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MEASUREMENT AND DIAGNOSIS OF THE NOISE FROM A GENERAL ELECTRIC C36-7 DIESEL ELECTRIC LOCOMOTIVE

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16. Abstract

Measurements of the noise from a General Electric C36-7 diesel electric locomotive were performed with the locomotive stationary and attached to a load cell during powered and unpowered pass-by tests. The pass-by tests demonstrated that wheel/rail noise contributes little to both interior and wayside noise when the locomotive is operating under load at throttle 8. Stationary tests examined the directivity of noise around the locomotive and the contribution of the major sources to the noise signature. At throttle 8, under load and at idle, the exhaust and radiator cooling fan were the primary sources. At throttle 8, unloaded, the radiator cooling fan exhaust and equipment blower dominated the noise.

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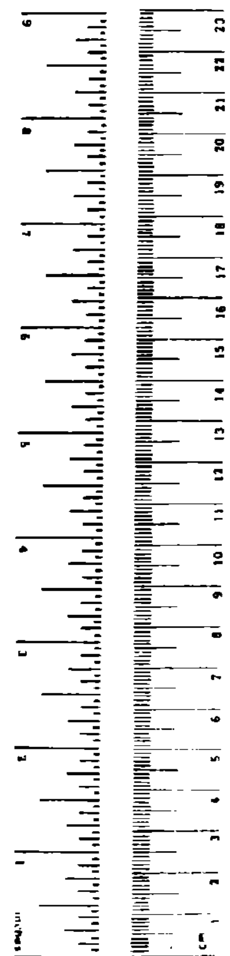
PREFACE

The study described in this report was carried out by Bolt Beranek and Newman Inc. under contract to the Transportation Systems Center of the U.S. Department of Transportation. The study was technically coordinated at the Transportation Systems Center by Mr. Robert Mason. The test locomotive, test site, and personnel to operate and modify the test locomotive, were provided by General Electric. Technical coordination at G.E. was provided by Mr. Fred Stein with the assistance of Mr. David Konko. The exhaust silencer used in the diagnostic tests was designed and built by Universal Silencer.

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



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

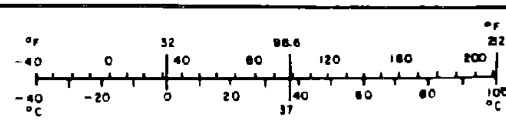


TABLE OF CONTENTS

Section		page
1.	INTRODUCTION	1
	1.1 Background	1
	1.2 Overview	1
	1.3 Organization of Report	2
2.	TEST LOCOMOTIVE	3
3.	TEST SITE AND INSTRUMENTATION	7
	3.1 Test Site	7
	3.2 Instrumentation	7
4.	TEST PROCEDURES AND RESULTS	15
	4.1 Pass-by Tests	15
	4.2 Stationary Tests	19
	4.2.1 Baseline tests	19
	4.2.2 Shielding tests	23
	4.2.3 Diagnostic tests	28
5.	CONCLUSIONS	48
	5.1 Overview	48
	5.2 Noise Control	48
APPENDIX A:	TRANSFER FUNCTIONS	51
APPENDIX B:	REPORT OF NEW TECHNOLOGY	55
REFERENCES		56

LIST OF ILLUSTRATIONS

Figure		page
1.	Test Locomotive	3
2.	Location of Locomotive Components	5
3.	Test Site	8
4.	Test-Site Plan and General Microphone Locations	9
5.	On-Board Instrumentation System	10
6.	Wayside Instrumentation for Pass-by Tests	10
7.	Pass-by Test Wayside Microphone Locations	11
8.	Instrumentation for Stationary Tests	12
9.	Baseline Test Microphone Locations	13
10.	Shielding Test Microphone Locations	14
11.	Cab-Noise Levels	16
12.	Pass-by Noise at 100 Ft Microphone (Location No. 3) .	17
13.	Sound Level at 100 Ft Microphone (Location No. 3) vs Throttle Setting With Locomotive Loaded by Load Cell.	20
14.	In-Cab Noise Levels vs Throttle Setting With Locomotive Loaded by Load Cell	21
15.	Locomotive Noise at 100 Ft Microphone Measured During Throttle Wipe Tests Employing AAR Smoke Test Procedure	22
16.	Directivity of Noise Around Locomotive	23
17.	A-Weighted Sound Levels During Shielding Tests With Locomotive in Normal Operating Condition	25
18.	A-Weighted Sound Levels During Shielding Tests With Locomotive in Configuration With all Sources Fully Quieted, *Except Radiator Cooling Fan*	26

LIST OF ILLUSTRATIONS *(Cont'd.)*

Figure		page
19.	A-Weighted Sound Levels During Shielding Tests With Locomotive in Configuration With all Sources, *Except Exhaust* Fully Quieted	27
20.	Fully Treated Locomotive	30
21.	Fan, Right Angle Gear Drive	32
22.	Typical Microphone Location in Engine Compartment for Engine/Main Generator Transfer Function Test	36
23.	Engine Mount Instrumented for Structureborne Transfer Function Test	37
24.	Lower Bound One-Third-Octave Source Spectra; Idle, 100 Ft Microphone	38
25.	Lower Bound One-Third-Octave Source Spectra; Throttle 8, Loaded; 100 Ft Microphone	39
26.	Lower Bound One-Third-Octave Source Spectra; Throttle 8, Unloaded; 100 Ft Microphone	39
27.	Lower Bound One-Third-Octave Source Spectra; Idle; 50 Ft Microphone	40
28.	Lower Bound One-Third-Octave Source Spectra; Throttle 8, Loaded; 50 Ft Microphone	40
29.	Lower Bound One-Third-Octave Source Spectra; Throttle 8, Unloaded; 50 Ft Microphone	41
30.	Lower Bound One-Third-Octave Source Spectra; Idle; 25 Ft Microphone	41
31.	Lower Bound One-Third-Octave Source Spectra; Throttle 8, Loaded; 25 Ft Microphone	42
32.	Lower Bound One-Third-Octave Source Spectra; Throttle 8, Unloaded; 25 Ft Microphone	42
33.	Comparison of Fully Quieted Noise Levels at Idle With Baseline Noise Levels	44

LIST OF ILLUSTRATIONS *(Cont'd.)*

Figure		page
34.	Upper and Lower Bound Source Levels at 25 Ft	45
35.	Upper and Lower Bound Source Levels at 50 Ft	46
36.	Upper and Lower Bound Source Levels at 100 Ft	46
37.	Equipment Blower Source Levels at Throttle 8 at Three Microphone Positions, Determined from Both "Cover and Expose" and Transfer Function Techniques	47
A.1.	Airborne Transfer Functions for Compartment	51
A.2.	Airborne Transfer Functions for Compartment (Cont'd.)	52
A.3.	Airborne Transfer Functions for Compartment (Concl'd)	52
A.4.	Structureborne Transfer Functions for Compartment ...	53
A.5.	Structureborne Transfer Functions for Compartment (Cont'd.)	53
A.6.	Structureborne Transfer Functions for Compartment (Concl'd.)	54

LIST OF TABLES

Table		page
1.	Diesel Locomotive Engine Speed and Power Schedule	4
2.	Pass-by Noise Levels	18
3.	A-Weighted Sound Levels Measured During "Cover and Expose" Tests	34
4.	Noise Levels at 100 Ft Achievable Through Engine Exhaust and Radiator Cooling Fan Treatment	50

1. INTRODUCTION

1.1 Background

On December 31, 1976 locomotive noise emission standards issued by the U.S. Environmental Protection Agency became effective [1]. On December 31, 1979 those standards became even more stringent. Since many existing diesel electric locomotives do not comply with the more stringent standards considerable interest in the control of diesel-electric locomotive noise has been generated. The study described in this report provides information on the noise characteristics of and primary noise sources on a General Electric C36-7 six-axle 3600 hp diesel electric locomotive.

General Electric and the Electro-Motive Division of General Motors (EMD) are the only two active manufacturers of locomotives in the U.S. In an earlier study [2], the noise characteristic and noise source were determined for an EMD SD40-2, a six-axle 3000 hp diesel electric locomotive, typical of those produced by General Motors. The program described in this report provides similar information on a diesel electric locomotive typical of those produced by General Electric. Together, the two programs provide a fairly complete picture of the noise characteristics and sources of noise in domestically produced diesel electric locomotives.

1.2 Overview

The acoustic test program was designed and carried out by Bolt Beranek and Newman Inc. The test locomotive, test site, and personnel to operate and modify the locomotive were provided by General Electric. A load cell test site in Erie, Pennsylvania recently constructed by GE and in compliance with the EPA standard [1] was used for all tests. Both stationary tests and pass-by tests were performed.

During the stationary noise measurements, *baseline tests* were performed to determine the characteristics of the noise emitted by the locomotive such as the directivity and dependence on throttle setting. *Shielding tests* examined the barrier effects that the hood of the locomotive applies to shield nearby observers from the locomotive noise. Finally, *diagnostic tests* determined and quantified the major sources of noise on the locomotive including both airborne and structureborne sources.

The pass-by tests were performed at the stationary test site using the track on which the locomotive was positioned for the stationary tests. These tests included *coast-by tests* to determine the contribution of wheel/rail noise at various speeds, *throttle 8 drive-by tests* to determine the noise from the locomotive accelerating by in throttle 8 at various speeds, and *throttle 8 brake-by tests* to determine the noise from the locomotive passing by in throttle 8 at low speed with the brakes applied so as to draw full power from the locomotive.

1.3 Organization of Report

The details of the test locomotive and test site are discussed in Sec. 2 and 3, respectively. The test program and results are described in Sec. 4. Conclusions may be found in Sec. 5.

2. TEST LOCOMOTIVE

The test locomotive was the General Electric (GE) C36-7 diesel electric locomotive shown in Fig. 1. It is a six-axle, 3600 hp locomotive equipped with a GE Model GE-FDL16, 16-cylinder, 45°V, 4-stroke-per-cycle, turbocharged, intercooled, diesel engine. The unit used in the test was owned by GE's engineering department. It differed from standard production units in a number of minor ways. The only difference of concern here is the engine speed schedule.

Diesel electric locomotives in the U.S. are set up with an idle setting and 8 discrete throttle or notch settings. During steady operation the throttle setting fixes both engine speed and output power.* The engine speed and power vs throttle setting

*If main generator output voltage or current exceeds certain preset levels the output power of the locomotive will be automatically reduced so that the voltage or current does not reach levels that would be damaging to the equipment.

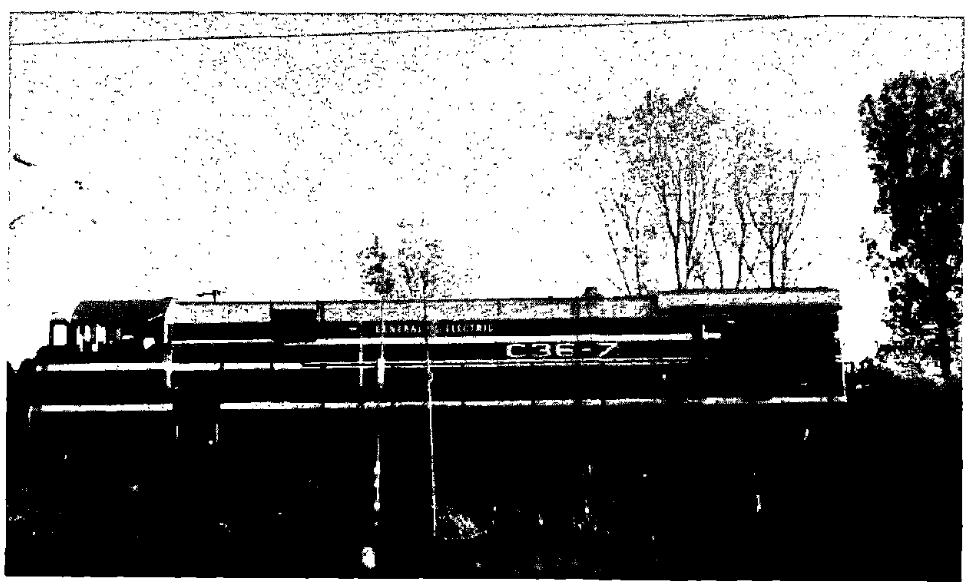


FIG. 1. TEST LOCOMOTIVE.

for this locomotive is shown in Table 1. Notice that the three highest throttle settings have the same engine speed. Standard production units are different in that the engine speed is not the same in the last three throttle settings but increases gradually with increased throttle setting to a maximum of 1050 rpm on throttle 8.

TABLE 1. DIESEL LOCOMOTIVE ENGINE SPEED AND POWER SCHEDULE.

Throttle Setting	Engine Speed (rpm)	Engine Power (Horsepower)
Idle	450	0
1	450	100
2	535	380
3	705	690
4	878	1150
5	964	1730
6	1050	2320
7	1050	3000
8	1050	3672

Figure 2 shows the location of the components of the locomotive thought to be the primary sources of noise.

The *diesel engine* powers the *main generator* which delivers electric power to the six *traction motors*, one on each axle. The *equipment blower*, a large 8-bladed fan (~150 hp), is located forward of the engine and is mechanically driven at 2.38 times engine speed by a drive shaft from the main generator. The equipment blower provides cooling air to the traction motors and main generator. The cooling air to the main generator is exhausted into the engine compartment where it creates a slight positive pressure to keep dirt and dust from entering the compartment. The equipment

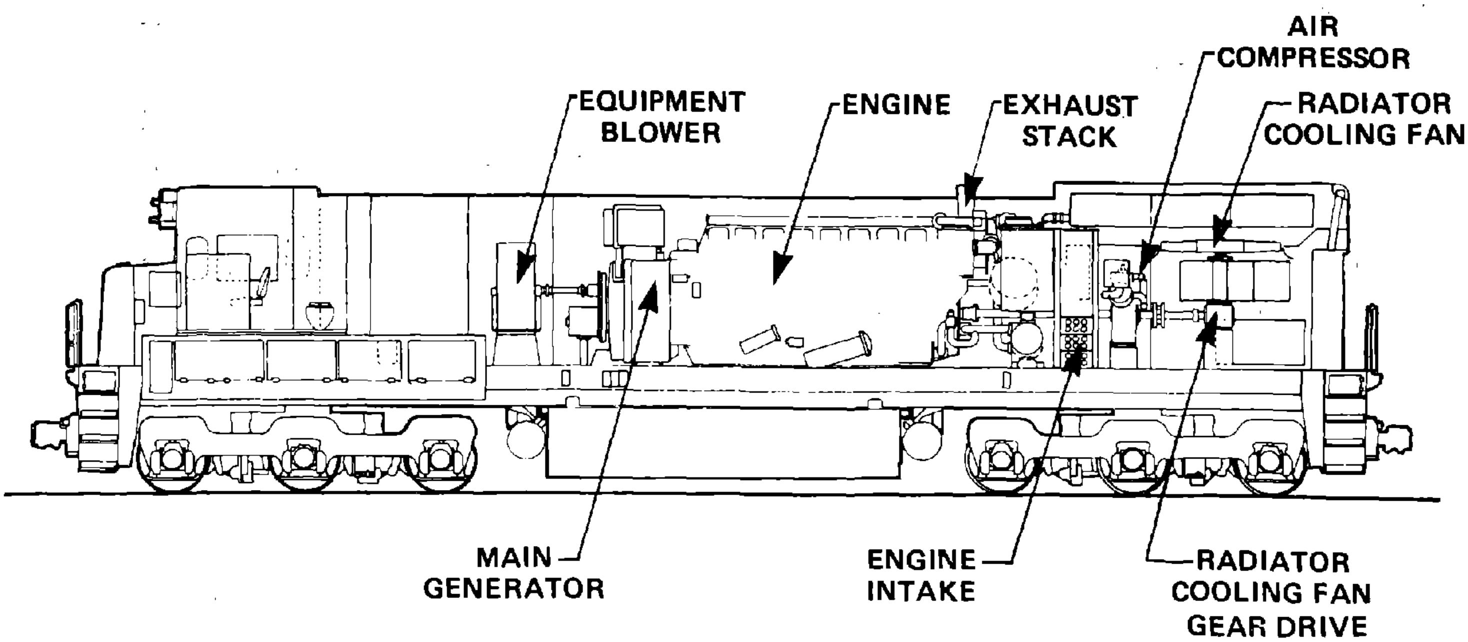


FIG. 2. LOCATION OF LOCOMOTIVE COMPONENTS.

blower is in a separate compartment from the engine and main generator. Two large mesh covered openings in the equipment blower compartment admit air to the blower. The engine/main generator compartment located aft of the equipment blower compartment is a sealed compartment except for one opening around the *exhaust stack* and two small openings for the passage of drive shafts, one forward to the equipment blower compartment and one aft to the air compressor compartment.

The *engine intake* admits air to the diesel engine. The air is cleaned first by an inertial filter to remove large particles of dirt which are carried away by an aspiration system connected to the exhaust stack. The air then passes through paper filters to remove finer particles.

The *air compressor* provides compressed air to the locomotive and train brake system. It is mechanically driven by a drive shaft from the diesel engine. The compressor is located in its own compartment just aft of the diesel engine. Louvers located in the access doors admit cooling air.

Just aft of the air compressor in a separate compartment is a single *radiator cooling fan,* an 8-bladed, 6-ft-diameter axial flow fan. The fan is driven mechanically by the diesel engine through a right angle gear box at 1.073 times engine speed. The fan draws exterior cooling air through louvers in the side of the fan compartment, and blows it vertically through the radiators mounted above the compartment.

3. TEST SITE AND INSTRUMENTATION

3.1 Test Site

The site for both stationary and pass-by tests was one specially prepared by General Electric to conform to the requirements in the EPA Railroad Noise Emission Standard [*1*]. Figures 3a and 3b show views of the site and Fig. 4 shows a plan with the load cell building and the seven wayside microphone locations on the north side of the track.*

The recording instrumentation, preamplifiers, etc. were all located in the load cell building (the white concrete block building in Fig. 3a) and long cables were run to the microphones. The resistor bank load cell for loading the locomotive was also located in the load cell building. The load cell was equipped with special low speed silenced blowers for cooling the resistors. When operating, the load cell could not be heard at any of the microphone locations even with the locomotive shut down and the load cell fans operating at maximum speed.

