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NOISE CONTROL FOR RAPID TRANSIT CARS ON ELEVATED STRUCTURES:

PRELIMINARY INVESTIGATION OF VEHICLE SKIRTS, UNDERCAR ABSORPTION, AND NOISE BARRIERS

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16. Abstract

Procedures to reduce the propulsion system noise of urban rail transit vehicles on elevated structures are studied. Experiments in a laboratory use a scale model transit vehicle to evaluate the acoustical effectiveness of noise barrier walls, vehicle skirts, and undercar absorption. These experiments assume that the propulsion system noise is the only source of noise. Field measurement of urban rail transit vehicles at the Port Authority Transit Corporation (PATCO) in New Jersey provide additional data to compare the noise from elevated-structure and at-grade track sections. The results show that vehicle skirts and undercar absorption can provide a cost-effective noise reduction alternative to noise barriers if the propulsion system is the dominant noise source.

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PREFACE

The data and analyses contained in this report represent a preliminary investigation into noise control alternatives for modern rapid transit systems. The results are intended to serve transit property personnel, transit system planners, and their consultants. In addition, this document provides some background information which will be used for more comprehensive investigations of all aspects of urban rail propulsion system noise control.

This report has been prepared under the sponsorship of the Urban Mass Transportation Administration (UMTA), Office of Rail and Construction Technology. The work was performed under the technical direction of the Transportation Systems Center (TSC), which manages the Urban Rail Noise Abatement Program.

Leonard Kurzweil and Robert Kendig of the Transportation Systems Center coordinated the technical effort carried out by the acoustical consulting firm of Bolt, Beranek, and Newman, Inc.

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

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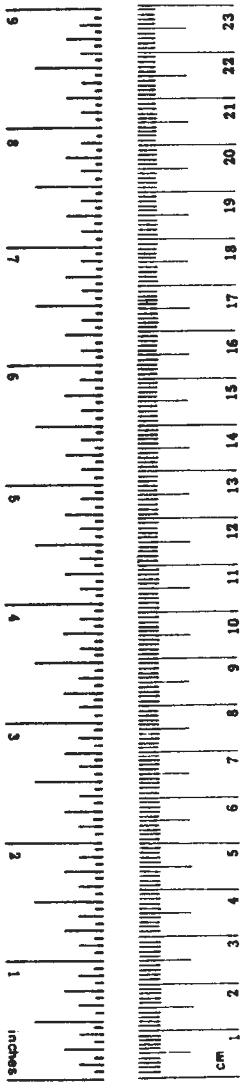
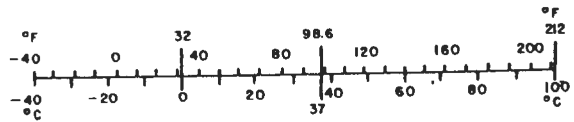
*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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



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1. INTRODUCTION

1.1 Background

The control of noise is an important factor in the design of new rail rapid transit systems. Attention to noise control is focused primarily on the vehicle and the guideway. Noise from trains is speed dependent, with wheel/rail noise dominant at low speeds and the propulsion system noise dominant at high speeds. The noise problem is aggravated when the trains are run on elevated structures – even new, modern concrete guideways. Noise levels are roughly 5 to 7 dB higher for trains on concrete elevated structures than for trains on at-grade tie and ballast track. This effect is produced by three factors:

1. The concrete deck absorbs less sound than tie and ballast track.
2. The height of the elevated structure influences the propagation of noise over the surrounding terrain.
3. The structure itself radiates noise.

Acoustical barriers can be used along the sides of the guideway to reduce wayside noise from the vehicle. Barriers, however, have several drawbacks. Construction costs are increased by the initial procurement and installation of barriers, as well as by the design and building of guideways to accommodate the barriers. To reduce noise adequately at a single sensitive receptor, barriers need to extend for several train lengths. Moreover, barriers provide limited shielding for people who live above the guideway (e.g., occupants of high-rise apartment buildings).

An alternative to acoustical barriers is to reduce the noise at the source, the vehicle. Wheel/rail noise provides the baseline for vehicle noise: its control is the subject of current research. Propulsion system noise has been found to be significant at all speeds and dominant at high speed. The cooling fan is generally the major source of noise in self-ventilated traction motors, although in some cases gear noise is significant. Control of propulsion noise could be accomplished by redesign of the traction motor and fan or by redesign of the vehicle body. An example of vehicle treatment is the use of undercar acoustical absorption and car body skirts. Preliminary engineering calculations show that such treatments could reduce wayside noise levels from trains on concrete elevated structure by 5 dB. This approach to the problem has the additional benefit of reducing *interior* noise levels in subway vehicles operating in tunnels on concrete inverts.

1.2 PROJECT OBJECTIVE

Thus far, no thorough investigation has been made of the costs and benefits of concentrating acoustical treatments on the rapid transit car. Two such treatments include undercar absorption and vehicle skirts. The following investigation is a pilot study to evaluate these basic acoustical treatments. The investigation compares the acoustical effects of vehicle treatments with the effects of acoustical barriers on elevated structures. This information is valuable, in general, to the transit industry and, in particular, to systems with extensive route mileage on elevated structures.

1.3 OVERVIEW

The acoustical tradeoffs among undercar absorption, vehicle skirts, and guideway barriers are determined primarily through acoustical scale models. Section 2 describes scale model experiments with vehicle skirts, noise barriers, undercar absorption, and with various combinations of these treatments. To translate the scale model results to full-scale conditions, wayside noise measurements are made on elevated and at-grade tracks of the Port Authority Transit Corporation (PATCO). The results of these measurements are documented in Section 3. Section 4 explains how noise on rapid transit vehicles, such as those at PATCO, would be reduced by the treatments tested on scale models. This section also offers a cost/benefit estimate which may be useful to the new transit system currently under construction in Metropolitan Dade County, Florida.

