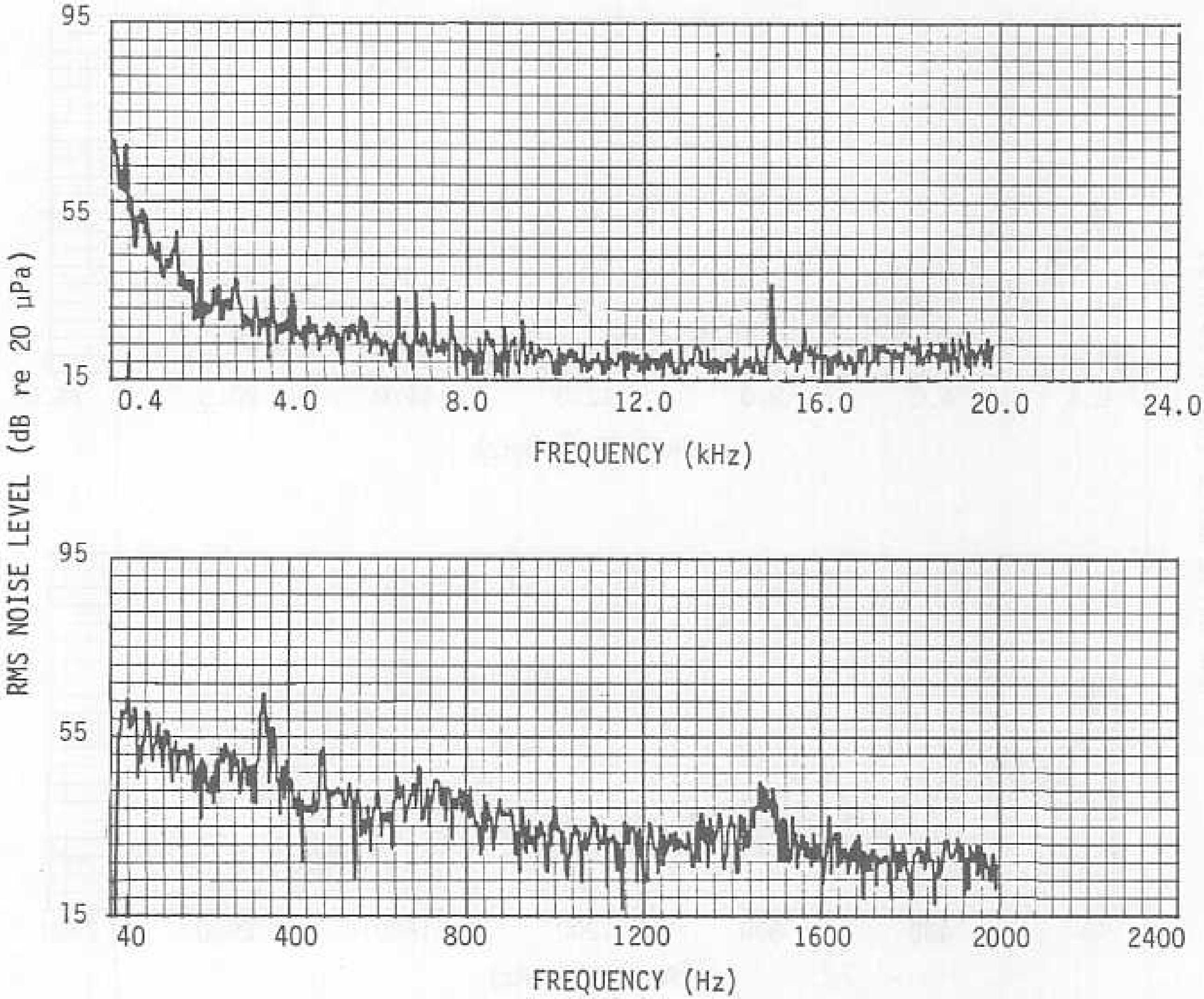


Figure C.5(a) Narrow Band Frequency Spectrum. Wayside Noise-Level Data - Lechmere Loop Run No. A1. LRV S/N 3419 w/Acoustaflex Wheels