The track on which the locomotive was positioned for the stationary tests is part of General Electric's test track for dynamic testing of their locomotives. It is constructed of 140 lb/yd bolted rail on wooden ties and limestone ballast in excellent condition. That same track was used for all of the passby tests. Consequently, we were able to use the same microphone locations for both stationary and passby tests.

3.2 Instrumentation

Two separate instrumentation systems were used during the testing: an on-board system and a wayside system. The on-board system is shown in Fig. 5. These systems were used essentially

*The south side of the track was covered with low brush and was not suitable for placing microphones.

(a) Looking West; the Load Cell Building is on the Right and the Test Locomotive is on the Left.

(b) Looking Southwest; the Test Locomotive is on the Left.

FIG. 3. TEST SITE.

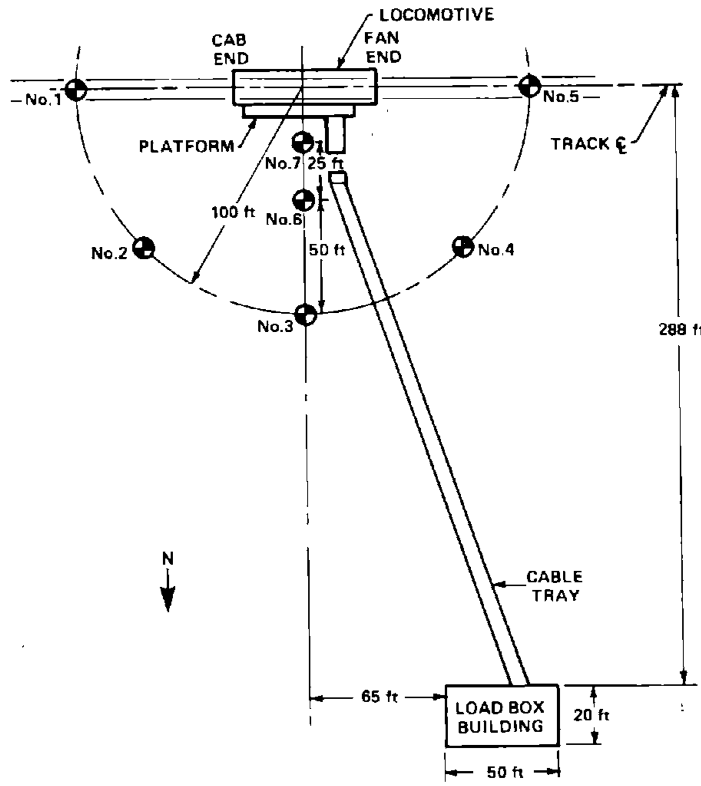


FIG. 4. TEST-SITE PLAN AND GENERAL MICROPHONE LOCATIONS.

unchanged for all except the diagnostic tests where no on-board recordings were made. The system shown for recording locomotive output-current and voltage (power) was eliminated during the course of the testing because of repeated failure of the dc pre-amplifiers. Fortunately, the locomotive had an on-board system that provided a voltage proportional to output power. This was monitored and recorded on a strip-chart recorder. The on-board microphone was located at a position approximately 1 ft to the left of the engineer's left ear. The time-code generator was used so that wayside and on-board tape recorders could be synchronized, if necessary, during data reduction.

The wayside instrumentation system changed slightly depending on the particular test being performed. Figure 6 shows the recording system for the pass-by tests. The heart of the system

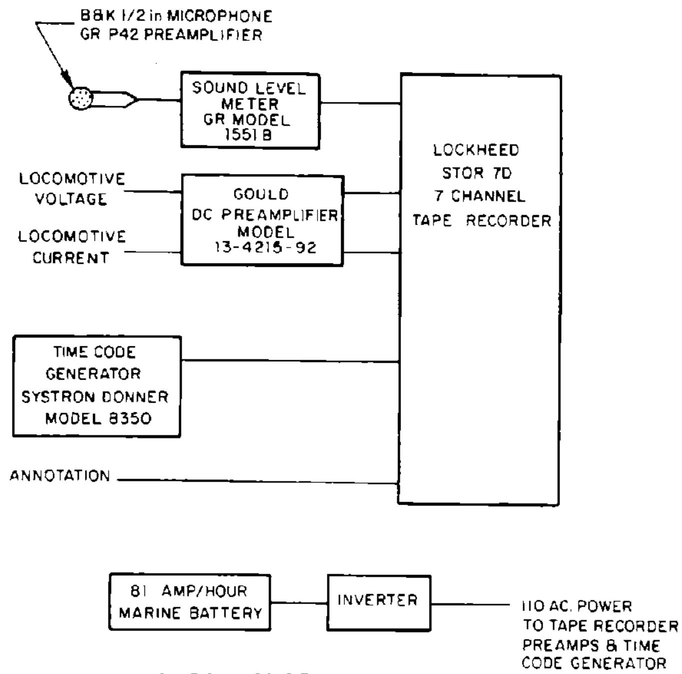


FIG. 5. ON-BOARD INSTRUMENTATION SYSTEM.

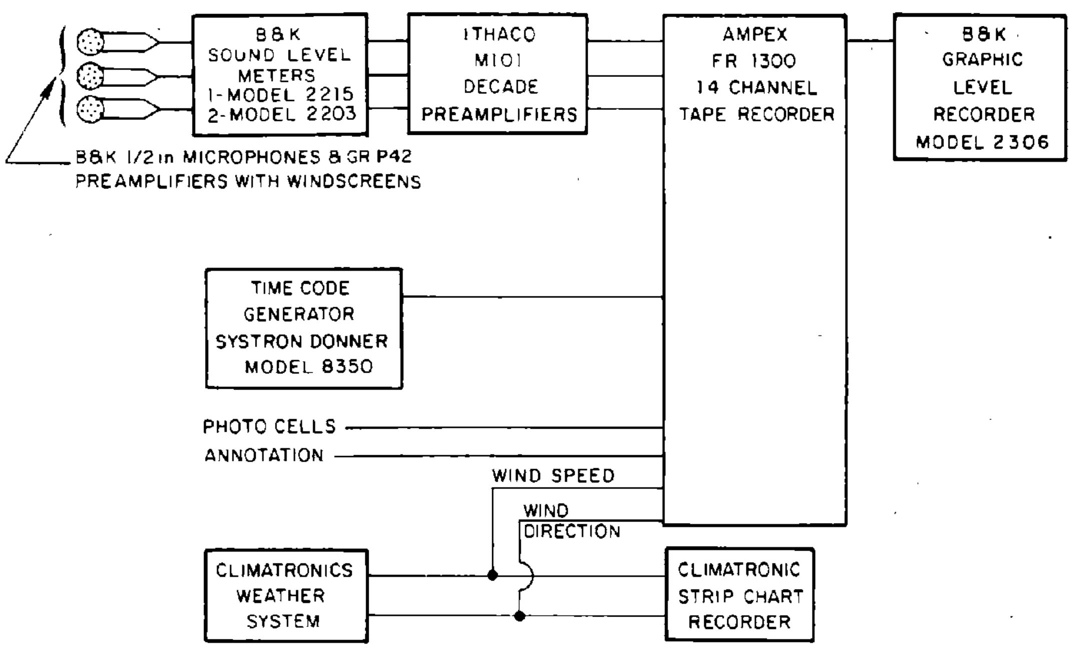


FIG. 6. WAYSIDE INSTRUMENTATION FOR PASS-BY TESTS.

is a 14-channel FM tape recorder operating at 30 ips intermediate band (0-10 KHz frequency response). Three microphones at locations 3, 6, and 7 in Fig. 4 were used at the wayside. To minimize the shielding effects of the locomotive hood, the microphones were placed at gradually increasing heights as they approached the locomotives. Figure 7 shows the configuration of the microphone array. Six photocells were placed at 20 ft intervals at the wayside to obtain locomotive position and speed. An automotive

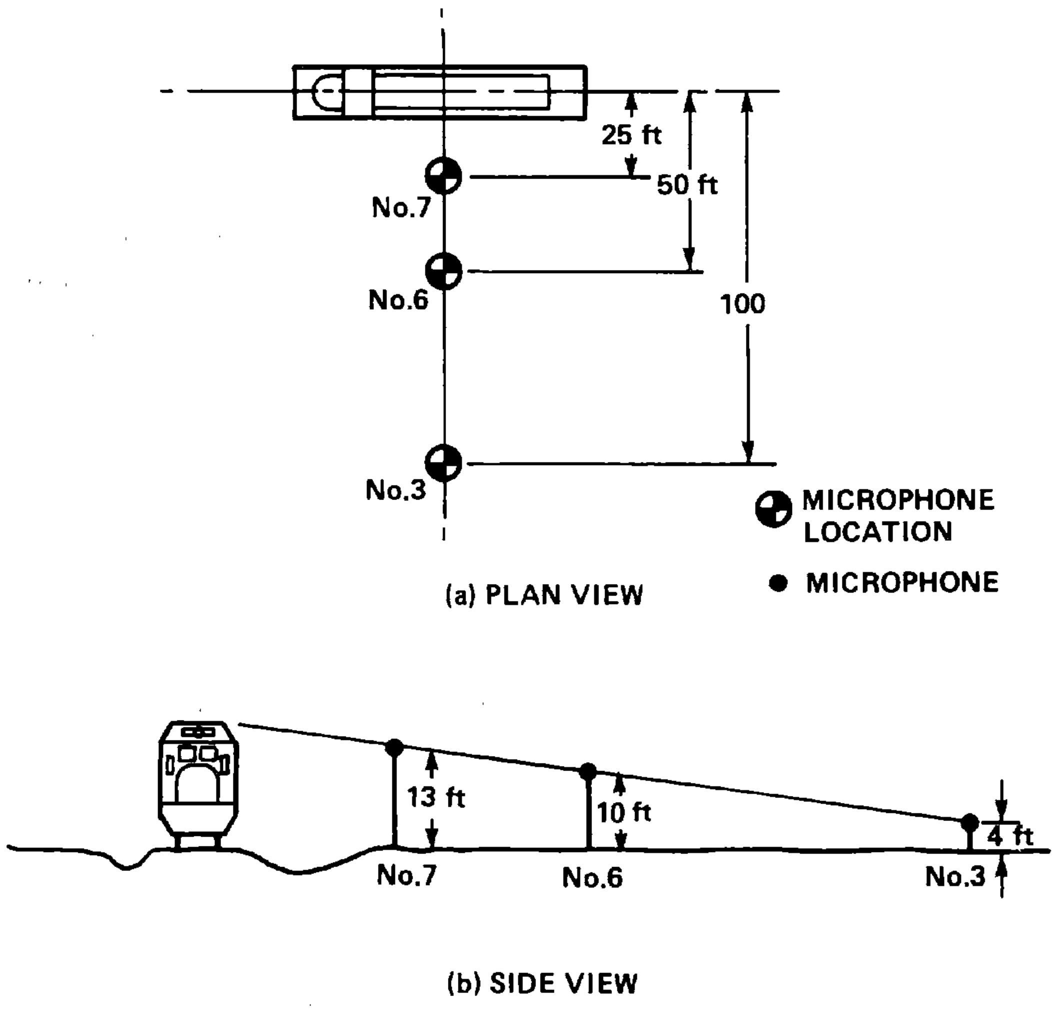


FIG. 7. PASS-BY TEST WAYSIDE MICROPHONE LOCATIONS.

headlamp was mounted to the front of the locomotive and aimed down at the photocells. The photocells were wired in series so that as the light passed over each photocell, a pulse was generated and recorded on the tape recorder. Wind speed and wind direction were monitored by a Climatronics Weather System and recorded on the tape recorder. As with the on-board system, the output of a time-code generator was recorded on one of the channels so that the two recording systems could be synchronized if required during data reduction.

For the stationary tests, the recording system used is shown in Fig. 8. A number of different microphone arrays were used with that system depending on the test. For the baseline tests

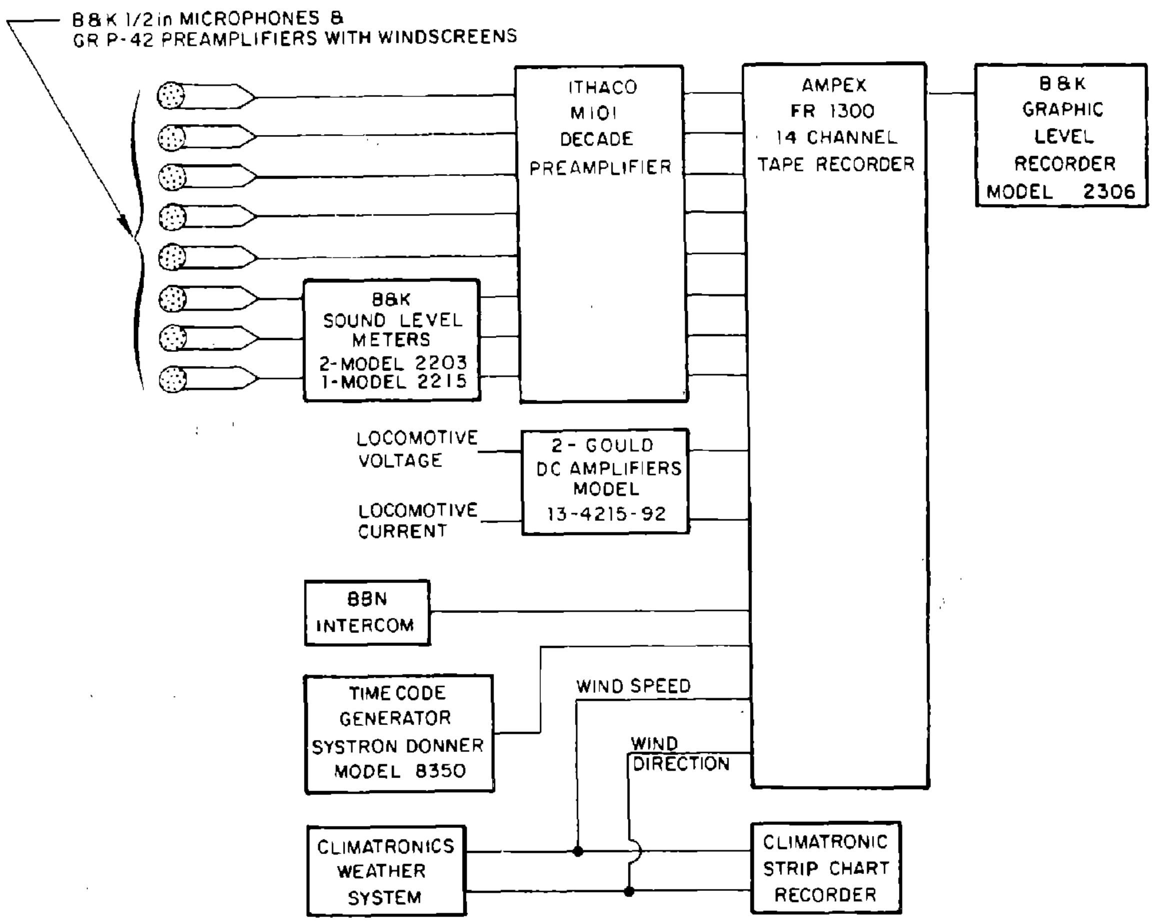
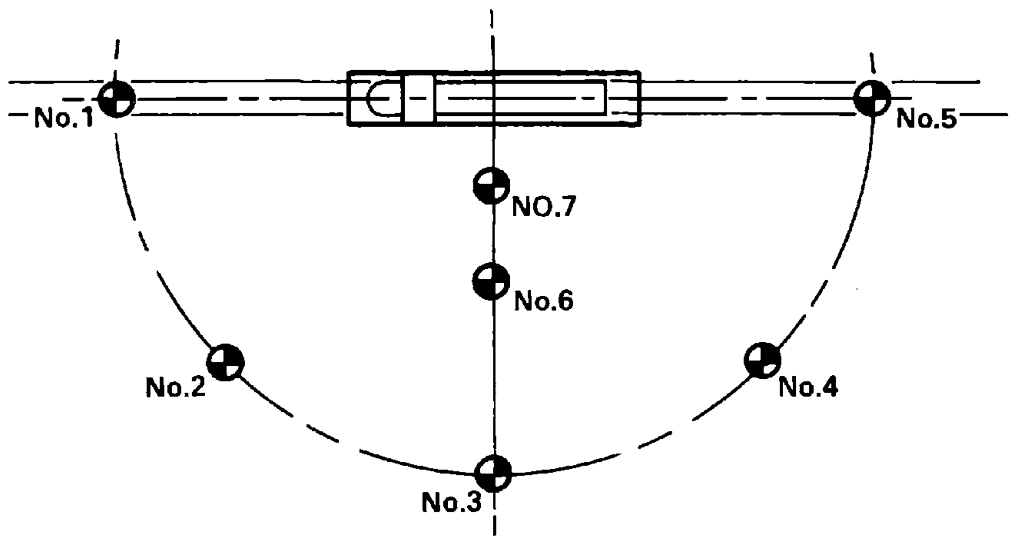


FIG. 8. INSTRUMENTATION FOR STATIONARY TESTS.

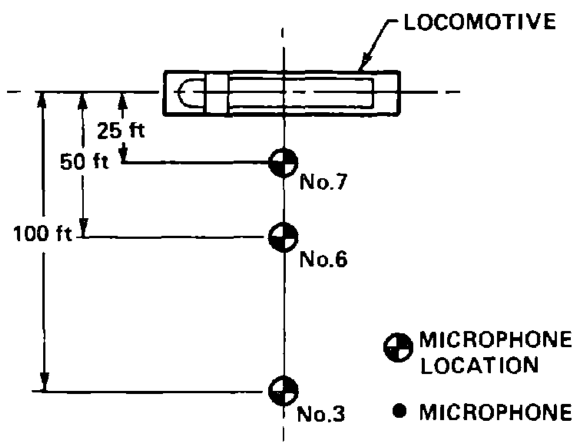
all microphone locations in Fig. 9 were used (see Fig. 4 also). For the shielding test, a seven-microphone array was again used at locations 3, 6, and 7 as shown in Fig. 10. The diagnostic tests used the same three microphone array as the pass-by tests (Fig. 7). During all testing, the output of the microphone at location 3 in Fig. 4 (the microphone location specified in the EPA railroad noise-emission standard) was monitored on a graphic level recorder.

During the stationary tests, an intercom system was used that interconnected the operators in the locomotive and the load cell building. All intercom communication was recorded on both the wayside and the on-board recording systems.