The details of the scale model tests are described in Appendices A, B, and C. Appendix D describes the instrumentation used during the full-scale tests, and Appendix E contains tables showing the PATCO test results and the insertion loss from all noise control treatments.

2. ACOUSTICAL SCALE MODEL MEASUREMENTS OF RAPID TRANSIT CARS ON AN ELEVATED GUIDEWAY

Acoustical scale modeling is a laboratory technique by which full-scale phenomena may be investigated quickly and inexpensively. Properly done, it provides accurate analyses of parameters that would be too costly to evaluate full-scale, and too complex to model using analytical or computer methods. Scale models, therefore, are ideally suited to the comparison of preliminary design trade-offs. In this case, scale modeling is used to investigate the tradeoffs among different vehicle treatments and to compare these tradeoffs with those of noise barriers on the guideway.

2.1 MEASUREMENT PROCEDURE

The acoustical scale model measurements were conducted in an anechoic chamber using a 1/20th scale model transit car and elevated guideway (Fig. 1). Noise from the transit car was simulated using a spark source and was measured by microphones. Instruments located outside the test chamber were used to analyze the electrical signals from the microphones. Details are provided in Appendices A, B, and C.

Various combinations of skirts, barriers, and undercar absorption were investigated. For each configuration, measurements were taken at a reference position and at two far-field positions. Tests for each configuration were conducted with and without a reflective ground plane in order to determine the effect of ground conditions.

The results were obtained by measuring insertion loss of each treatment. The insertion loss at a given receiver location is a ratio of two noise measurements. The ratio compares a noise level with noise control treatments installed to a reference noise level with no noise control treatments installed. The reference condition, called the "basic configuration," is the untreated car on an untreated guideway. This technique was used for the scale model noise reduction measurements because calibration of

FIGURE 1. SCALE MODEL TRANSIT CAR ON ELEVATED GUIDEWAY IN ANECHOIC TEST ROOM (Scale 20:1)

absolute sound levels is not important; only the differences between levels are taken. The tests are described below.

1. *Shielding by Guideway Deck:* Position of vehicle on the guideway and position of receiver height were tested for their sensitivity in noise reduction.
2. *Barrier Configurations:* Two barrier configurations were examined (Fig. 2). In all cases, the sound barriers had absorptive linings.
   - High barrier. This condition simulated a barrier 57 in. (145 cm) above the guideway deck. An 18-gauge aluminum strip was placed along both sides of the guideway for the full length of the structure. A 0.1-in. (0.25-cm)-thick layer of Owens Corning PF-105 glass fiber was glued to the surface of the aluminum strip to model a 2-in. (5-cm)-thick full-scale treatment.
   - Low barrier. This condition simulated a barrier 28.5 in. (76 cm) above the guideway deck.
3. *Skirt Configurations:* Four skirt configurations were examined.
   - Full skirt, no absorption. An 18-gauge aluminum strip was attached to the side of the model transit car, running the full length of the car. The skirts extended down from the sills to a position corresponding to a full-scale height of 6 in. (15 cm) above top-of-rail. There were no skirts on the front or back of the car.
   - Half skirt, no absorption. The skirt length was reduced to one half of a full skirt length, corresponding to a full-scale height of 18.75 in. (48 cm) above top-of-rail.
   - Full skirt, skirt absorption. A 0.1-in. (0.25-cm)-thick layer of Owens-Corning PF-105 glass fiber was glued to the surface of the aluminum strip to model a 2-in. (5-cm)-thick full-scale treatment.

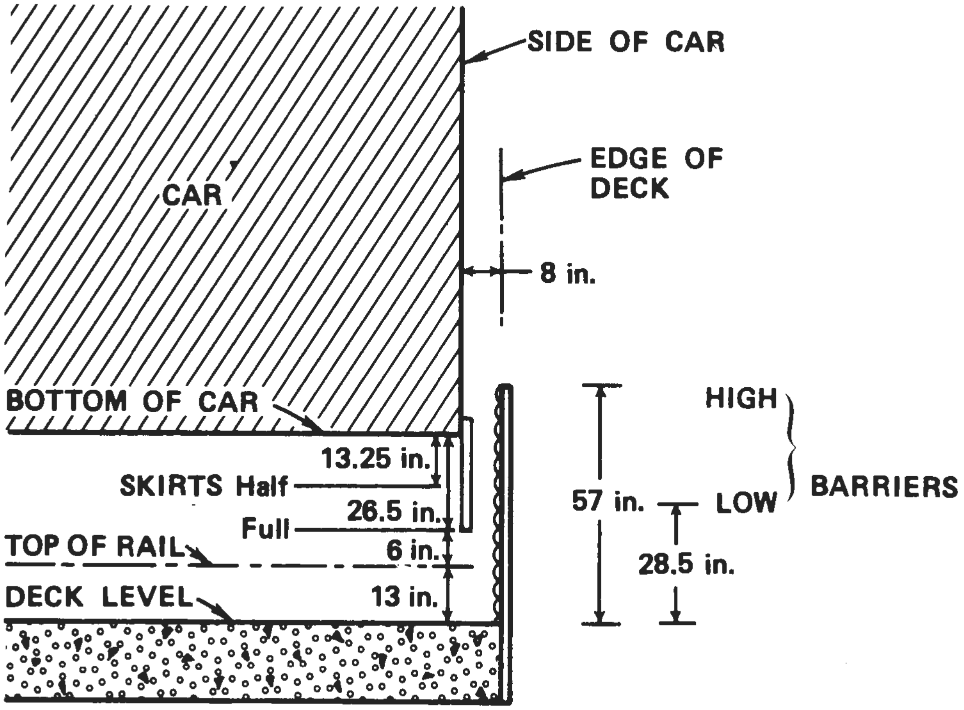


FIGURE 2. BARRIER AND SKIRT DIMENSIONS IN FULL-SCALE UNITS

- Half skirt, skirt absorption. The lined skirt was raised to correspond to a full-scale clearance of 18.75 in. (48 cm) above top-of-rail.