SEE FIGURE 8(B) FOR IN-CAR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

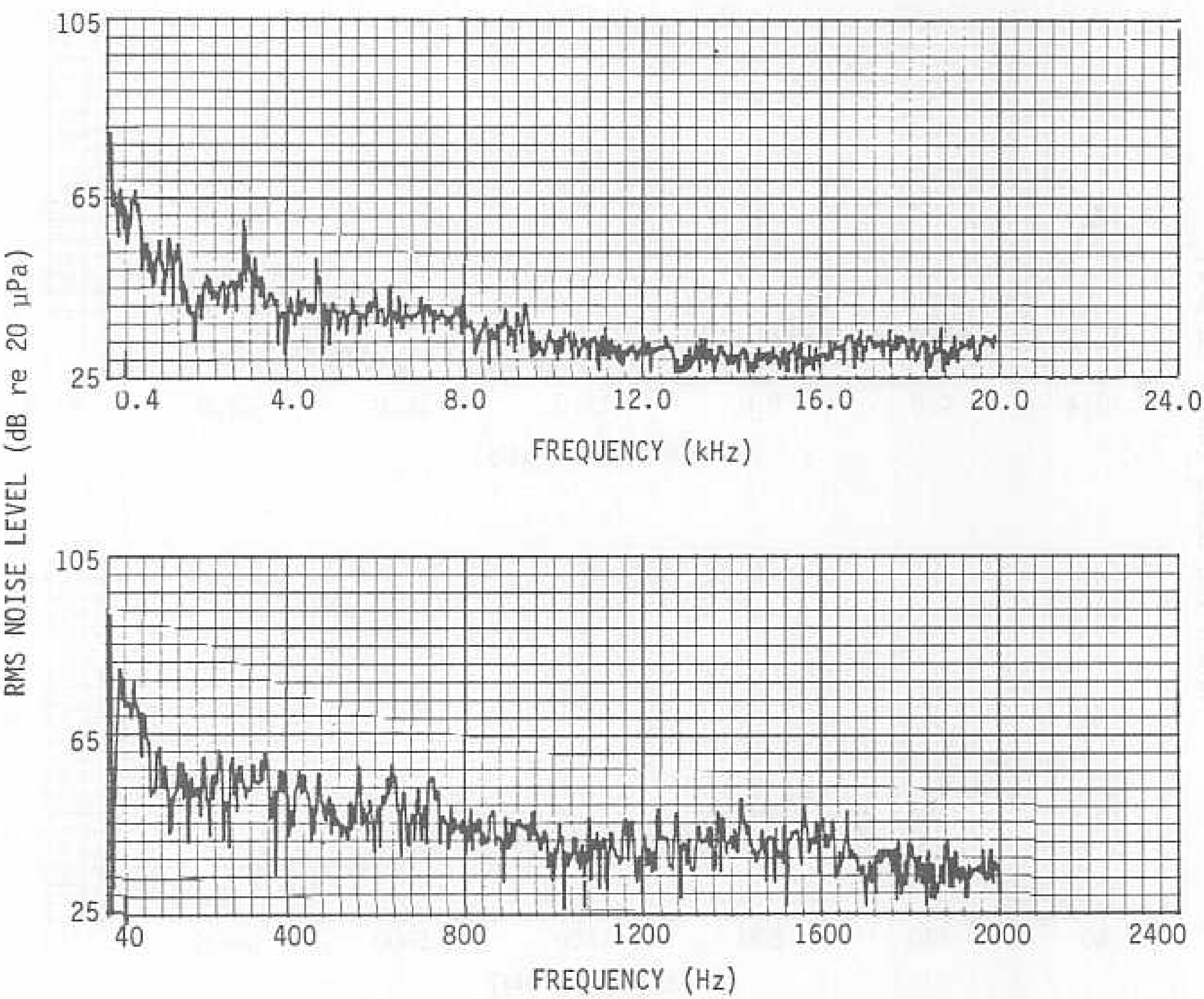


Figure C.5(b) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere Loop Run No. A1. LRV S/N 3419 w/Acoustaflex Wheels

SEE FIGURE 9(A) FOR WAYSIDE NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