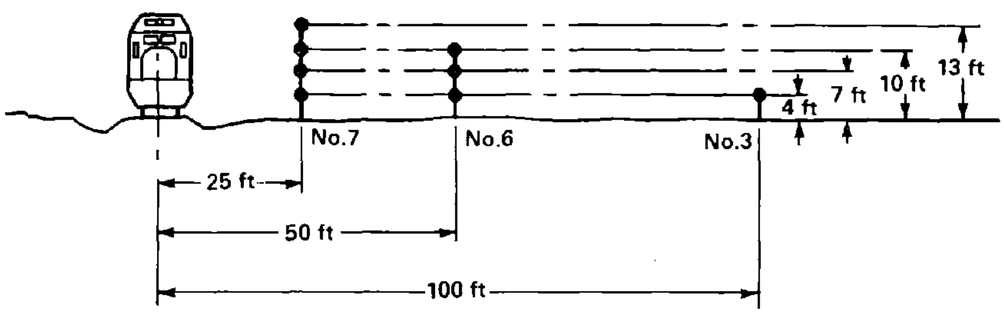


MICROPHONE LOCATION	MICROPHONE HEIGHTS ABOVE GROUND
No.1-No.5	4 ft
No.6	10 ft
No.7	13 ft

FIG. 9. BASELINE TEST MICROPHONE LOCATIONS.



(a) PLAN VIEW



(b) SIDE VIEW

FIG. 10. SHIELDING TEST MICROPHONE LOCATIONS.

4. TEST PROCEDURES AND RESULTS

4.1 Pass-by Tests

A series of pass-by tests were carried out to determine the wheel/rail noise contribution to the locomotive noise, to obtain the baseline noise from the moving locomotive (for comparison with stationary tests), and to examine the usefulness of a pass-by procedure that might be used in place of the stationary test procedure in the EPA standards.

a. Test Procedure

The locomotive was operated on the track at the stationary test site under the following conditions:

- Coasting-by the wayside microphones with the locomotive shut down (coast-by)
- Running by the wayside microphones at low speed in throttle 8 with a full service brake application (throttle 8 brake-by)
- Running by the wayside microphones at speeds from 10 – 60 mph in throttle 8; no brakes applied (throttle 8 drive-by).

Each test was run with cab windows open and then repeated with those windows closed so as to record the full range of cab interior sound levels. Wayside noise levels were recorded simultaneously.

b. In-Cab Test Results

The results of the in-cab measurements are presented in Fig. 11. Noise levels with windows open and closed are shown vs locomotive speed. Opening the windows appears to increase cab noise levels by up to 2.5 dBA. Coast-by noise levels with the

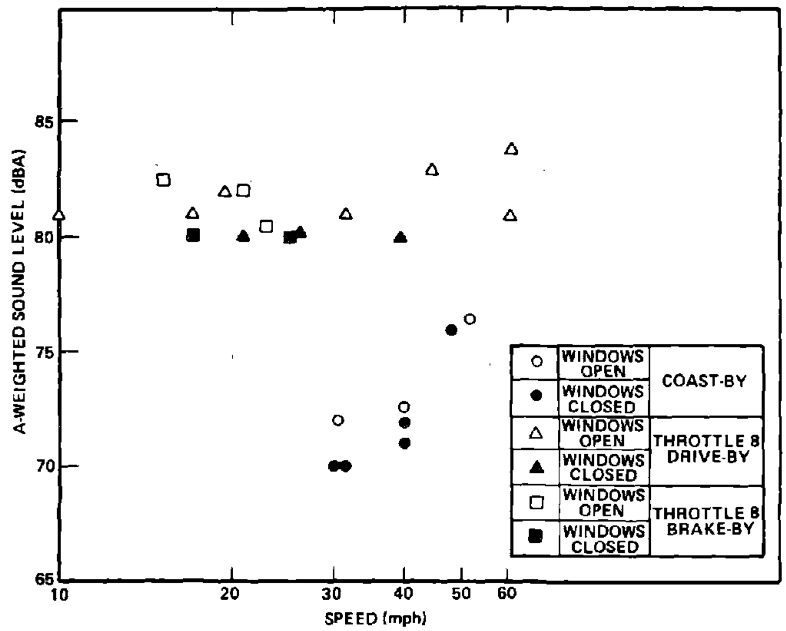


FIG. 11. CAB-NOISE LEVELS.

engine at idle are generally well below the levels at comparable speed with the locomotive in throttle 8. The difference indicates that wheel/rail noise is not a significant source of cab noise until the locomotive achieves speeds of 50 mph or more. Throttle 8 brake-by noise levels are generally comparable to the low-speed throttle 8 drive-by levels, despite the fact that the power generated by the locomotive during the brake-by tests was up to twice that generated during the drive-by tests at comparable speeds (see Table 2).

c. Wayside Test Results

The wayside vs speed noise at the 100 ft microphone (location No. 3 in Fig. 9) is plotted in Fig. 12. Coast-by noise levels are generally well-below the pass-by levels with the locomotive in throttle 8 for all speeds up to 50 mph. Throttle 8 brake-by noise levels are generally comparable to throttle 8 drive-by levels.

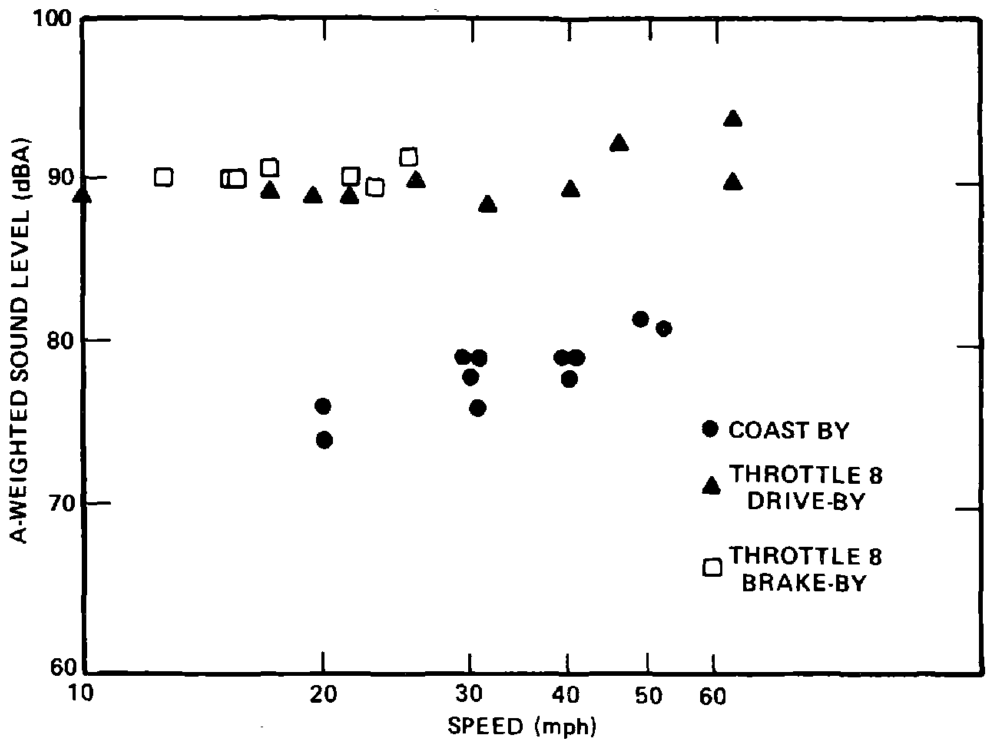


FIG. 12. PASS-BY NOISE AT 100 FT MICROPHONE (LOCATION NO. 3).

Table 2 provides a detailed listing of wayside and in-cab noise levels and locomotive power for all tests. The data from all three wayside microphones (25 ft, 50 ft, and 100 ft, locations 7, 6, and 3, respectively, in Fig. 7) are shown. During the throttle 8 drive-by and throttle 8 brake-by tests, the noise levels at the 50 ft microphone were 3 - 5 dBA higher than the levels at the 100 ft microphone; and the 25 ft microphone noise levels were 8 - 9.5 dBA higher than the 100 ft microphone levels. For the coast-by noise levels the differences were 3 - 6 dBA and 6 - 10 dBA, respectively.

The power generated by the locomotive during the throttle 8 drive-bys was substantially less than full power except at high speed (46 and 62 mph). During the brake-by test, full power operation was achieved at 25 mph. Part of the problem with dynamic testing of a locomotive is that there is protective

TABLE 2. PASS-BY NOISE LEVELS.

Speed (mph)	Direction	Condition	Windows	Wayside Microphones (dBA)			Cab Microphone (dBA)	Power (H.P.)
				100 ft	50 ft	25 ft		
9.5	E	Coast-By	—	—	70	73	—	—
10	W		—	70	73	80	—	—
20	E		—	74	82	83	—	—
20	W		—	76.5	82	84.5	—	—
30	E		—	78	84	86	—	—
30	E		Closed	79	83.5	85	70	—
31	W		Open	76.5	83	86	72	—
31	E		Closed	79	83.5	85	70	—
40	W		Closed	78	84	87	71	—
40	E		Open	79	85	87.5	72.5	—
49	E		Closed	81.5	87.5	90	76	—
53	E		Open	81	87.5	90	76.5	—
10	W	Throttle 8 Drive-By	Open	89	93	98.5	81	1700
21	E		Closed	89	93	98	80	1200
20	W		Open	89	93	98	82	1600
17	E		Open	89.5	93.5	99	81	2300
26	W		Closed	90	94	99	80	1600
33	E		Open	88.5	92.5	97.5	81	1600
39	W		Closed	89.5	92.5	98	80	2000
46	E		Open	92.5	97.5	101.5	83	3600
62	W		Closed	90	95	99.5	81	2200
62	E		Open	94	—	102	84	3600
15	E	Throttle 8 Brake-By	Open	90	94	99	—	2600
17	W		Closed	90.5	94	99.5	80	2400
23	E		Open	89.5	93.5	98.5	80.5	1700
12	W		Closed	90	94	100	—	2300
21	E		Open	90	94	100	82	3200
15	W		Open	90	94	99.5	82.5	2500
25	E		Closed	91.5	96	101	80	3600
8	E	Brake-by With Engine Shut Down	Open	75	80	83	71.5	—
17	W		Closed	77	81.5	85	—	—

circuitry onboard that prevents the locomotive taking on load too quickly. Consequently, when throttle 8 is suddenly applied the power slowly builds up and the power achieved depends on the amount of time the locomotive is left in throttle 8 before reaching the microphones. With the brakes applied as in a brake-by test, the locomotive cannot accelerate so quickly and full power can be achieved at lower speed. During a throttle 8 passby the locomotive accelerates retarded only by its own interia. As a result, fairly high speeds are achieved before full power is reached.

4.2 Stationary Tests

A series of three stationary tests was performed: baseline tests, shielding tests, and diagnostic tests. In the first we determined the characteristics of the noise from the normally operating locomotive. In the shielding tests we examined how the locomotive hood acted as a barrier to the propagation of sound to a nearby wayside observer. The diagnostic tests determined the contributions of the various sources to the overall noise. Each set of tests is described below.

4.2.1 Baseline tests

a. Test Procedure

With the locomotive connected to the load cell and in normal operating condition we used the microphone array shown in Fig. 9 and one microphone in the cab to measure the noise from the locomotive under the following operating conditions:

- Steady operation at idle, and throttles 1 through 8 both loaded and unloaded, and with cab windows open and closed
- Operating through the AAR smoke test procedure,* loaded and unloaded, and with cab windows open and closed.

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*The smoke test procedure is a series of throttle changes used to test for smoke emissions from the locomotive stack. The throttle sequence is 1-4, 4-8, 8-6, 6-8, 8-idle, idle-8.

b. Test Results

The change in noise level at the 100 ft microphone (location No. 3 in Fig. 9) with throttle settings is shown in Fig. 13 for the locomotive loaded by the load cell. In-cab levels are shown in Fig. 14 for windows open and closed. When the AAR smoke test procedure was run, the noise levels obtained were essentially the same as the steady state levels in Fig. 13 and 14; i.e., during each throttle change the noise changed smoothly without "overshoot" to the steady state level of the final throttle setting as shown in Fig. 15. Consequently, no throttle wipe test results are presented in this report.

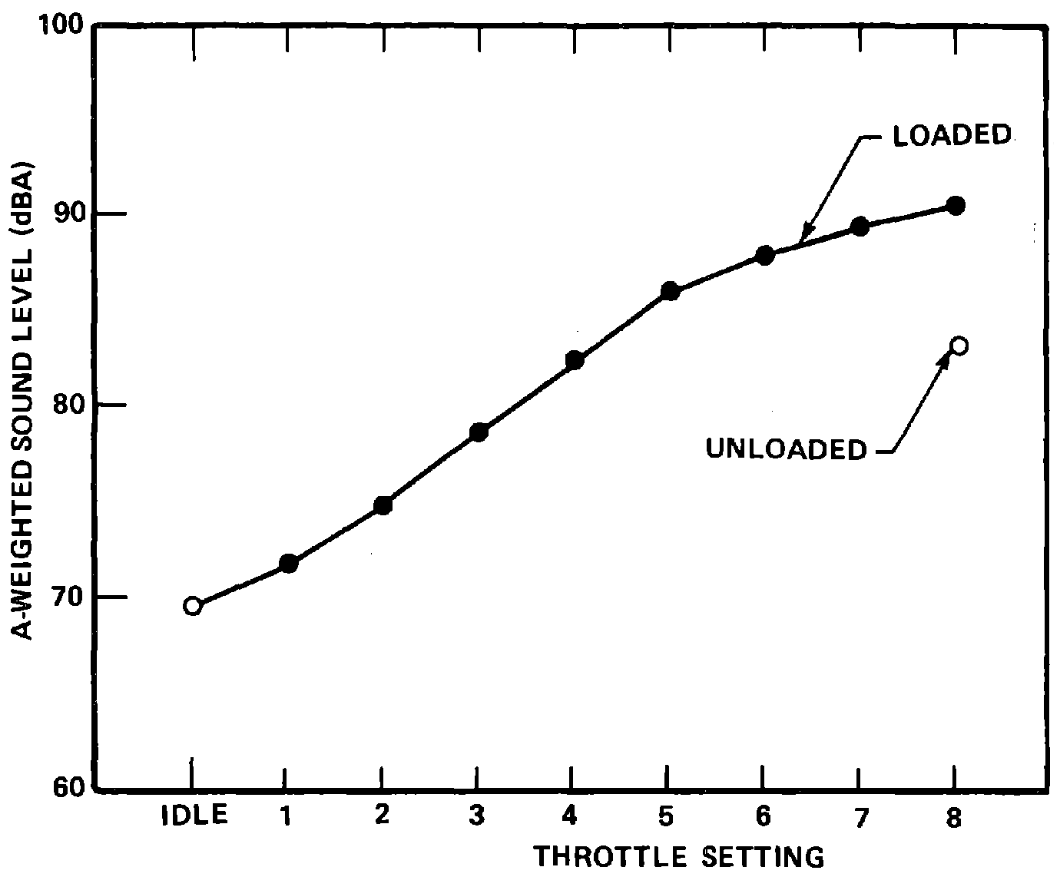


FIG. 13. SOUND LEVEL AT 100 FT MICROPHONE (LOCATION NO. 3) VS THROTTLE SETTING WITH LOCOMOTIVE LOADED BY LOAD CELL.

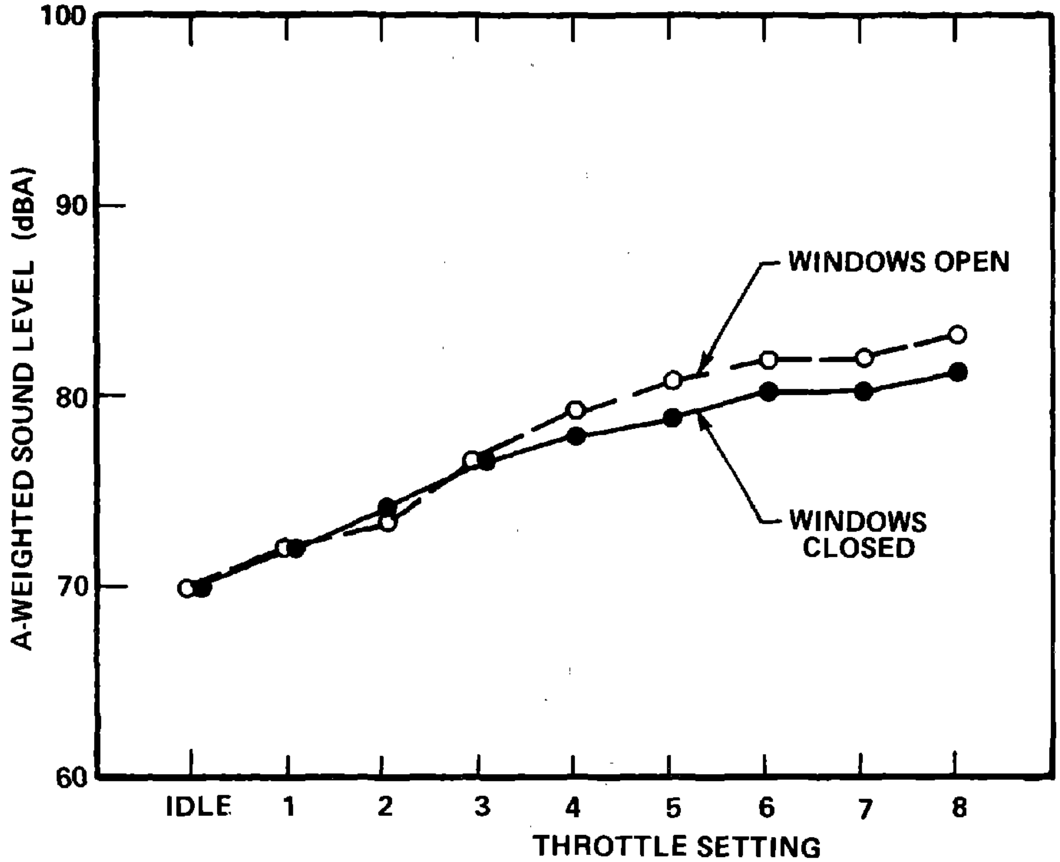


FIG. 14. IN-CAB NOISE LEVELS VS THROTTLE SETTING WITH LOCOMOTIVE LOADED BY LOAD CELL.