4. *Undercar Absorption:* Tests were conducted to determine the effectiveness of an undercar sound-absorbing treatment, alone and in combination with skirt absorption (called "Full Absorption").
   - Undercar absorption. A layer of Owens-Corning PF-105 glass fiber was glued to the car bottom, covering a surface area equal to one half the total underside area.
   - No absorption.
5. *Ballast Absorption:* A limited test was conducted to simulate the effectiveness of ballast as an acoustical absorber for at-grade track. Strips of Owens-Corning PF-105 glass fiber were placed beneath the car in the approximate position of ballast. The surface area of the glass fiber was 45 to 50 percent of the undercar area.

2.2 DATA ANALYSIS

Results are based on the insertion loss for each configuration found by subtracting the measured sound pressure level in octave bands from those measured in the basic configuration. Analysis centered on the 5-, 10-, 20-, and 40-kHz octave bands (250-, 500-, 1000-, and 2000-Hz full scale) since these are the dominant octave bands from high-speed propulsion noise. The octave band sound pressure level was obtained from the frequency spectrum for each measurement. Since the analysis equipment's upper frequency limit was 50 kHz, the 40-kHz octave band was truncated at 76 percent of its full bandwidth.

2.3 RESULTS

The results of the scale model experiment program indicate the noise reduction of the treatments, singly and in combination. Table E-2 (Appendix E) contains all the data.

2.3.1 Guideway Deck

The vehicle on the near track and the top-of-rail microphone position was used as the reference configuration. Compared to this condition, moving the microphone down to the lower position, 5 ft (1.5 m) above ground surface, caused a reduction of 3 dB (Fig. 3). Simple barrier theory [*1*] applied to the geometry of this case predicts a 3- to 5- dB reduction because of the placement of the vehicle noise source with respect to the edge of the deck. Moving the vehicle to the far track resulted in a 2-dB reduction from the reference condition at the high microphone position and a 10-dB reduction for the low microphone position. A reduction of 2 dB is slightly greater than that expected from the increased distance from source to receiver, suggesting that there is some effect of the interaction of the sound field with the guideway deck. The low micriphone result is within 1 dB of that expected from theory.

2.3.2 Barriers

The sound barrier walls used in these tests were lined with acoustically absorbing material in all cases.

The "high barriers" provided approximately 20-dB noise reduction for the vehicle on the track nearest the barrier and a 12-dB noise reduction for a vehicle on the far track (Fig. 4). Little difference was observed for the two microphone heights, top-of-rail position and 5 ft (1.5 m) above the ground.

In comparison, the "low barriers" provided noise reductions of 11 dB and 7 dB at the top-of-rail microphone positions for the vehicle on the near and far track, respectively. In contrast to the high barrier results, however, insertion loss at the lower microphone height showed greater sensitivity to vehicle placement on the guideway: 14 dB and 4 dB for the corresponding vehicle positions. These variations are explicable from sound barrier theory [1], which accounts for the position of the edge of deck in the latter case.