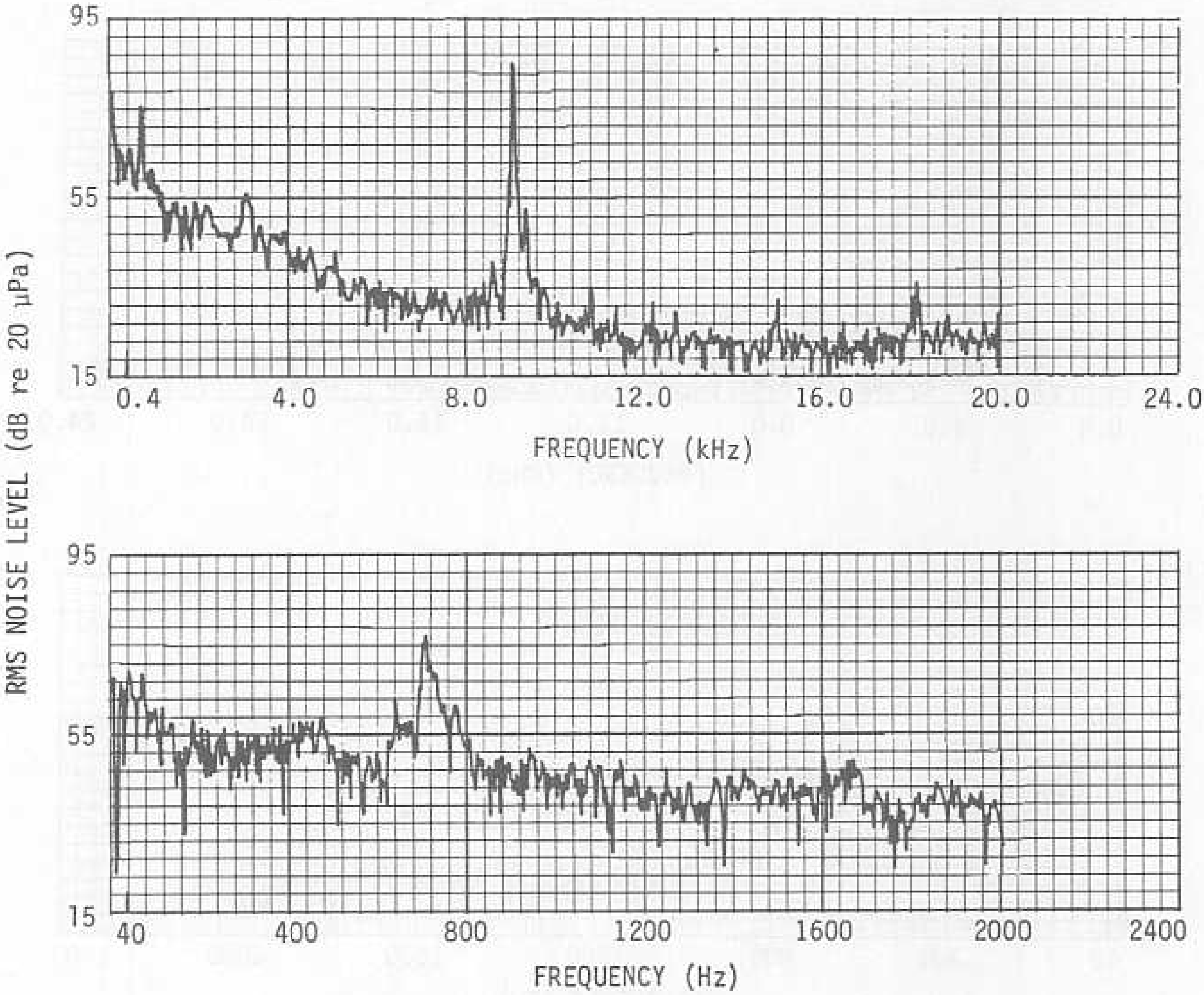


Figure C.6(a) Narrow Band Frequency Spectrum. Wayside Noise-Level Data - Lechmere Loop Run No. P6. PCC S/N 3270 w/Solid-Steel Wheels