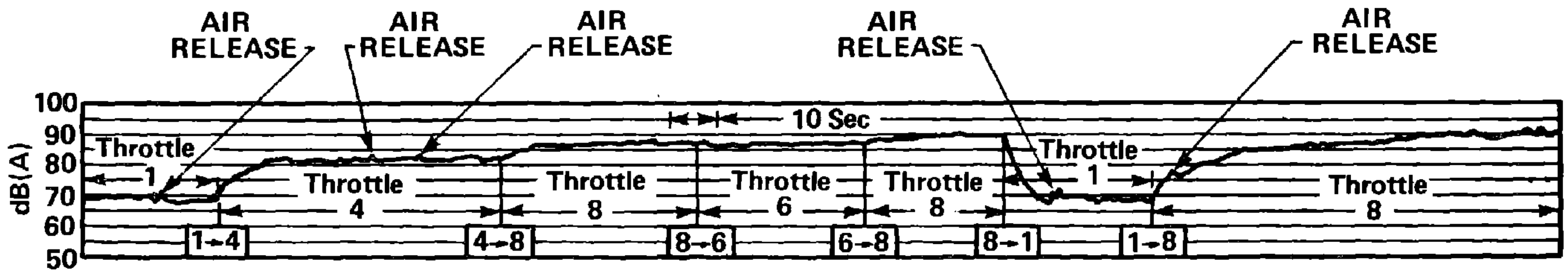


FIG. 15. LOCOMOTIVE NOISE AT 100 FT MICROPHONE MEASURED DURING THROTTLE WIPE TESTS EMPLOYING AAR SMOKE TEST PROCEDURE.

The directivity of the noise around the locomotive is shown in Fig. 16. The data are the noise levels measured on a 100 ft radius half circle (microphone locations 1 through 5 in Fig. 9) at idle, throttle 8 loaded, and throttle 8 unloaded. Data are shown for only one side of the locomotive. Simultaneous measurement of the noise on both sides of the locomotive 100 ft away (microphone location 3 and the symmetric location on the opposite side of the locomotive) gave noise levels that were within 1/2 dB of one another at throttle 8, loaded. That result confirms what one would naturally suspect, i.e., that the noise is symmetrically distributed about the axis of the locomotive.

4.2.2 Shielding tests

a. Test Procedure

The shielding tests used different microphone locations from the baseline tests. The microphone array for these tests is shown

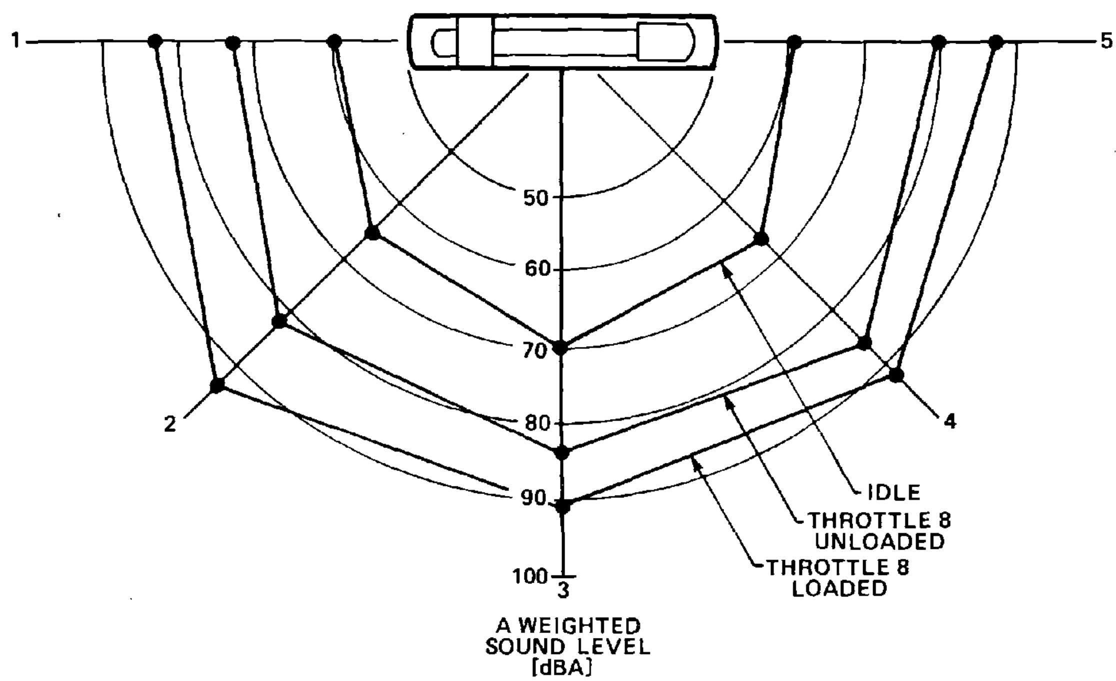


FIG. 16. DIRECTIVITY OF NOISE AROUND LOCOMOTIVE.

in Fig. 10. The locomotive noise was measured with the locomotive in normal operating condition. During the diagnostic tests, additional shielding measurements were carried out with the locomotive placed in a configuration first to enhance exhaust-noise, and then to enhance radiator cooling fan noise. Section 4.2.3 describes the locomotive configuration for these tests.

For all of the shielding tests, the locomotive was operated in the following conditions:

- Steady operation at idle; throttle 8, loaded; and throttle 8, unloaded.
- Operating through the AAR smoke test procedure both loaded and unloaded.

b. Test Results

The overall A-weighted sound levels, measured at each of the 8 microphone positions of Fig. 10 for the locomotive in normal operating condition, are shown in Fig. 17. The positions of the boxes to the right of the locomotive, in the figure, correspond to the microphone positions in Fig. 10. The number in each box is the overall A-weighted sound level measured at the corresponding microphone position. Data are presented for the locomotive at idle, throttle 8, loaded and throttle 8, unloaded. No data from the AAR smoke test procedure throttle-wipes are shown for reasons previously given. Similar data are presented in Figs. 18 and 19 for the locomotive configurations in which radiator cooling fan and exhaust noise are enhanced, respectively.

The data show that there is generally no significant overall noise level variation with height at the 50 ft microphone for any locomotive configuration or operating condition.

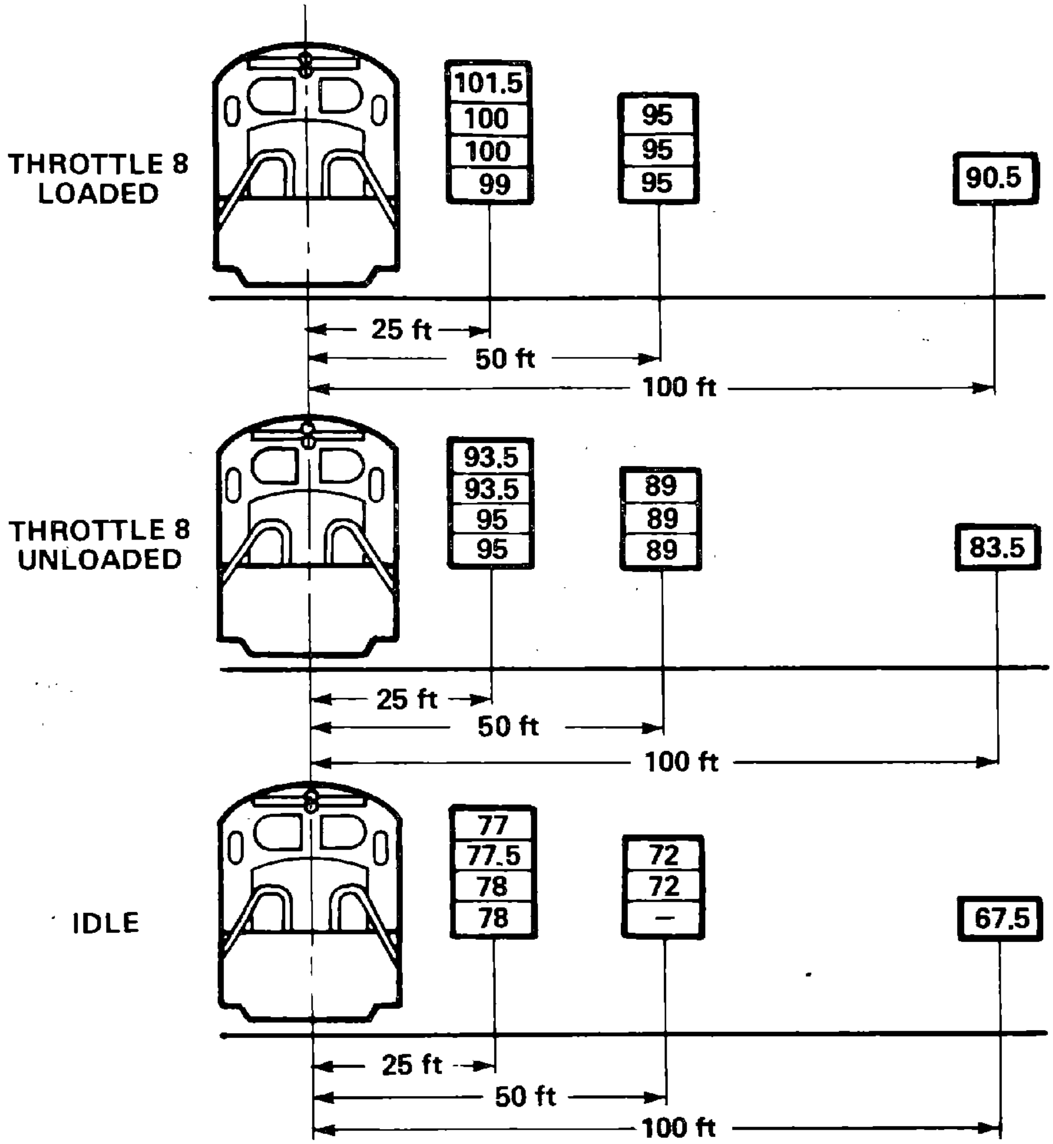


FIG. 17. A-WEIGHTED SOUND LEVELS DURING SHIELDING TESTS WITH LOCOMOTIVE IN NORMAL OPERATING CONDITION.

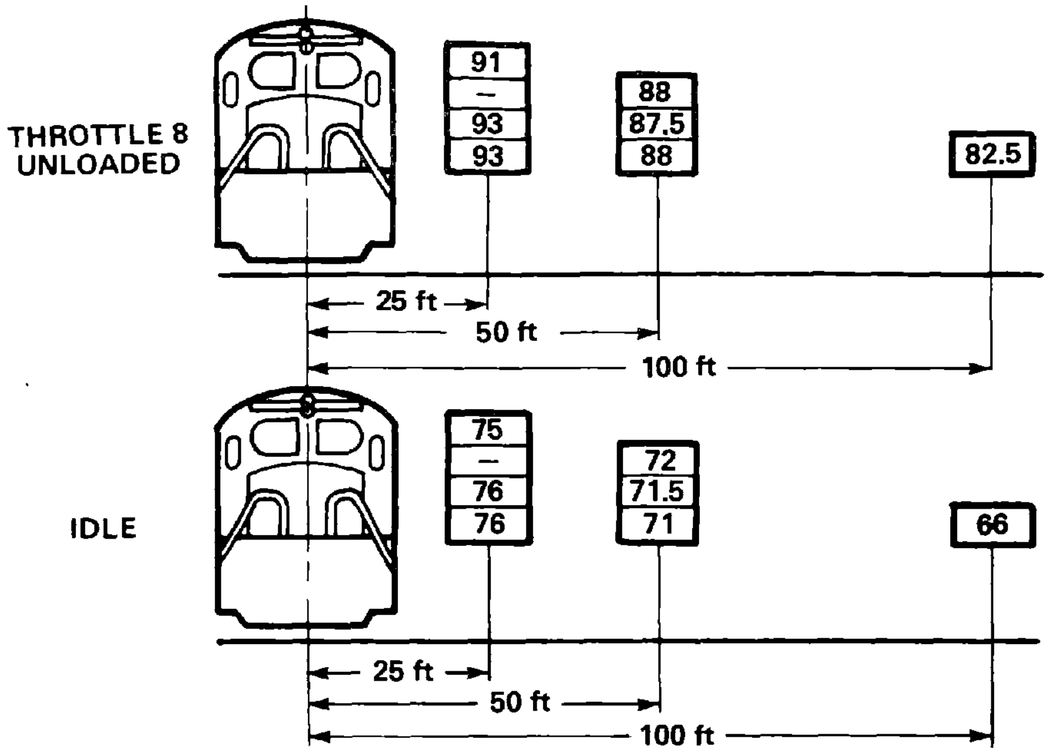


FIG. 18. A-WEIGHTED SOUND LEVELS DURING SHIELDING TESTS WITH LOCOMOTIVE IN CONFIGURATION WITH ALL SOURCES FULLY QUIETED, *EXCEPT RADIATOR COOLING FAN*.

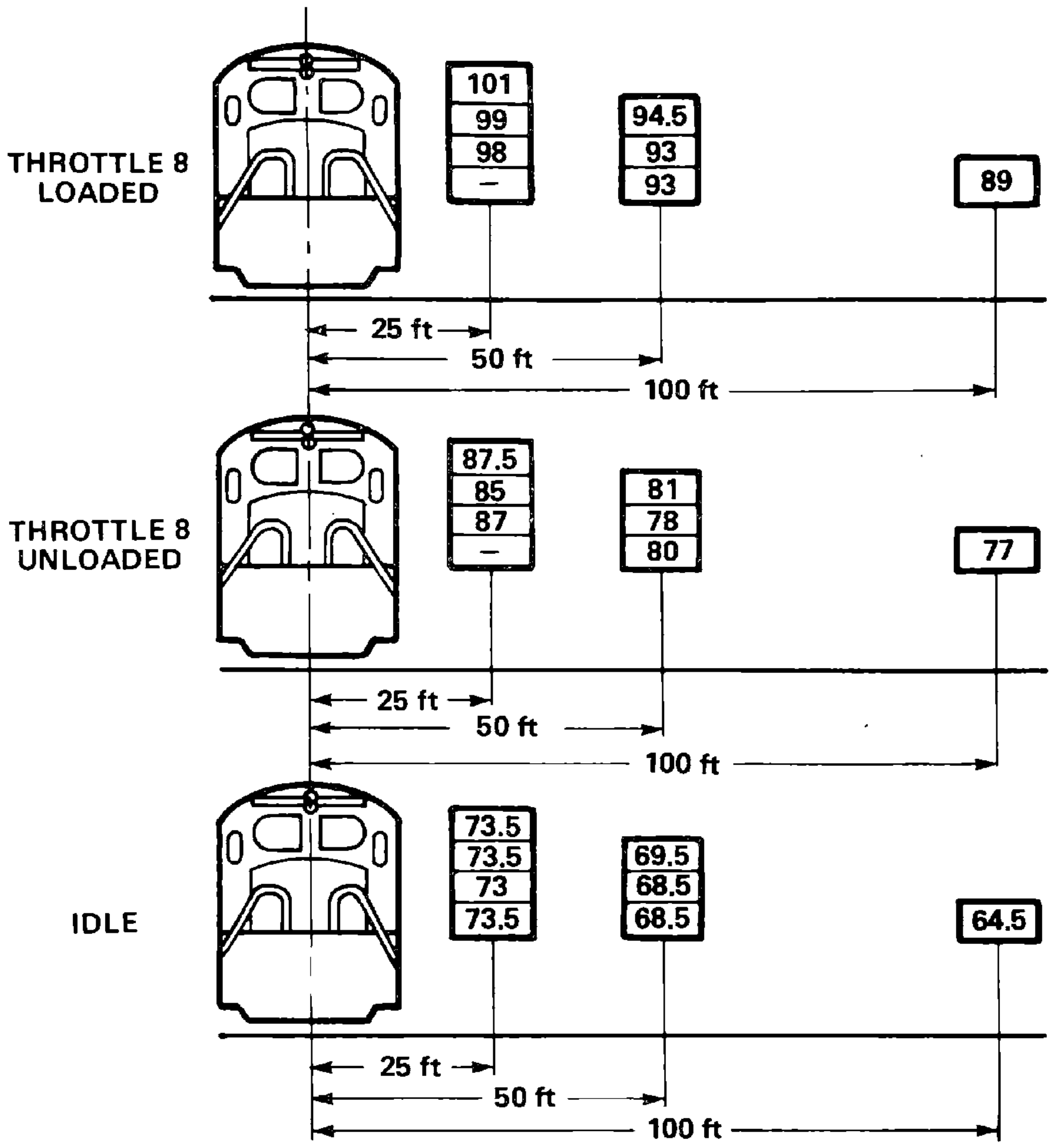


FIG. 19. A-WEIGHTED SOUND LEVELS DURING SHIELDING TESTS WITH LOCOMOTIVE IN CONFIGURATION WITH ALL SOURCES, *EXCEPT EXHAUST* FULLY QUIETED.

At the 25 ft microphone, however, there is a noticeable change in noise level with microphone height for certain locomotive configurations and operating conditions. For the locomotive operating fully loaded in throttle 8 and in normal operating condition (Fig. 17) or configured to enhance exhaust noises (Fig. 19), the noise level increases with height. At idle or throttle 8, unloaded, the effect is absent or at least less prominent. Since in these latter two throttle and load settings exhaust noise is significantly reduced, the 2.5 to 3 dBA increase in noise level with height, when operating fully loaded at throttle 8, appears to be due to a decrease in the shielding of exhaust noise by the locomotive hood at the higher microphones.

For the tests with the locomotive configured to enhance radiator cooling for noise, the opposite effect is seen at the 25 ft microphone (Fig. 18); i.e., the noise level decreases slightly with height, indicating increased shielding of the fan by the hood with increasing microphone height. The reason for the increased shielding becomes apparent after examining Fig. 2 at the beginning of this report. The figure shows that the radiator cooling fan is located below the radiator near the top of the hood. Louvers in the side of the hood allow an almost unobstructed view of the fan from positions near the ground. As the observer's height above the ground increases his view of the fan becomes gradually more obstructed by the hood. Consequently the hood begins to provide more acoustic shielding.

4.2.3 Diagnostic tests

The so-called "cover and expose" technique was used to quantify the strengths of the major sources of noise. All major sources were treated to reduce their noise to the maximum extent possible. The treatments were then removed from one source, and the resulting increase in noise was attributed to that source.