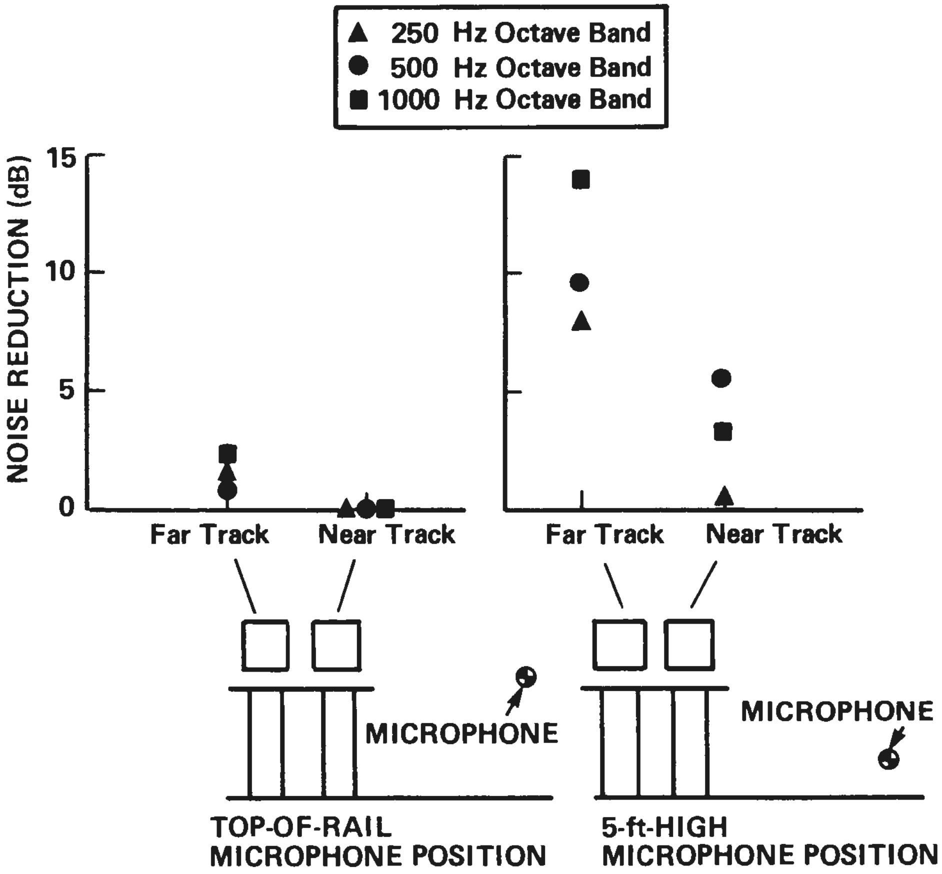


FIGURE 3. NOISE REDUCTION AS A RESULT OF TRAIN ON FAR TRACK COMPARED WITH NEAR-TRACK TOP-OF-RAIL MICROPHONE POSITION

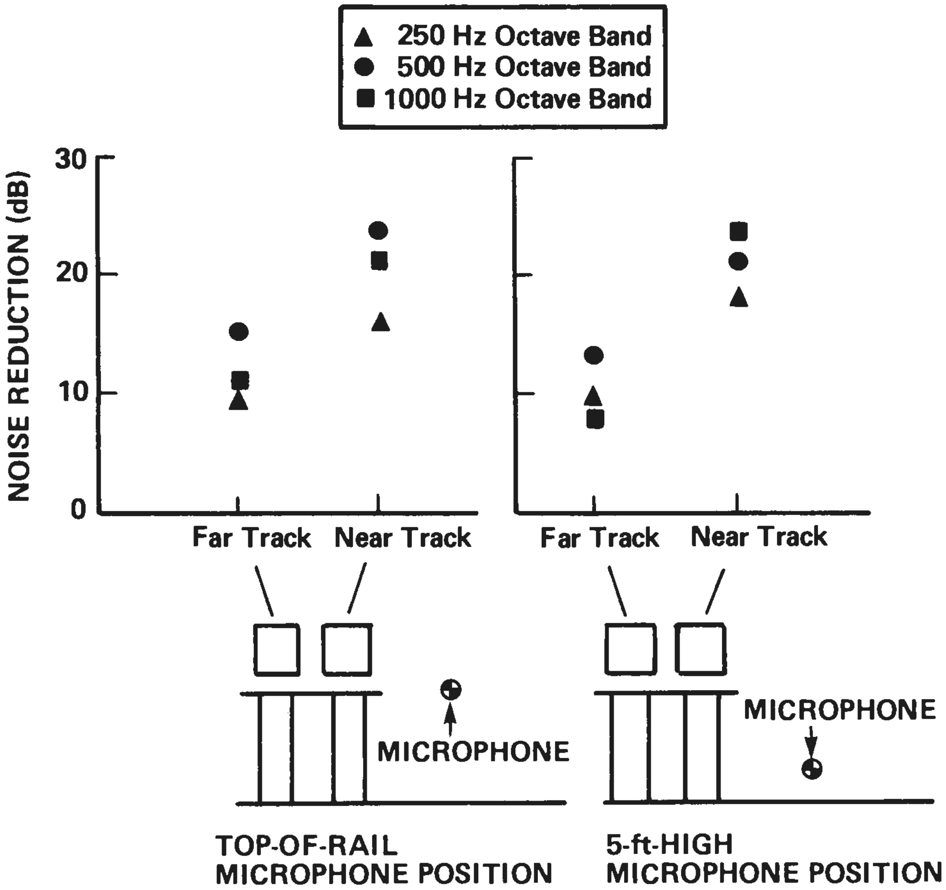


FIGURE 4. NOISE REDUCTION FROM HIGH BARRIER WITH RESPECT TO "BASIC/NO BARRIER" IN SAME POSITION

2.3.3 Vehicle Skirts

Insertion loss by octave band for vehicle skirts with and without absorptive liners is shown in Fig. 5. Full skirts provide average noise reductions of 7 dB and 5 dB for the lined and unlined cases, respectively. As expected, half skirts are less effective, with 4-dB and 3-dB average noise reductions for the lined and unlined configurations.

Vehicle skirts shield the noise source in much the same way as barriers, but in addition, skirts create a semi-enclosed cavity underneath the vehicle. Without skirts, the noise from underfloor equipment propagates directly out from underneath the car. The skirts cause this sound to be partially confined, with only a limited space – the skirt/guideway clearance – through which to escape to the environment. Decreasing the clearance between guideway and skirt with a longer skirt increases the confinement and decreases the area available for sound propagation. However, confining the sound energy beneath the car may have the detrimental effect of increasing noise levels within the passenger compartment. This effect can, in turn, be treated by use of undercar absorption, which is discussed in the next section.

Skirts act most effectively when used with other noise reduction treatments such as those discussed in Section 2.3.5.

2.3.4 Undercar Absorption

The noise reduction benefit of undercar absorptive material increases with the surface area covered. Application of absorptive material to the skirts reduced noise levels by an additional 1 to 2 dB, depending upon the size of the skirt. Full undercar coverage by absorption resulted in an average of 3 to 4 dB of additional noise reduction (Fig. 6). Although this result is indicative of the full-scale trend, caution is advised in interpretation to full-scale transit vehicles: absorptive material used in the full undercar absorption cases represented a 10-in. (25.4-cm)-thick full-scale treatment. This is much more than is likely to be applied to a transit vehicle understructure.