SEE FIGURE 9(B) FOR IN-CAR NOISE LEVEL TIME HISTORY DATA

AVERAGING PERIOD: 0.5 second

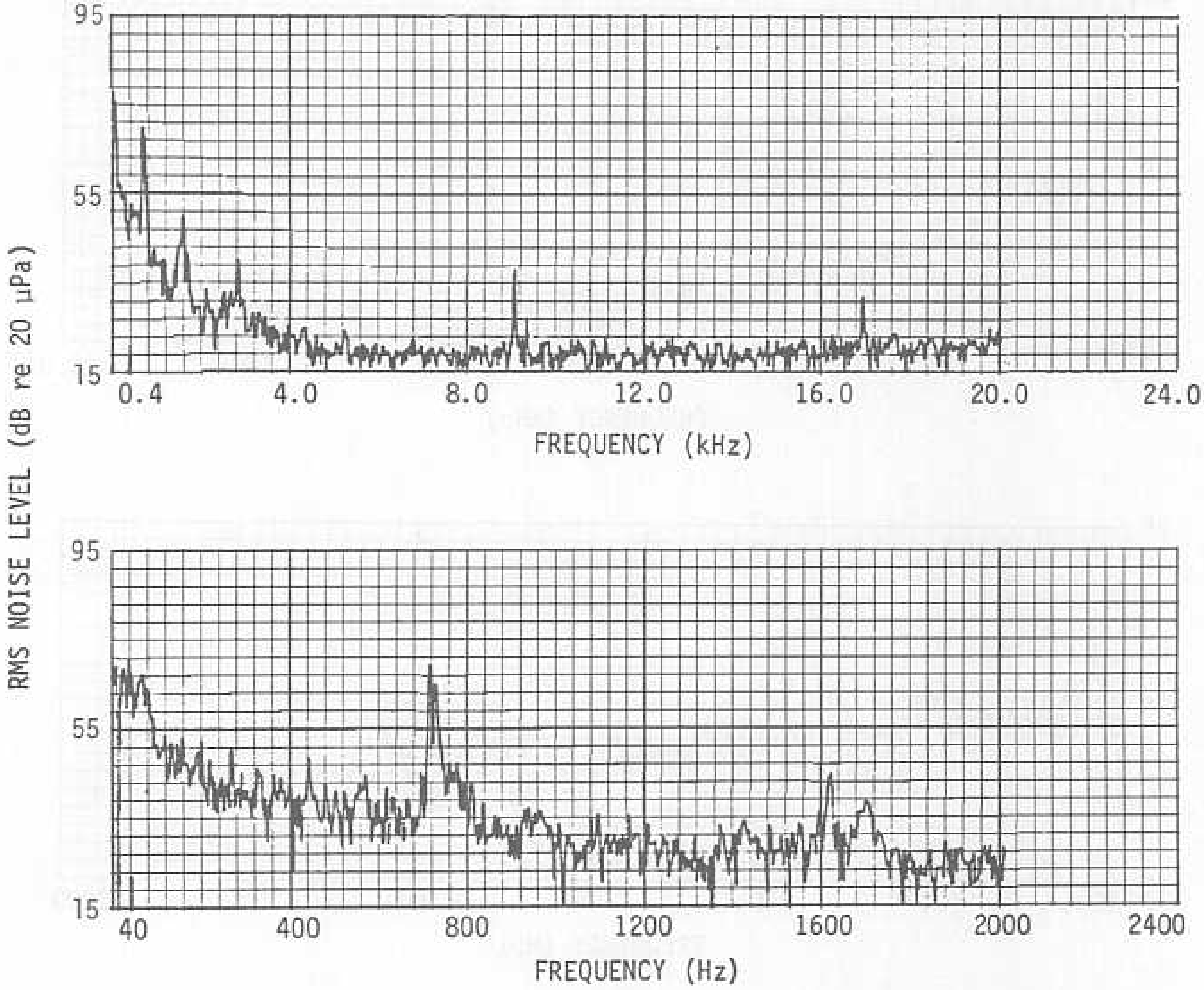


Figure C.6(b) Narrow Band Frequency Spectrum. In-Car Noise-Level Data over Front Wheel Truck - Lechmere Loop Run No. P6. PCC S/N 3270 w/Solid-Steel Wheels