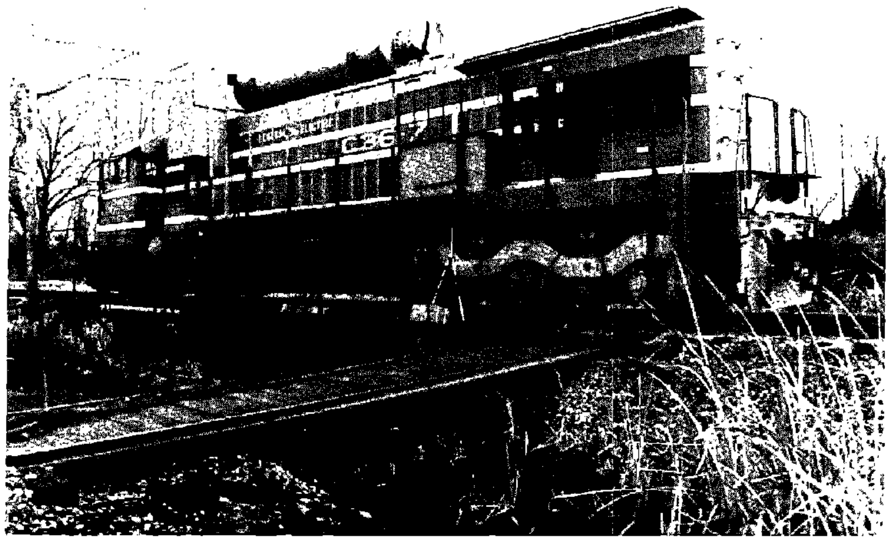
The process was repeated for each source. The "cover and expose" technique will generally work well if, when a source is exposed, there is a significant increase in noise over the fully quieted condition. For the tests described here, the cover and expose technique worked well at most throttle settings for the exhaust, radiator cooling fan, and equipment blower. For all other sources and for structureborne noise a transfer function technique was employed that extrapolated noise measurements near the source (vibration measurements for structureborne noise) to the far field.

a. Locomotive Treatments

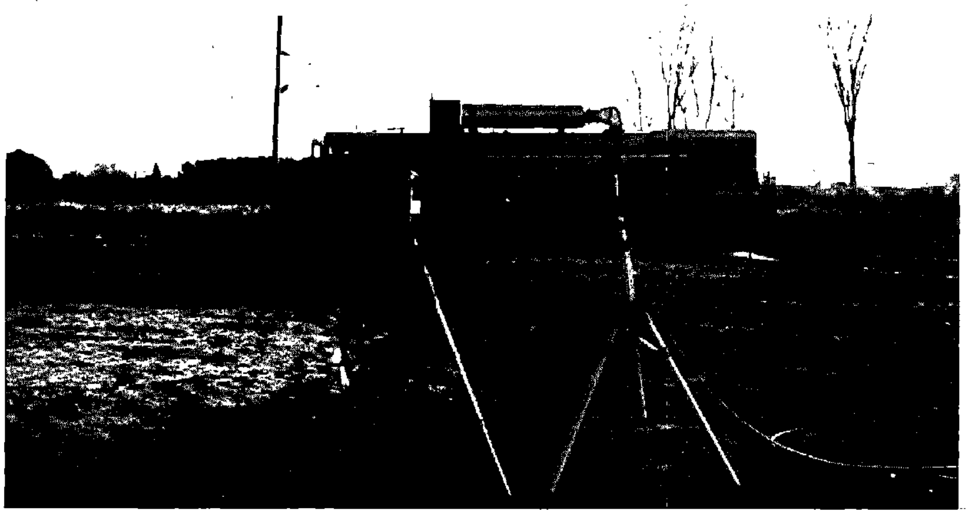
To carry out the "cover and expose" technique, each major source on the locomotive had to be treated. The treatments consisted of the following:

- Exhaust – industrial exhaust silencer
- Radiator cooling fan – disconnected from the engine
- Radiator cooling fan gear drive – wrapped with glass fiber mat and lead vinyl
- Engine/main generator – the inside of the hood lined with 3 in. of glass fiber mat and all access doors sealed with duct tape
- Equipment blower – a silencer over the air inlets on both sides of the hood
- Engine intake – a silencer over the inlet on both sides of the hood
- Air compressor – the bypass engaged so that the compressor is unloaded.

The fully quieted locomotive is shown in Fig. 20. The exhaust silencer can be seen mounted on top of the hood. Duct work constructed by G.E. connects the silencer to the exhaust stack

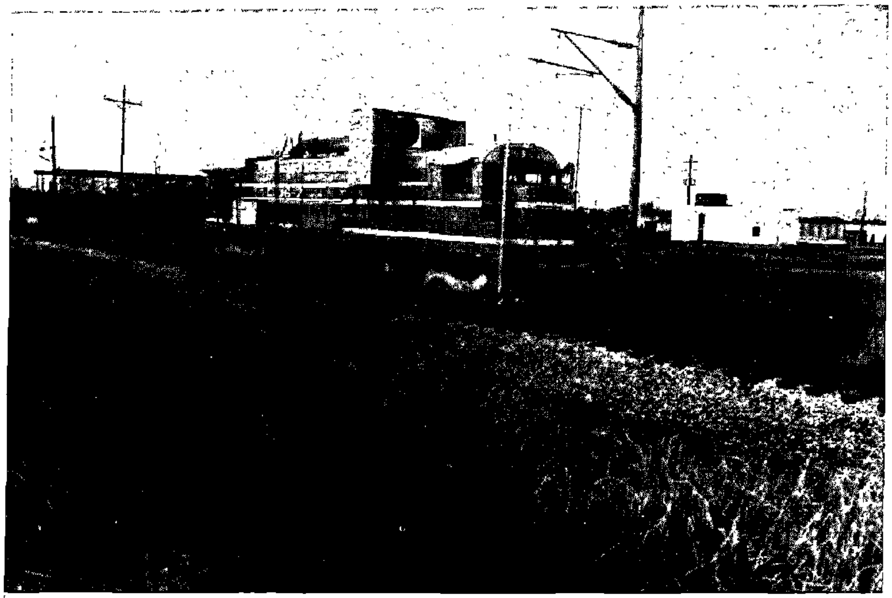


(a) Looking Southeast.



(b) Looking South Towards the Test Locomotive from the 100 Ft Microphone.

FIG. 20. FULLY TREATED LOCOMOTIVE.



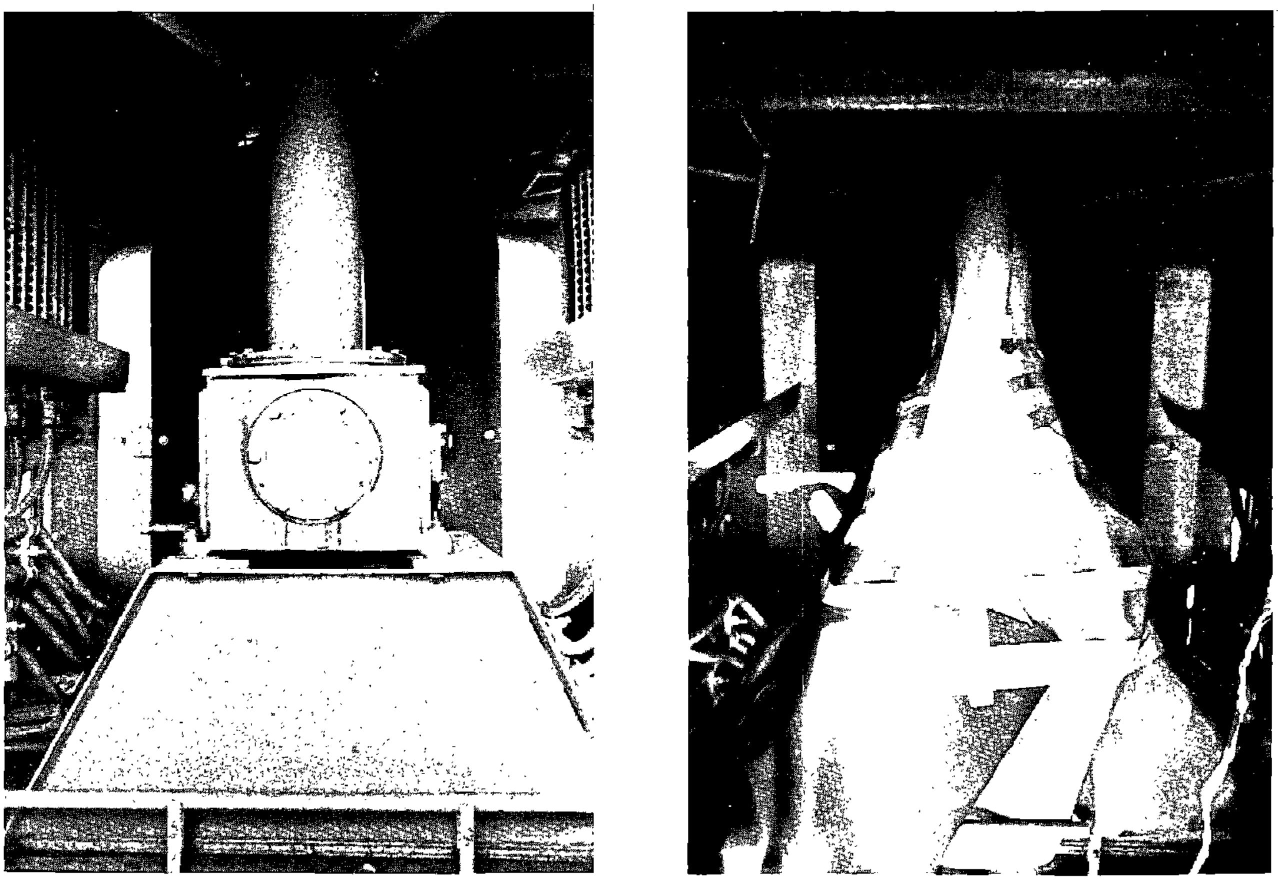
(c) Looking Northwest Toward the Load Cell Building

(d) Looking West, the Load Cell Building is Out of the Picture to the Right.

FIG. 20. CONTINUED.

through an expansion bellows, best seen in Fig. 20a. The silencer was designed and built by Universal Silencer. It is a 22-in. diameter straight flow type designed to minimize backpressure, but still provide 20 dB of exhaust noise attenuation.

The radiator cooling fan is mechanically driven by the engine through a right-angle-gear drive. To eliminate fan and gear-drive noise, we disconnected the drive to the fan at a flexible coupling between the air compressor and the fan gear drive. To control noise from the gear-drive when the fan was running, we wrapped the gear drive with glass fiber mat and covered that with 12 oz/ft^2 leaded vinyl sheet as shown in Fig. 21.



(a) Drive Before Wrapping (b) Drive Wrapped

FIG. 21. FAN, RIGHT ANGLE GEAR DRIVE.

The equipment-blower silencers are the two large boxes mounted high on the hood between the exhaust-silencer outlet and the cab. They were constructed of 1/2-in. plywood and lined with 3-in.-thick glass fiber mat. Air to the equipment blower flows in the top of the boxes and makes a right angle turn to flow through the air inlet in the side of the hood to the equipment blower compartment.

The engine inlet silencers best seen in Fig. 20a on the catwalk forward of the radiator cooling fan inlet were constructed similarly to the equipment blower silencers. Air flows in the forward end of the box and makes a right angle turn to enter the engine air inlet opening in the side of the hood.

b. Cover and Expose Test Procedure and Preliminary Results

The test procedure consisted of removing the treatment from a particular source with the locomotive in an otherwise fully quieted condition; operating the locomotive at idle, throttle 8, loaded, and throttle 8, unloaded; and recording the noise at the microphone locations of Fig. 7.

The results of the cover and expose tests are shown in Table 3. The A-weighted sound levels shown are those measured after the treatment on the indicated source was removed. For those sources unaffected by engine power, measurements were performed only at idle and throttle 8, unloaded. To determine the strength of a given source the noise levels measured after removal of a treatment from that source must be corrected to account for the fact that the measured level is due not only to the source of interest but also to contributions from the remaining treated sources (and, possible other sources that were not treated). The noise levels measured with the locomotive in the fully quieted

TABLE 3. A-WEIGHTED SOUND LEVELS MEASURED DURING "COVER AND EXPOSE" TESTS.

Treatment	100 Ft Microphone			50 Ft Microphone			25 Ft Microphone		
	Idle	T-8 Loaded	T-8 Unloaded	Idle	T-8 Loaded	T-8 Unloaded	Idle	T-8 Loaded	T-8 Unloaded
Baseline (No Treatment)	66	90.5	83.5	72.5	95	89	77	101.5	94
Exhaust	64.5	88.5	77	69.5	94.5	81	73.5	101	87.5
Radiator Cooling Fan	66	-	82.5	72	-	88	75	-	91
Cooling Fan Gear Drive	64	-	81.5	72.5	-	88.5	74.5	-	90.5
Engine Intake	62.5	78.5	73.5	70	83.5	-	75	90	85.5
Engine & Main Generator	62	79.5	73.5	70	84	80	76.5	90.5	85.5
Equipment Blower	61	-	76	70	-	83	73.5	-	89.5
Compressor	61	-	76*	70	-	81*	73.5	-	84.5
Fully Quieted	61.5	78	72.5	69	83.5	78.5	73.5	90.5	84.5

*The data for these two conditions was questionable. Consequently, we have relied on transfer function measurements to quantify the compressor source strength.

condition are a combination of the noise levels from all treated sources including the source of interest before the treatment was removed. It is these fully quieted noise levels that must be used to carry out the above correction and the following two limiting cases can be considered:

- If the treatment to the source of interest is very effective, then the fully quieted levels can be assumed to represent the sum of all the *other* treated source levels with essentially no contribution from the source of interest. The proper correction, then, is to logarithmically subtract the fully quieted level from the measured source. That result is a *lower bound* on the source strength* level.

*Note that this is the only proper assumption for the radiator cooling fan since it is shut off in the fully quieted condition.

- If the treatment to the source is not very effective, but all *other* source treatments are, then the fully quieted level can be assumed to represent the treated level of the source of interest alone and no correction is required to the level measured with the treatment removed from the source. That result is an *upper bound* on the source strength.

Of course, the true situation lies somewhere between these two extremes, and if the difference between the measured noise level with the treatment removed and the fully quieted level is large enough, then the source levels predicted by the upper and lower bounds are essentially the same. We will describe the results of applying these corrections to the measured source levels after describing the transfer function measurements, used to supplement the cover and expose measurements.

c. *Transfer Function Test Procedure*

To quantify the sources not diagnosed by the cover and expose technique, and to deal with structureborne sources, we resorted to a transfer function approach. To begin with, we must distinguish between airborne and structureborne paths. So far the "cover and expose" procedure has dealt only with the airborne path, i.e., the path by which the sound from a source is transmitted through the air (including for some sources transmission through the locomotive hood) to the wayside. In the structureborne path the source excites the locomotive structure into vibration and the vibrating structure including the hood radiates sound to the wayside. In the "cover and expose" measurements no attempt was made to silence the structureborne path by vibration isolating sources from the locomotive structure. Previous tests [2] showed that this would not be necessary.

For the airborne path transfer functions, we focused on the engine/generator, equipment blower, air compressor, and engine intake.* For all but the engine intake, we measured the airborne transfer functions. A loudspeaker was placed under the hood in the compartment containing the source of interest and driven with pink noise filtered in octave bands. The sound level at one or more positions in the compartment and at the three wayside microphones were then measured in corresponding octave bands. The differences between farfield and nearfield sound levels in each octave band then defined transfer functions that were used to extrapolate nearfield noise levels measured in each compartment with the locomotive operating at idle, throttle 8, loaded, and throttle 8, unloaded, to the levels at the farfield microphones. Figure 22 shows one of the three microphone locations in the

*No measureable increase in noise was found 3 ft in front of the engine intake or at the farfield microphones after removal of the intake silencer. Consequently, no intake source levels have been derived.

FIG. 22. TYPICAL MICROPHONE LOCATION IN ENGINE COMPARTMENT FOR ENGINE/MAIN GENERATOR TRANSFER FUNCTION TEST.

engine compartment over the engine. A single microphone was used in the equipment blower and air compressor compartments.

The structureborne transfer function measurements focused on the engine/generator, air compressor, and cooling fan right-angle-gear drive.* The test procedure consisted of instrumenting the mounts of each piece of equipment with accelerometers measuring vibration in the three orthogonal directions, vertical axial, and lateral as shown in Fig. 23. Each mount was then struck with a hammer in the three orthogonal directions. Simultaneous recordings were then made of the three accelerometer signals and the signals from the three microphones at the locations in Fig. 7. In general, the vibration in the direction of hammering dominated. The transfer functions were then derived by simply subtracting the acceleration level in the direction of hammering in octave

*Restrictions on availability of the test site resulted in there not being enough time to carry out the measurements on the equipment-blower structureborne noise.

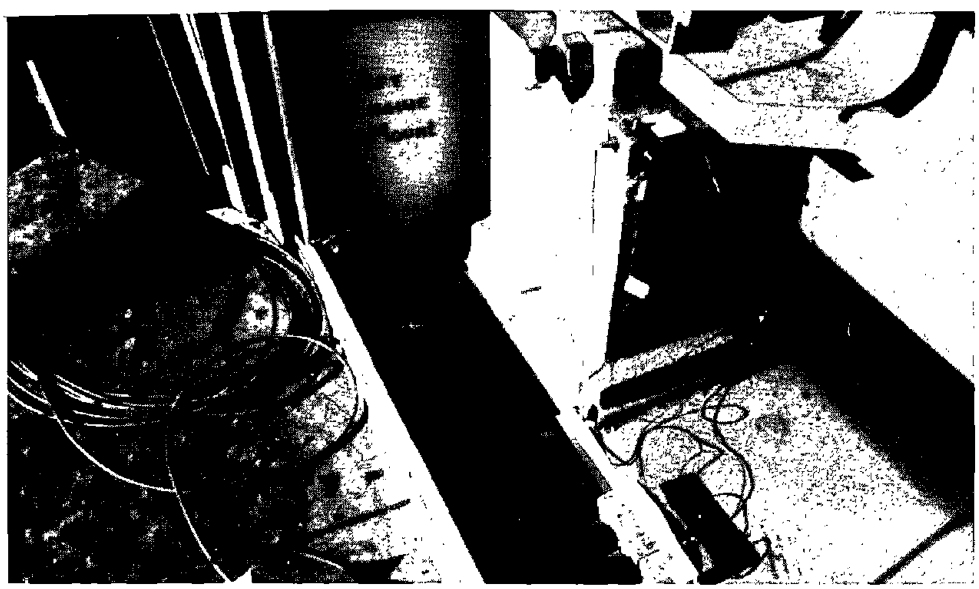


FIG. 23. ENGINE MOUNT INSTRUMENTED FOR STRUCTUREBORNE TRANSFER FUNCTION TEST.

bands from the sound level in octave bands at each of the three microphone positions.