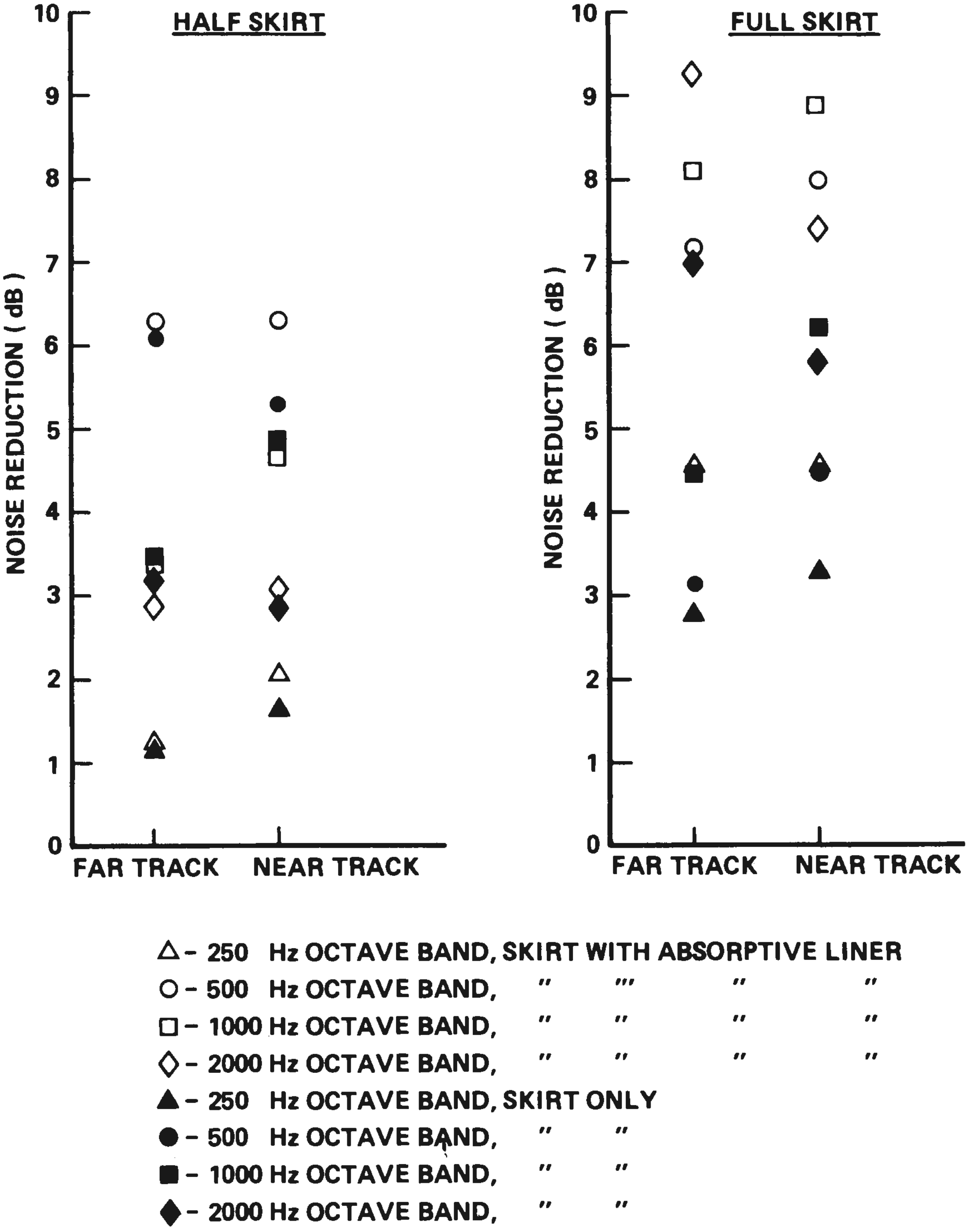
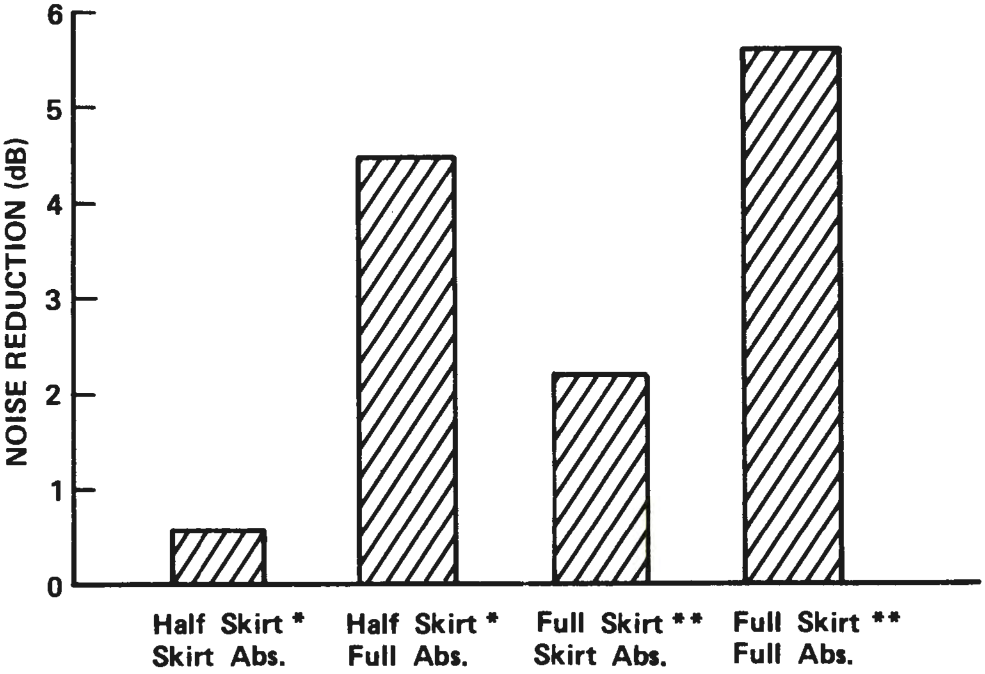


FIGURE 5. NOISE REDUCTION OF VEHICLE SKIRTS ON ACOUSTICAL SCALE MODEL MEASURED AT TOP-OF-RAIL HEIGHT AND EQUIVALENT OF 50 FT (15m) AWAY



* Reduction with Respect to Half Skirt, No Absorption Case
** Reduction with Respect to Full Skirt, No Absorption Case

FIGURE 6. LEVELS OF NOISE REDUCTION PRODUCED BY VEHICLE SKIRTS AND UNDERCAR ABSORPTION

2.3.5 Combinations of Treatments

The combined effect of the various guideway and vehicle treatments is to produce noise reductions that are greater than the noise reductions caused by each treatment alone.

2.3.5.1 Near-Track Skirt/Barrier Interaction – Duct Effects

The combination of skirts and barriers with the vehicle on the near track produces 2 dB more noise reduction than the sum of the treatments employed singly. With full skirts and high barriers, up to 29 dB of noise reduction was measured in one frequency band. Even greater noise reduction (33 dB at 1000 Hz) resulted from absorptive lining on the skirts.

Together, the skirt and barrier effectively produce a "duct" through which the sound must travel in order to escape to the wayside. Since the barrier is lined with sound-absorbing material, sound reflections from the car body are absorbed by impinging on the barrier wall. This duct effect provides far greater noise reduction than would be available by barrier effects alone.