The locomotive was then operated at idle; throttle 8, loaded; and throttle 8, unloaded; and the signals from the acceleration in the three orthogonal directions on the mounting points of the engine, gear drive, and compressor recorded. By adding these levels to the appropriate transfer functions we determined the structureborne contribution from the mounts of each piece of equipment.

d. Results

Figures 24 through 32 show the 1/3-octave band source spectra at the three microphone positions of Fig. 7, for the locomotive operating at idle; throttle 8, loaded; and throttle 8, unloaded. Structureborne source levels were generally found to be

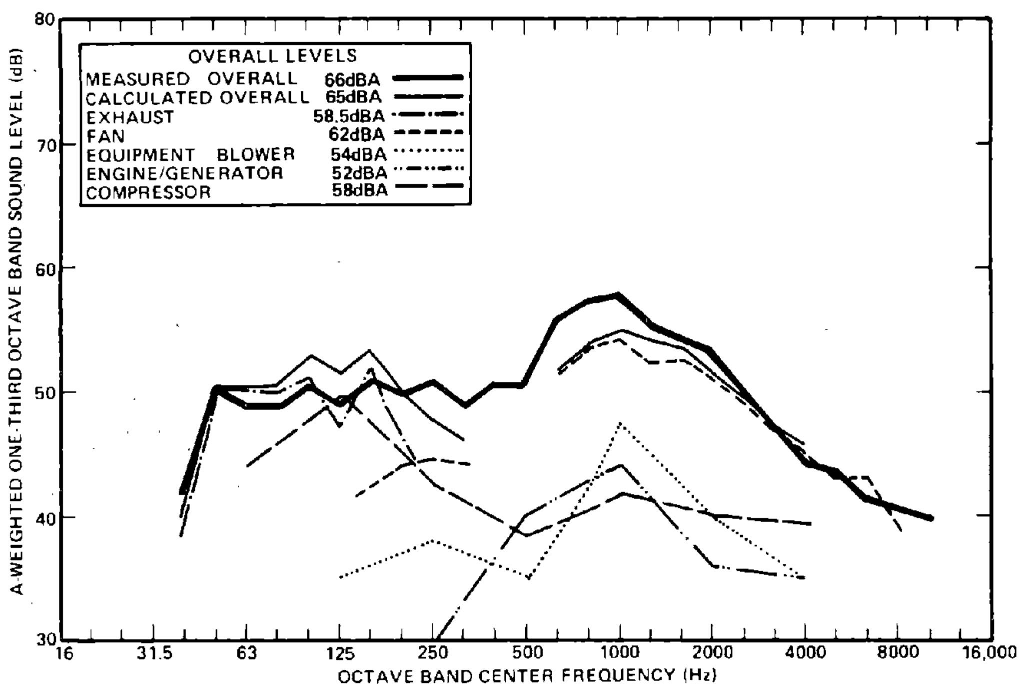


FIG. 24. LOWER BOUND ONE-THIRD-OCTAVE SOURCE SPECTRA; IDLE, 100 FT MICROPHONE.

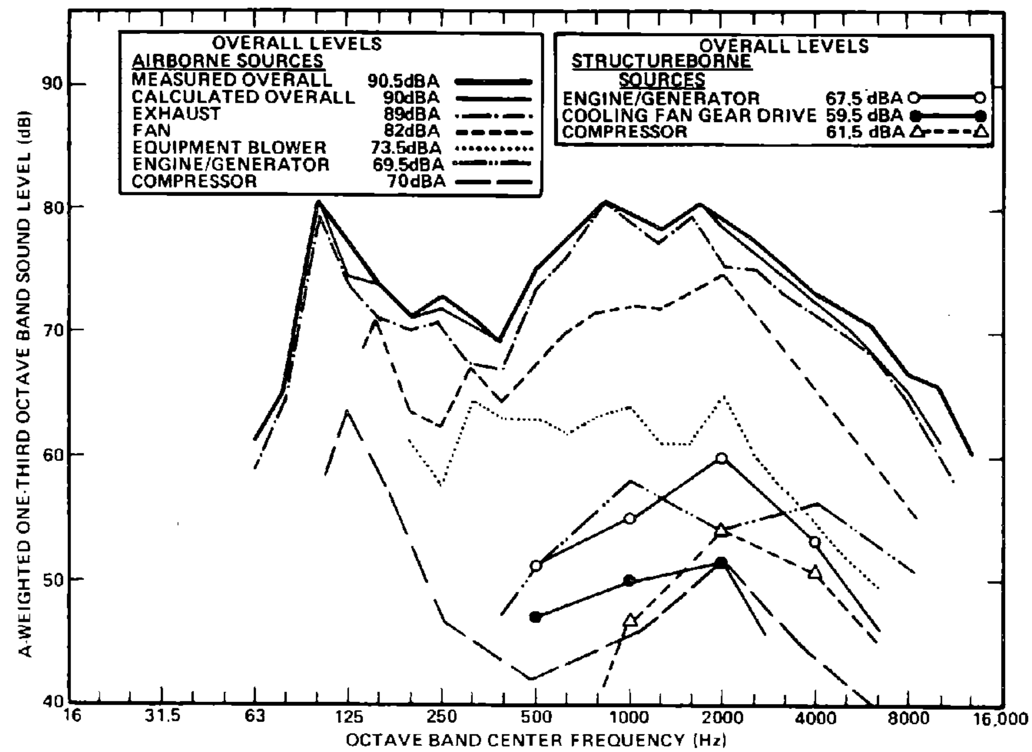


FIG. 25. LOWER BOUND ONE-THIRD-OCTAVE SOURCE SPECTRA; THROTTLE 8, LOADED; 100 FT MICROPHONE.

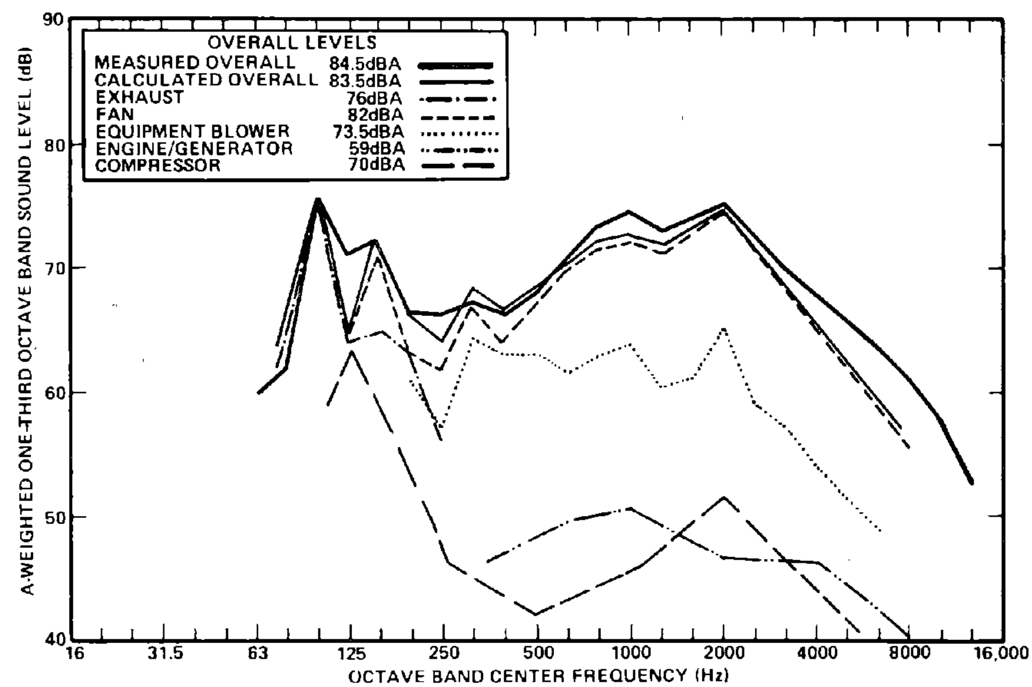


FIG. 26. LOWER BOUND ONE-THIRD-OCTAVE SOURCE SPECTRA; THROTTLE 8, UNLOADED; 100 FT MICROPHONE.

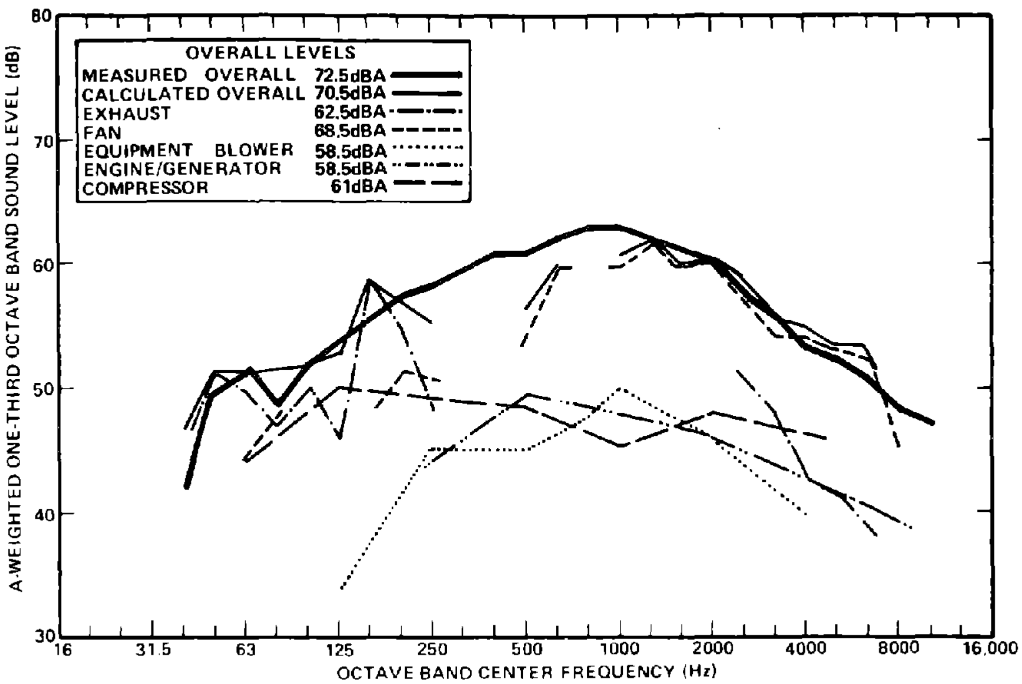


FIG. 27. LOWER BOUND ONE-THIRD-OCTAVE SOURCE SPECTRA; IDLE; 50 FT MICROPHONE.

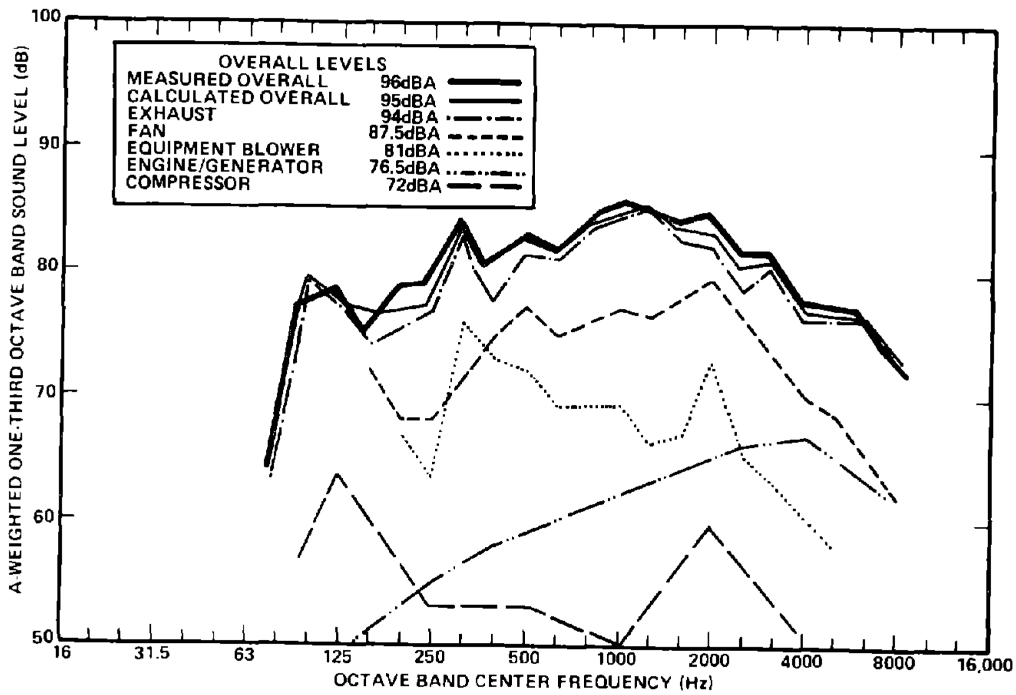


FIG. 28. LOWER BOUND ONE-THIRD-OCTAVE SOURCE SPECTRA; THROTTLE 8, LOADED; 50 FT MICROPHONE.

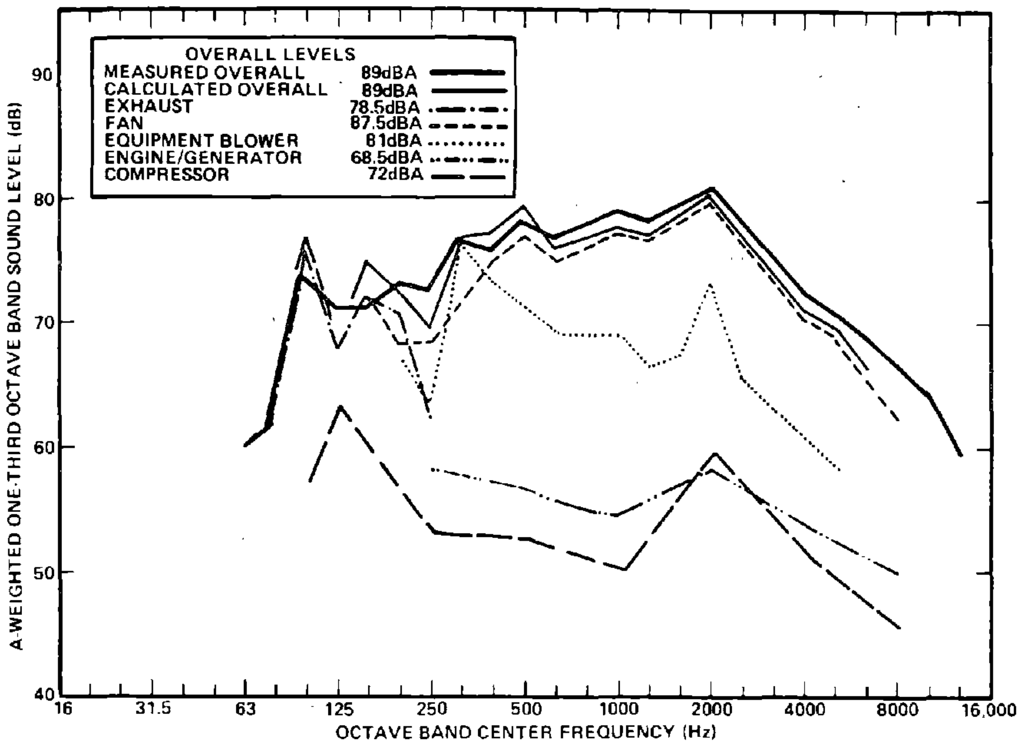


FIG. 29. LOWER BOUND ONE-THIRD-OCTAVE SOURCE SPECTRA; THROTTLE 8, UNLOADED; 50 FT MICROPHONE.

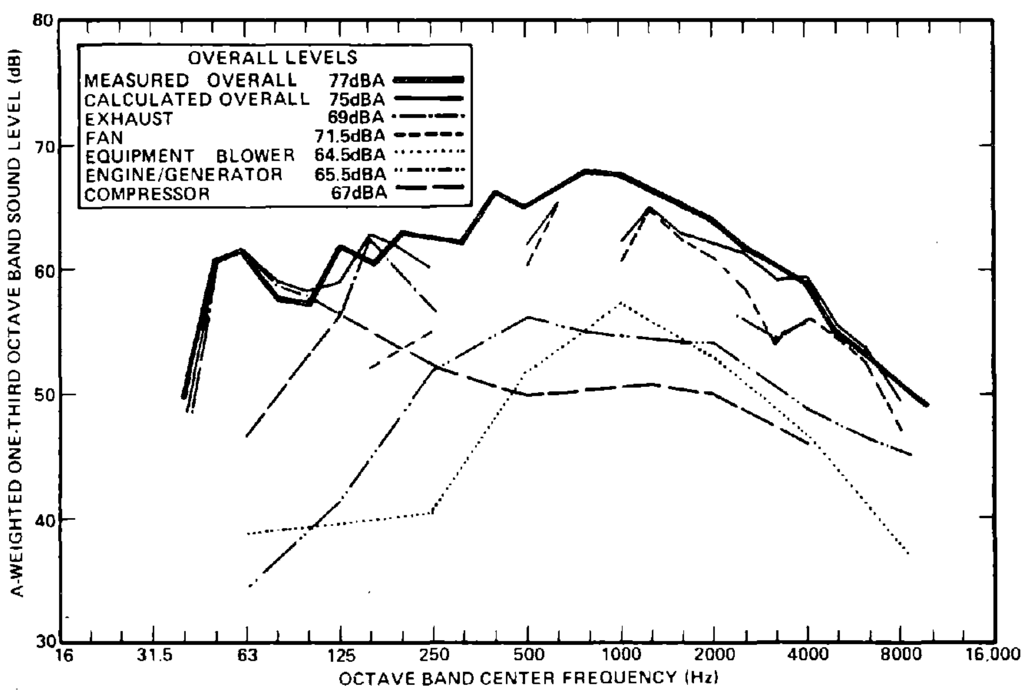


FIG. 30. LOWER BOUND ONE-THIRD-OCTAVE SOURCE SPECTRA; IDLE; 25 FT MICROPHONE.

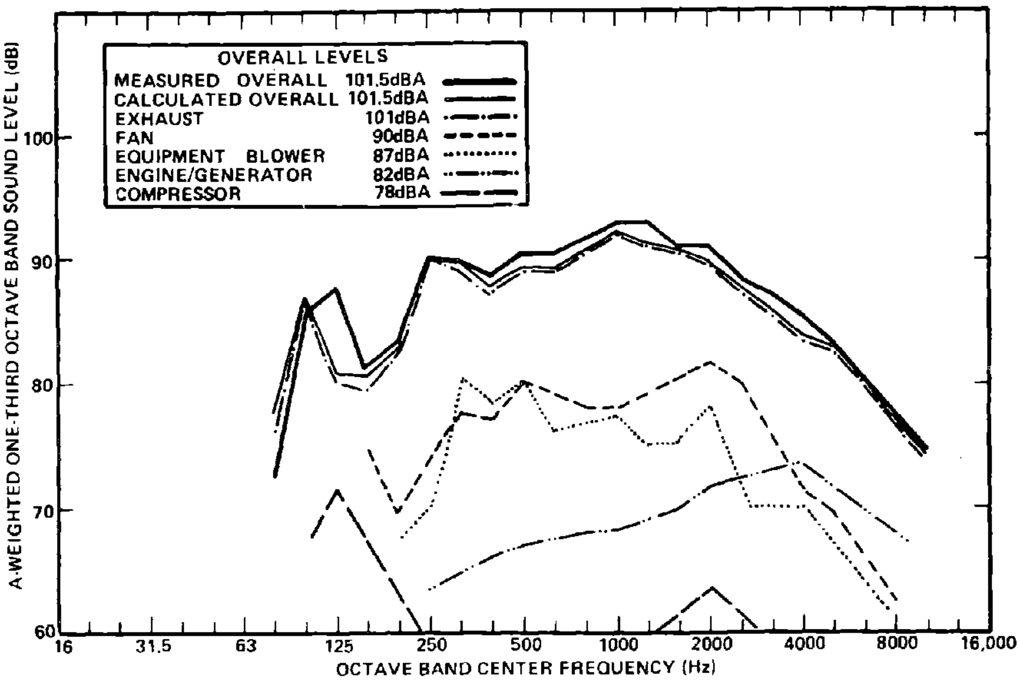


FIG. 31. LOWER BOUND ONE-THIRD-OCTAVE SOURCE SPECTRA; THROTTLE 8, LOADED; 25 FT MICROPHONE.

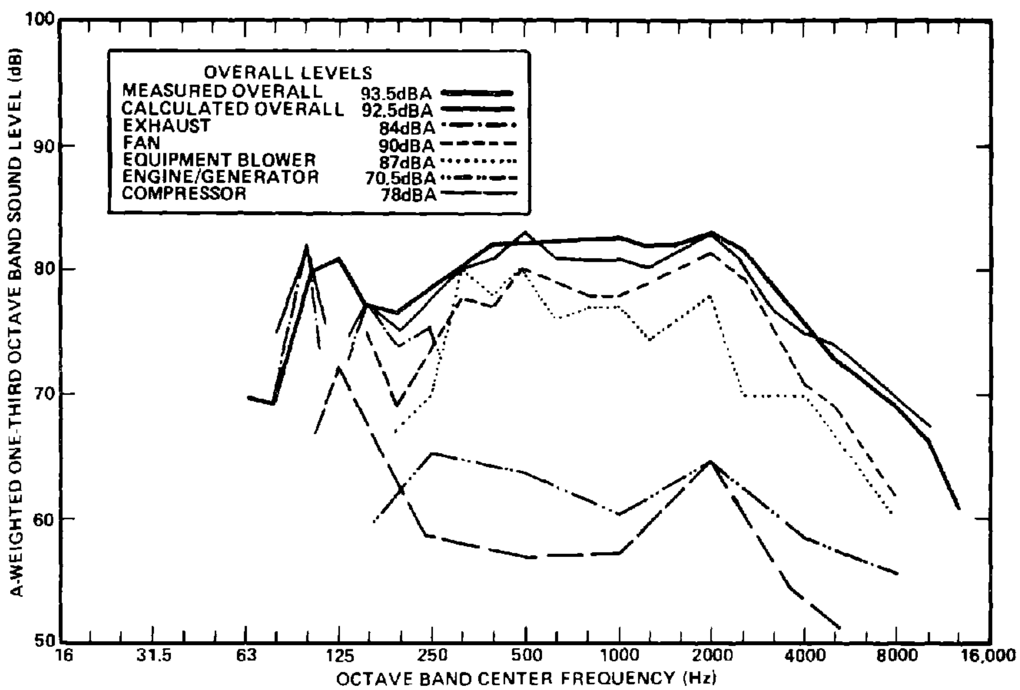


FIG. 32. LOWER BOUND ONE-THIRD-OCTAVE SOURCE SPECTRA; THROTTLE 8, UNLOADED; 25 FT MICROPHONE.

negligible. For illustrative purposes, Fig. 25 shows the structureborne source spectra for throttle 8, loaded. For throttle 8 operation, all but the engine/generator air-compressor source spectra have been obtained from cover and expose measurements by subtracting the fully quieted spectra from the spectra measured with a given treatment removed. As the discussion earlier pointed out, these spectra represent a lower bound on the source strengths. The upper bound has been omitted from these figures so as to avoid further complicating an already involved display. Both upper and lower bounds are given in the bar charts of Figs. 34 through 36.

For operation at idle the cover and expose procedure was not so successful as is evident in the incomplete source spectra in Figs. 24 through 26. No source level has been shown in any one-third-octave-band if the noise level with the treatment removed from that source was not at least 2 dB higher than the fully quieted level in that band. Consequently, for idle only, the exhaust source spectra at low frequency and the radiator cooling fan source spectra at high frequency have been obtained by cover and expose methods. For each of the other sources, no measurable change in the fully quieted spectra occurred as each noise reducing treatment was removed. Figure 33 compares the baseline spectra at idle with the fully quieted spectra. Only a small reduction (4-5 dBA) occurred after fully quieting the locomotive, whereas, at throttle 8 a much larger reduction in noise occurred (~12 dBA). That small reduction in noise at idle is the main reason the cover and expose procedure did not work well.

If we examine Fig. 33 carefully, strong tones in 400, 800 and 1250 Hz one-third-octave bands are visible in the fully quieted spectra at all three microphone locations, but most strongly at the 50 ft location. The strength of these tones especially at 800 Hz was highly variable from test to test. The tones were apparent only after treating the locomotive, and occurred in all of the source spectra, i.e., the spectra measured after removing each of the noise control treatments one at a time. Occasionally, the 800 Hz band had such a high level that it exceeded the level of that band in the baseline tests. The source of these tones is presently unclear. Of the potential candidate sources, the radiator cooling fan has a blade passage frequency of 64 Hz, the equipment blower 143 Hz, and the turbocharger (1200 rpm at idle and 73 blades) 1460 Hz. None of these fundamentals or their harmonics matches especially well with the three observed tones.

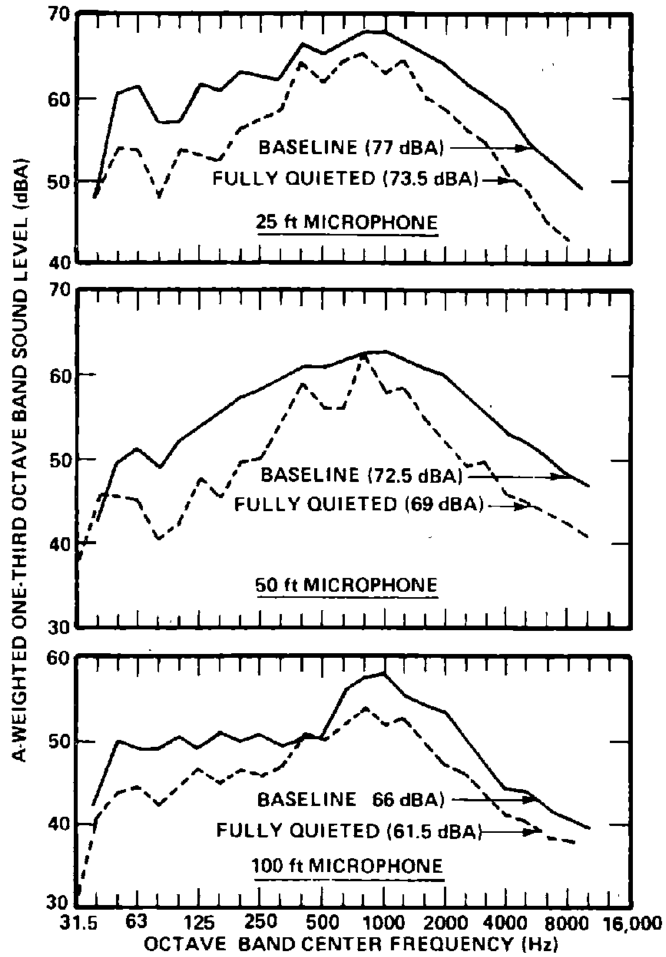


FIG. 33. COMPARISON OF FULLY QUIETED NOISE LEVELS AT IDLE WITH BASELINE NOISE LEVELS.

Figures 24 through 32 each present overall levels for each of the source spectra displayed. In some cases, especially at idle, the source spectra are incomplete as described above. The overall levels in the figures have been obtained by simply adding up the levels in each one-third-octave band where source spectrum levels have been obtained. The resulting levels are lower bounds and, in some cases, where incomplete spectra have been used, may significantly underestimate the source levels. This is especially evident in Figs. 34 through 36 in the exhaust levels at idle. The upper bound in those figures was obtained from the noise levels measured with the locomotive fully quieted (with the exhaust muffler removed), and is seen to be 5 - 6 dBA higher than the lower bound. It is interesting to note that the calculated overall levels agree best with the measured overall levels when the upper bound exhaust levels are used. This suggests that the exhaust muffler may not have been performing well at idle in the mid and high frequencies and that the fully quieted levels were controlled by exhaust noise.

Since source spectra have been obtained from both cover and expose measurements and transfer function measurements, it is useful to compare the results of the two techniques. Figure 37 makes that comparison for the equipment blower. The agreement, especially in the overall levels, is very encouraging.

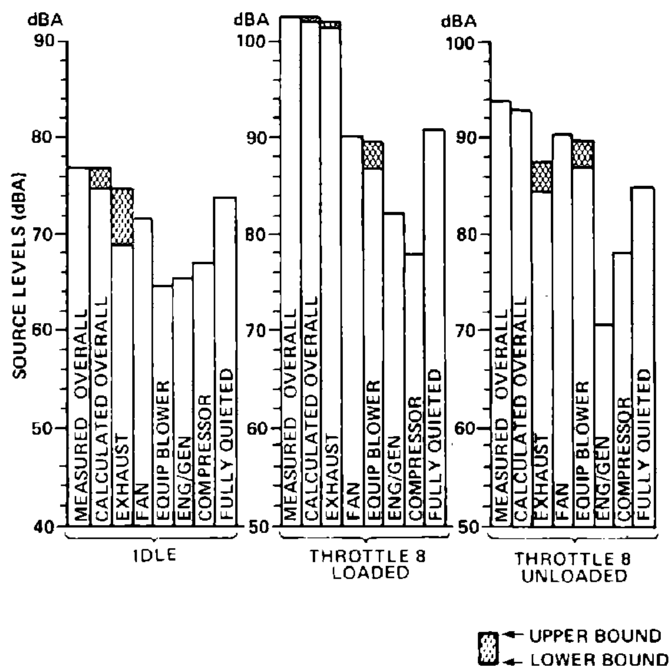


FIG. 34. UPPER AND LOWER BOUND SOURCE LEVELS AT 25 FT.

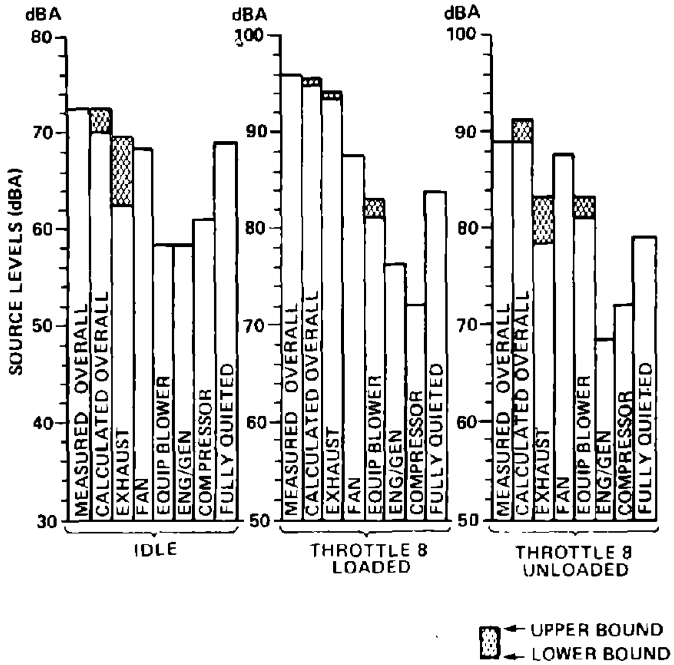


FIG. 35. UPPER AND LOWER BOUND SOURCE LEVELS AT 50 FT.

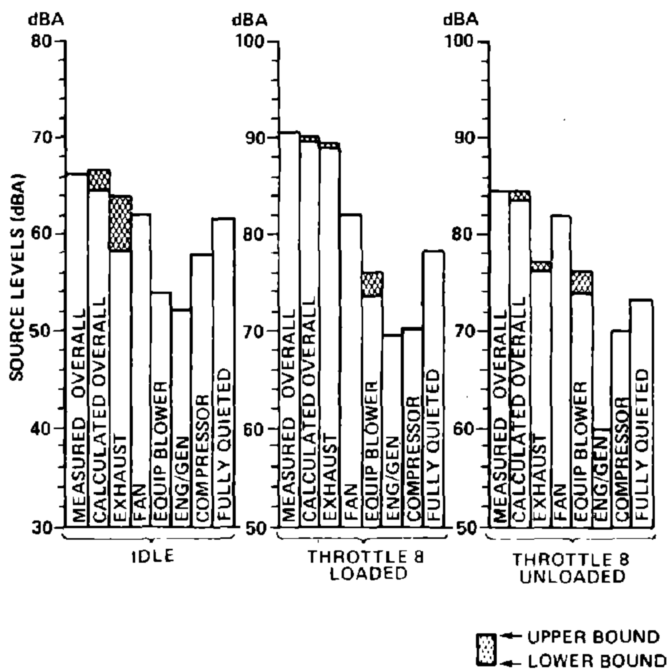


FIG. 36. UPPER AND LOWER BOUND SOURCE LEVELS AT 100 FT.

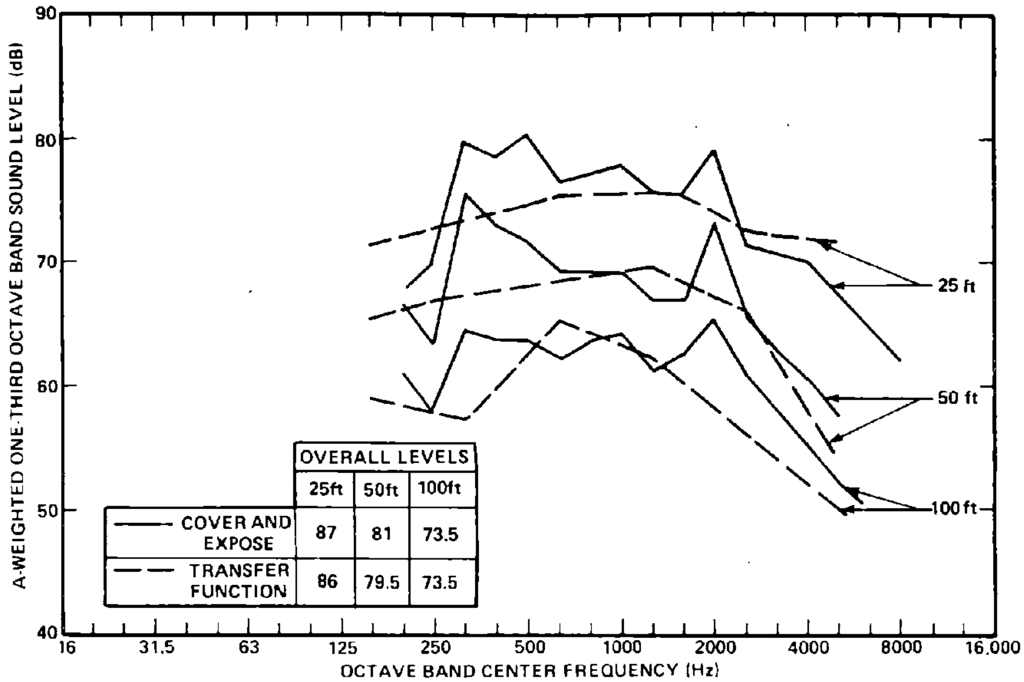


FIG. 37. EQUIPMENT BLOWER SOURCE LEVELS AT THROTTLE 8 AT THREE MICROPHONE POSITIONS, DETERMINED FROM BOTH "COVER AND EXPOSE" AND TRANSFER FUNCTION TECHNIQUES.

The overall picture that emerges is that:

- At throttle 8, loaded, exhaust noise is by far the predominant source
- At throttle 8, unloaded, the radiator cooling fan predominates followed by the engine exhaust and the equipment blower,
- At idle, the radiator cooling fan and engine exhaust predominates.

5. CONCLUSIONS

5.1 Overview

A series of measurements performed on a C36-7 and General Electric diesel-electric locomotive have characterized the noise it produces and quantified the sources of that noise. During a series of pass-by tests, wayside-noise levels at throttle 8, 100 ft from the track centerline, were found to be in excess of 90 dBA, whereas cab-interior noise was generally 80 - 84 dBA. Wheel/rail noise was generally not a significant contributor to wayside or cab-interior noise.