2.3.5.2 Far-Track Skirt/Barrier Interactions – Noise Source Height Effect

The noise reduction achieved by using skirts and barriers with the train on the far track was 1 dB more than would be predicted from the sum of the individual skirt and barrier reductions alone. This result comes from lowering the source height with respect to the barrier wall and can be verified by using simple barrier theory [1]. Skirts lower the effective height of the noise source by allowing propulsion noise to escape only from the clearance gap between the vehicle skirt and the guideway. When the train is on the far track, this lower source height actually serves to make structure-side barriers more effective.

2.3.5.3 Skirt/Absorption Interaction — Reverberant Effects

Tests show that the use of undercar absorption with skirts is 1 to 2 dB more effective than the sum of the two treatments used individually.

A possible explanation of this result is that skirts tend to confine the noise energy beneath the car so that it may be more effectively absorbed by the sound-absorbing material. With absorption on the undercar surface only, most of the sound energy escapes from beneath the car. With skirts alone, the sound energy is confined, but not absorbed, allowing most of the energy to flow out from under the skirt.

Undercar absorption with vehicle skirts may also reduce car interior noise levels, by absorbing the increased acoustical energy that is confined in the undercar area.

2.3.6 Other Effects

2.3.6.1 Ground Plane

The introduction of the ground plane resulted in an increase in noise levels of approximately 2 dB at both the 5-ft (1.53-m) and the top-of-rail positions. The increase was found to be the same within ± 1/2 dB for both position.

2.3.6.2 Ballast

Addition of sound-absorbing material to simulate ballast provided a 3-dB noise reduction over nonballast conditions on elevated structures.

3. FULL-SCALE NOISE MEASUREMENTS COMPARING RAPID TRANSIT NOISE FROM ELEVATED-STRUCTURE AND AT-GRADE TRACK SECTIONS

3.1 MEASUREMENT PROCEDURE

Full-scale rapid transit car noise measurements were conducted at selected locations of the Port Authority Transit Corporation (PATCO) system on 25 and 26 January 1979. The basic objective of the measurement program was to compare the wayside noise of high-speed rapid transit cars on ballast and tie track at-grade and on directly fixed track on elevated structure. In addition, the measurements were planned to provide a measure of the loss in ground effect by elevated structures. Details of the procedure are provided in Appendix D.

Measurement sites were selected where train speed was greater than 50 mph (80.7 km/h) so that the propulsion system noise component, rather than the wheel/rail noise component, would be dominant. In addition, locations with a hard, non-absorptive ground surface adjacent to the system alignment were selected. The measurement locations were:

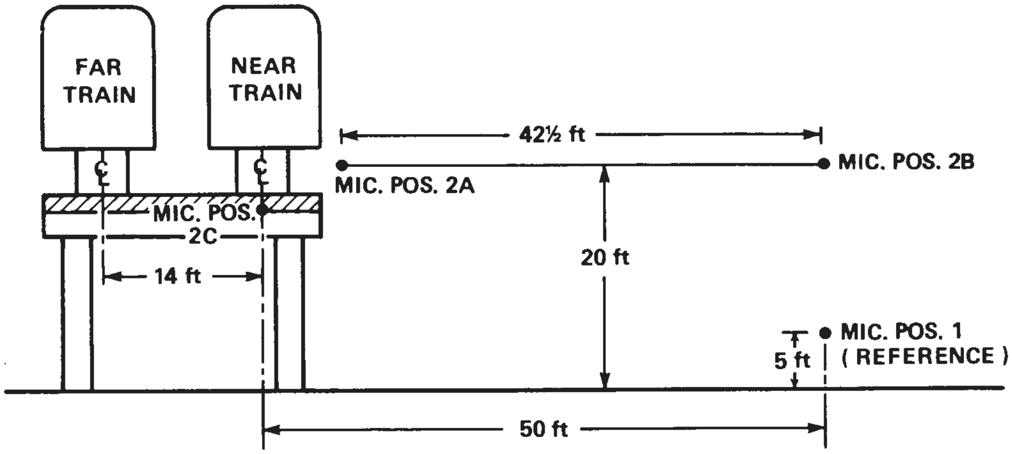
1. *Elevated Concrete Structure:* Parking lot south of the Collingswood, New Jersey Station (outbound side of alignment). (Figs. 7 and 8).
2. *At-Grade Ballast and Tie:* Prospect Avenue cul de sac near the Ashland, New Jersey Station (inbound side of alignment). (Fig. 9).

Train speeds were measured to be 55 to 60 mph (88.8 to 96.9 km/h) at these locations. The ground surface adjacent to the elevated structure site was paved. The ground surface adjacent to the at-grade site was paved beyond about 40 ft (12.2 m) from the nearest transit track (Fig. 10).

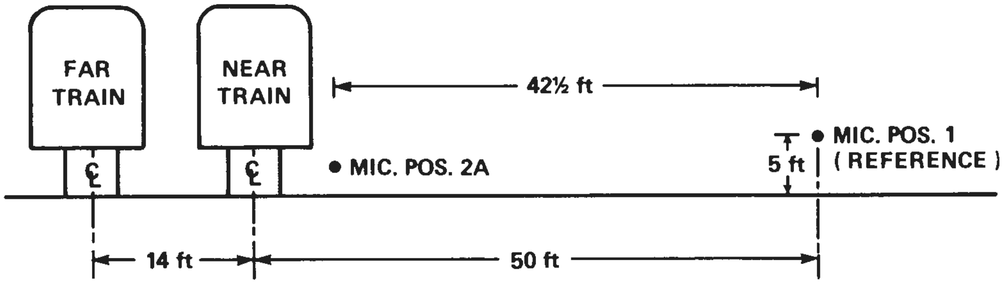
FIGURE 7. PATCO ELEVATED SITE FOR NOISE MEASUREMENT (TYPICAL CONSTRUCTION)

FIGURE 8. PATCO ELEVATED SITE FOR NOISE MEASUREMENT

FIGURE 9. PATCO AT-GRADE SITE FOR NOISE MEASUREMENT



ELEVATED STRUCTURE CONFIGURATION



AT-GRADE BALLAST AND TIE CONFIGURATION

FIGURE 10. DIAGRAM OF PATCO NOISE MEASURMENT POSITIONS FOR ELEVATED-STRUCTURE AND FOR AT-GRADE TRACK

3.2 DATA ANALYSIS

The tape-recorded data were reduced using a sound level meter with filter set along with a graphic level recorder to obtain A-weighted sound level time-history plots for each vehicle passby as well as octave band plots for selected measurements. Narrow-band analyses were performed for selected measurements, using an analyzer with a 1/10-octave filter set. In addition, A-weighted maximum sound level (L_{max}) and single event levels (SEL) were obtained using a BBN Model 614 noise monitor.

3.3 RESULTS

Typical A-weighted sound level time-history graphs are provided in Fig. 11. The near-field results show three distinct peaks, which may be attributed to the passage of the four wheel-trucks (two peaks for the end trucks and a peak for the two center trucks). The initial peak is lower in all cases, an unexpected result, since the vehicle is symmetrical. A possible explanation is that a momentary overloading of the measurement system occurs due to the initial wind gust preceding the near-field vehicle passby. On the other hand, the far-field results show a smooth bell-shaped time history, with the decay time generally exceeding the rise time.

Table E-1 in Appendix E provided L_{max} and SEL results for all of the relevant PATCO noise measurements. This table also shows the logarithmically averaged levels for each track configuration/ train position (near- or far-track) combinations, and, where necessary, the averaged levels are normalized to a speed of 60 mph (96.9 km/h), in order to provide comparable results for each measurement case. Speed normalization was accomplished using a 60 log and 50 log speed ratio correction factor for the L_{max} and SEL results, respectively, assuming the dominance of propulsion motor noise.

The data indicate that the change from an at-grade to an elevated configuration resulted in an average increase of 7.3 dB in the maximum A-weighted far-field sound level for a train passby.

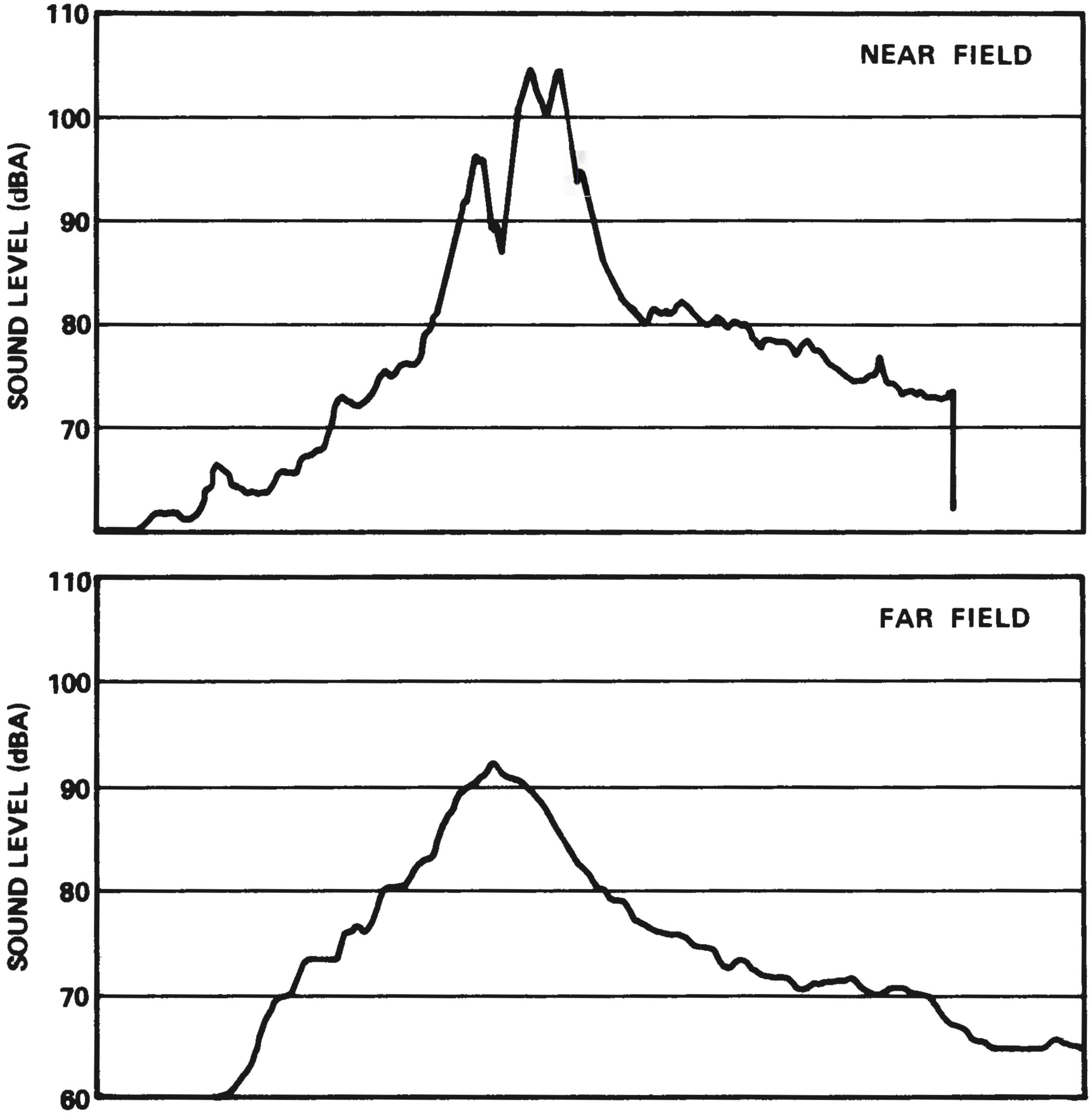


FIGURE 11. SOUND LEVEL TIME HISTORY OF NEAR-FIELD AND FAR-FIELD VEHICLE PASSBY

The average increase in the near-field maximum level was 4.5 dB. Similar changes are shown in terms of SEL data.