Stationary tests examined the shielding proved by the locomotive hood. Significant effects were found only for locations very near the locomotive (25 ft away). Additional tests quantified the sources of noise on the locomotive with it operating at idle; throttle 8, loaded; and throttle 8, unloaded. The radiator cooling fan and engine exhaust, are the primary sources at idle. At throttle 8, loaded, the exhaust is primarily responsible for the noise with the radiator cooling fan adding only an additional 1 dBA. The fan, however, is the primary source at throttle 8, unloaded, with the exhaust and equipment-blower together adding an additional 2 - 3 dBA.

5.2 Noise Control

For the control of noise at throttle 8 under full load and at idle, the diagnostic information obtained from this study indicate that significant reductions in noise from this GE locomotive could be achieved by treating just the engine exhaust and the radiator cooling fan.

Exhaust noise can be treated with an exhaust muffler. Limited space under the locomotive hood does, however, impose a severe design restriction. Exterior mounting of the muffler is generally not feasible because on the larger line-haul locomotives there is insufficient clearance between the hood and tunnels. Another severe restriction is the very low exhaust backpressure requirements (5 in. of H_2O) on turbocharged locomotives. It has been demonstrated, however, that these difficulties can be overcome. Both GE and EMD, for example, have been able to modify the vast majority of their locomotives to achieve the federally mandated 87 dBA regulation that will go into effect January 1, 1980. For most locomotives, the primary modification has been the addition of an exhaust muffler.

Fan noise is usually treated in one of two ways. Obstructions at the fan inlet are removed or the pumping efficiency of the fan is improved so that fan speed can be reduced. The first approach reduces turbulence entering the fan, and hence, the resulting noise (usually tones at multiplies of the blade passage frequency) due to the fluctuating pressures on the fan blades as they encounter the turbulent eddies. The second approach allows the fan speed to be reduced so as to take advantage of the dependence of fan noise on the fan speed to the sixth power.

In the first approach, any structure in the fan inlet is minimized or moved as far in front of the fan blades as possible. There are a number of struts supporting a grill work in front of the fan blades. Removing these struts would reduce any tones at the blade passage frequency or multiples of that frequency.

Improving the pumping efficiency of the fan may prove to be difficult since the fan cannot be made much larger and still fit under the hood, existing fan/shroud clearances are not excessive and existing fan blades are already somewhat sophisticated in shape. It may be possible through a redesigned cooling system to reduce required air flow rates and still achieve the required cooling. Reduced fan speeds could then be tolerated.

For illustrative purposes we have calculated in Table 4 the reduction in noise that would be achieved if exhaust and fan noise could each be reduced 10 dBA. We believe that such a reduction is achievable with present day technology although some investment in development would have to be made to design and build the required hardware.

TABLE 4. NOISE LEVELS AT 100 FT ACHIEVABLE THROUGH ENGINE EXHAUST AND RADIATOR COOLING FAN TREATMENT.

	No Treat-ment	Exhaust Reduced 10 dBA	Fan Reduced 10 dBA	Exhaust and Fan Reduced 10 dBA
Idle	66 dBA	63 - 65 dBA	63 - 64.5 dBA	59.5 - 61 dBA
Throttle 8 Full Load	90.5 dBA	84.5 - 86 dBA	89.5 - 90 dBA	81.5 - 83 dBA

Quieting beyond the levels shown would require additional exhaust treatment and silencing of the equipment blower. All of the techniques applicable to the control of radiator cooling fan-noise would apply to the equipment blower. In addition, there is sufficient space within the equipment blower compartment to consider installing a silencer.

APPENDIX A: TRANSFER FUNCTIONS

The airborne transfer functions measured as described in the text are shown in Figs. A.1 through A.3. High background noise at the 100 ft microphone interferred with the engine compartment measurements in some of the octave bands (250 and 2000 Hz). It is encouraging to note that the transfer functions for the 100 ft microphone agree quite well with comparable measurements made on an EMD locomotive in an earlier study [2].

The structureborne transfer functions for the 100 ft microphone are shown in Figs. A.4 through A.6. The engine mount transfer functions are comparable to those measured on the EMD locomotive mentioned above [2].

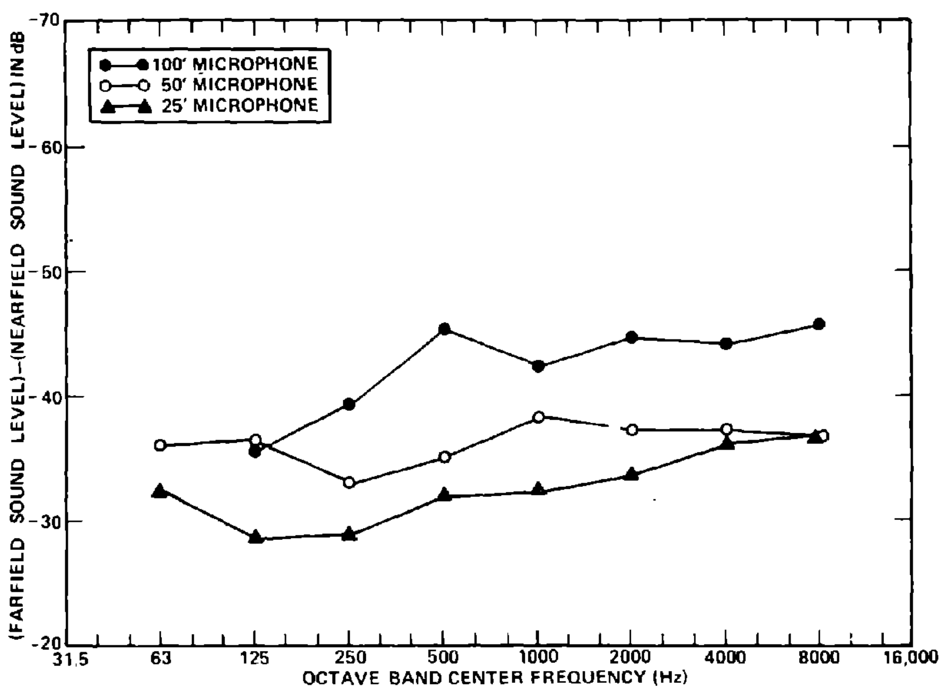


FIG. A.1. AIRBORNE TRANSFER FUNCTIONS FOR COMPARTMENT.

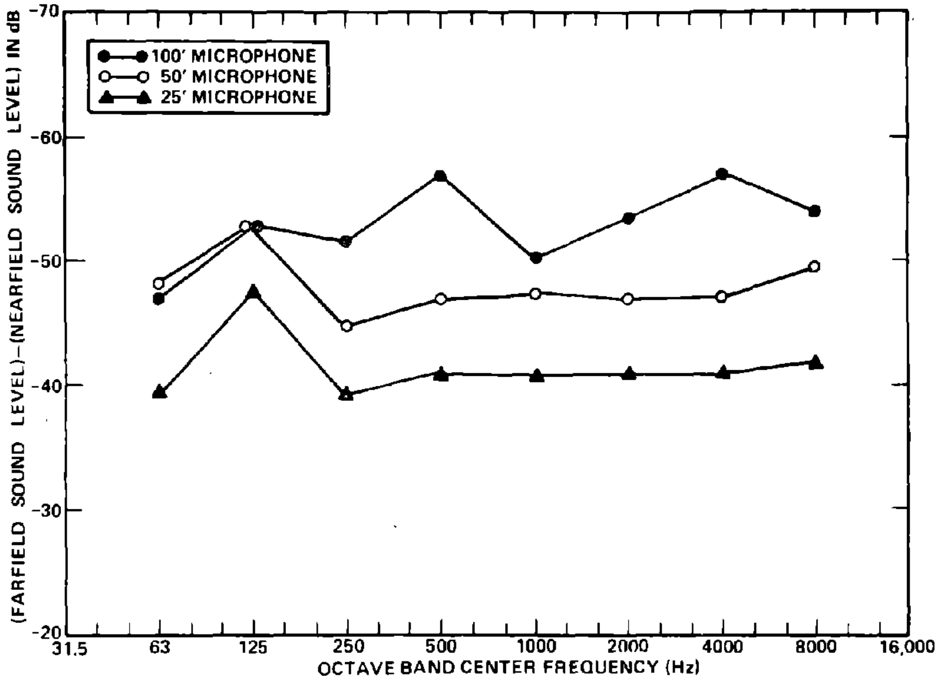


FIG. A.2. AIRBORNE TRANSFER FUNCTIONS FOR COMPARTMENT (Cont'd).

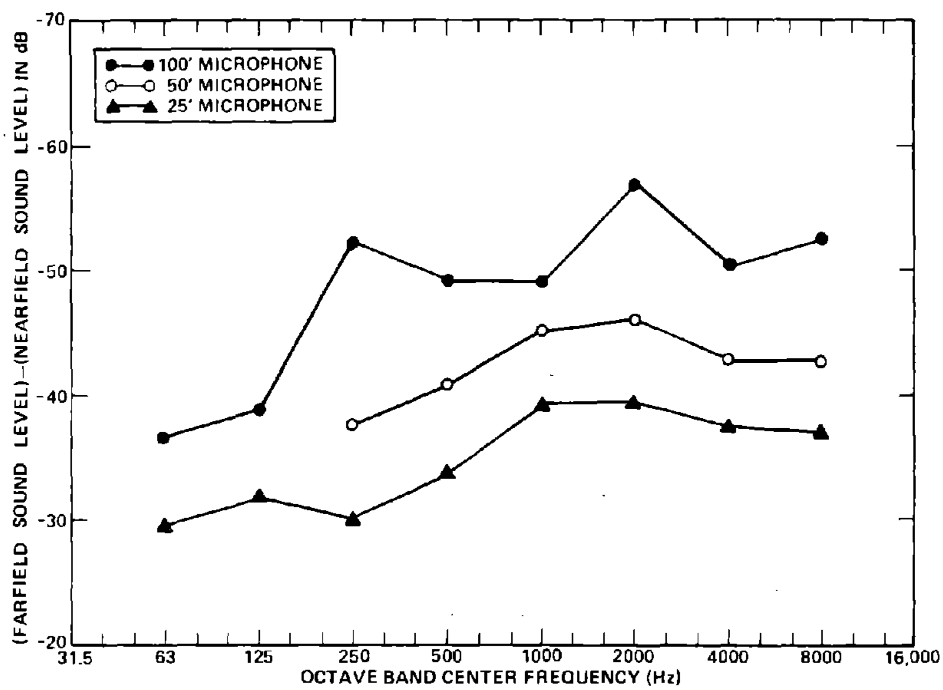


FIG. A.3. AIRBORNE TRANSFER FUNCTIONS FOR COMPARTMENT (Concl'd).

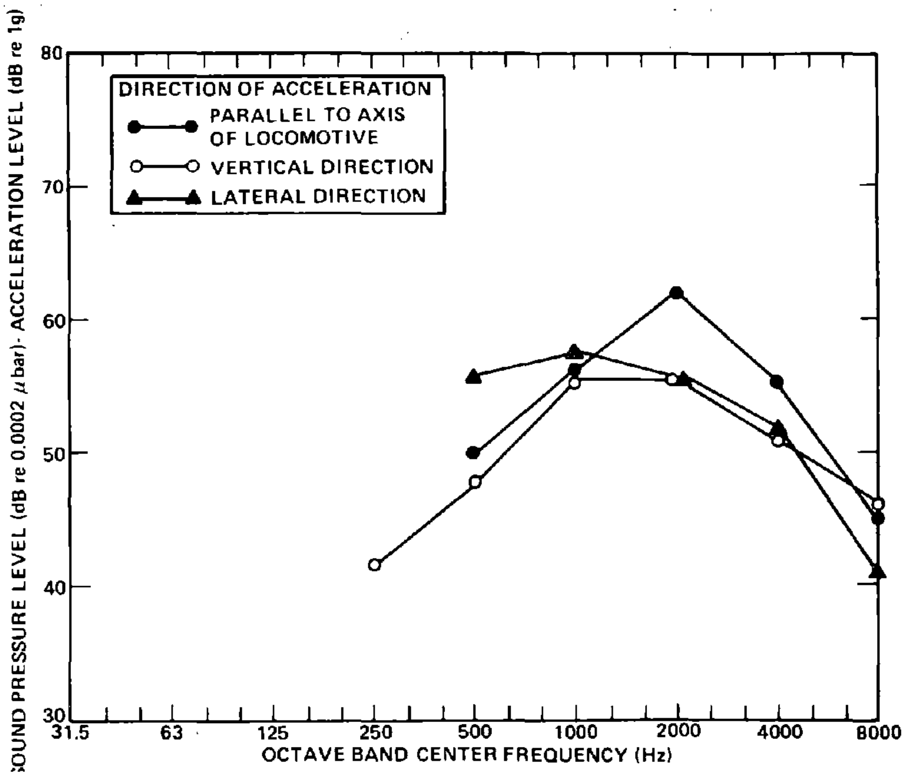


FIG. A.4. STRUCTUREBORNE TRANSFER FUNCTIONS FOR COMPARTMENT.

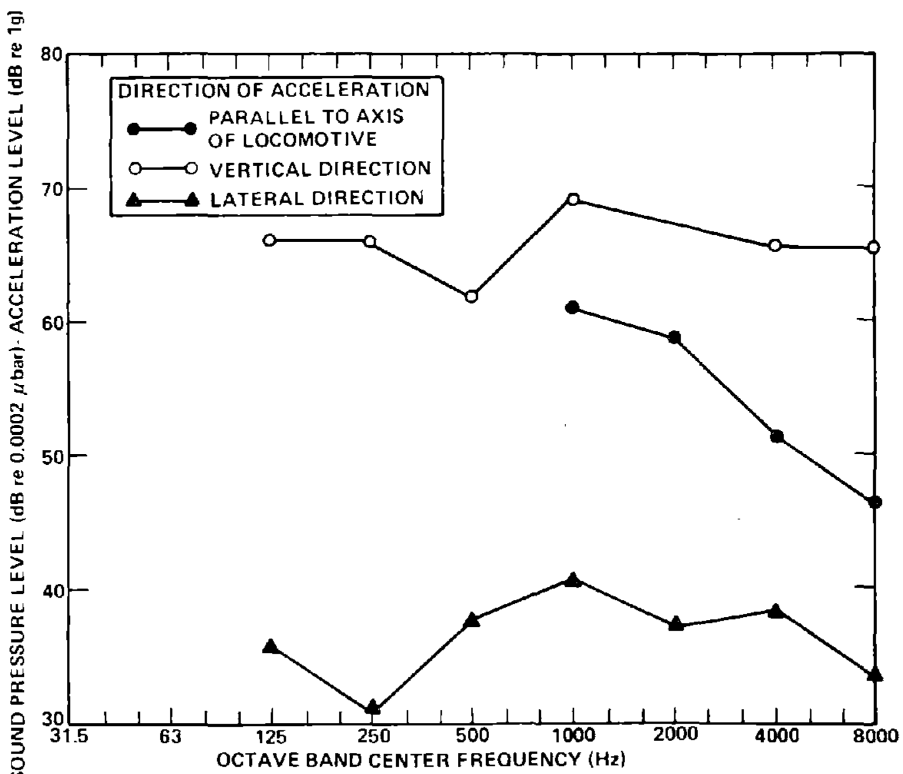


FIG. A.5. STRUCTUREBORNE TRANSFER FUNCTIONS FOR COMPARTMENT (Cont'd).

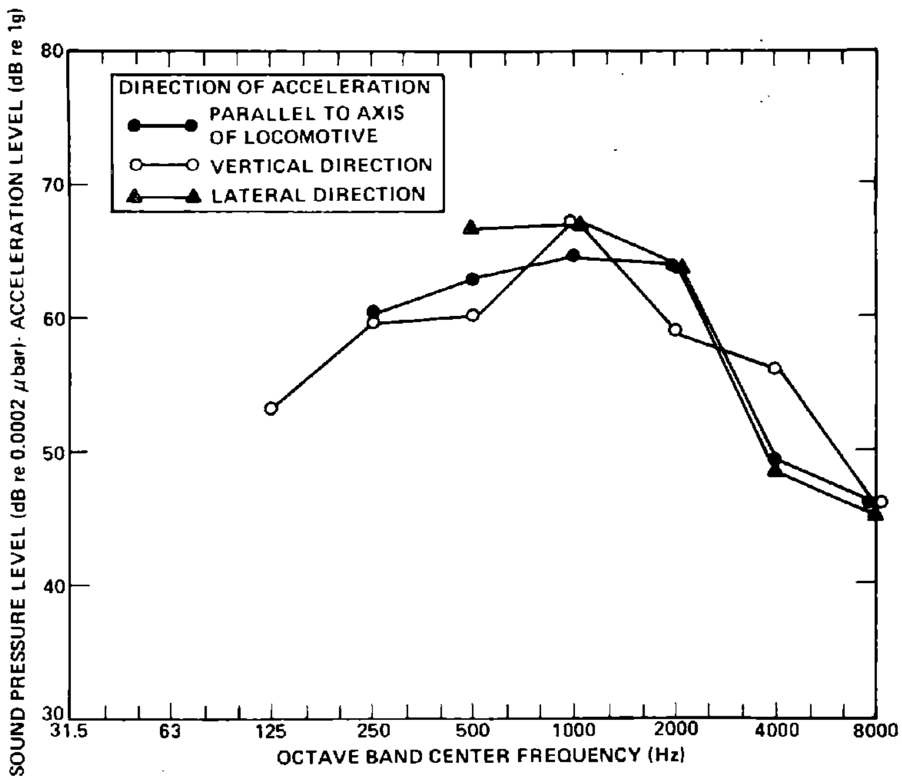


FIG. A.6. STRUCTUREBORNE TRANSFER FUNCTIONS FOR COMPARTMENT (Concl'd).

APPENDIX B: REPORT OF NEW TECHNOLOGY

During this program, a combination of the "cover and expose" and "transfer function" techniques was applied to the diagnosis of the noise sources in a locomotive. More importantly, the two techniques were compared and found to yield almost identical results. That comparison shows the two techniques to be valid diagnostic tools. We do not, however, anticipate any inventions being developed as a consequence of the information in this report.

REFERENCES

1. U.S. Environmental Protection, "Railroad Noise Emission Standards," CFR Title 40, Chapter 1, Part 201.

2. P.J. Remington and M.J. Rudd, "An Assessment of Railroad Locomotive Noise," U.S. Department of Transportation Report No. DOT-TSC-OST-76-4, 1976.

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