In order to understand these results, it is instructive to look at typical octave band noise spectra for selected data at similar speeds. Figure 12 provides spectra of the near-field measurement results for both elevated and at-grade configurations normalized to the same speed. Since the two speeds were within 5 mph (8.04 km/h), normalization was minimal. Two elevated structure measurements are shown: one at the side of the vehicle (Position 2A in Fig. 10) and one directly below and close to the structure (Position 2C in Fig. 10). A comparison of these two measurements shows that structureborne noise is not significant at and above the 500 Hz octave band. Thus, the reduction in near-field level from the elevated to at-grade configuration may be attributed to undercar ballast absorption. Note that the frequency range that dominates the A-level is also above 500 Hz. Structureborne noise is shown to dominate at 125 to 250 Hz. Elimination of structural vibration for the at-grade condition would be expected to result in a reduction in near-field level in this frequency range, which is indeed the case. It is not clear from the results at 31.5 and 63 Hz what is responsible for the reduction in near-field level; the reduction is possibly due to a combination of structural vibration and aerodynamic noise effects.

Figure 13 illustrates octave band spectra of the two track configurations for the 50-ft (15-m) microphone position. The figure also indicates the noise reduction caused by undercar ballast absorption effects. This estimate is based on the difference in near-field levels over the 500-Hz frequency range. The remaining 2.8-dB A-level noise reduction may be attributed to propagation (e.g., ground plane) effects. Below 500 Hz, the noise reduction is likely caused by the absence of the elevated structure and its structural vibration.

A comparison of the far-field measurements at 5 ft (1.5 m) and 20 ft (6.1 m) above ground surface indicate that the average

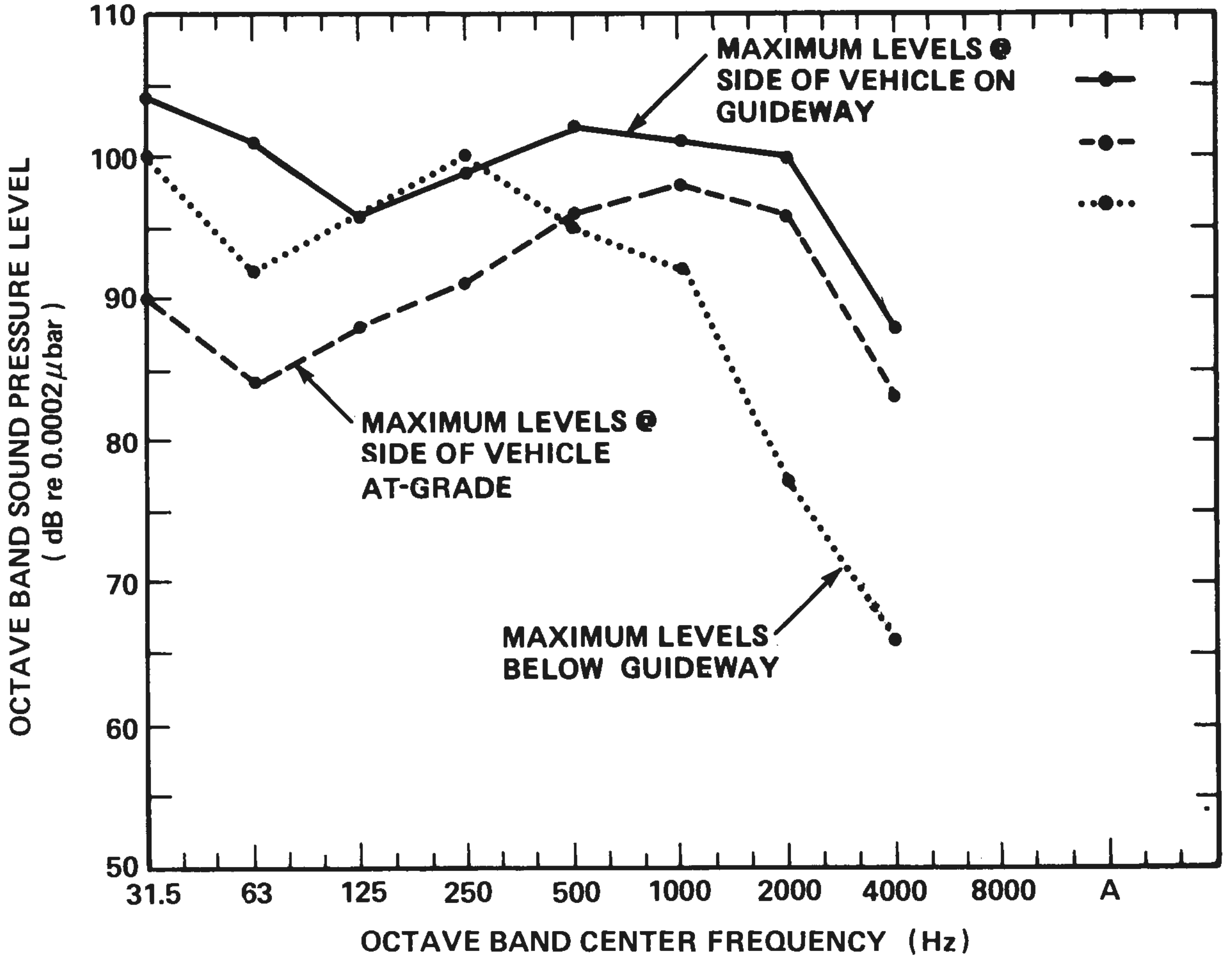


FIGURE 12. PATCO NEAR-FIELD SOUND SPECTRA FOR ELEVATED AND AT-GRADE CONFIGURATIONS NORMALIZED TO 60 MPH (97 KM/H)

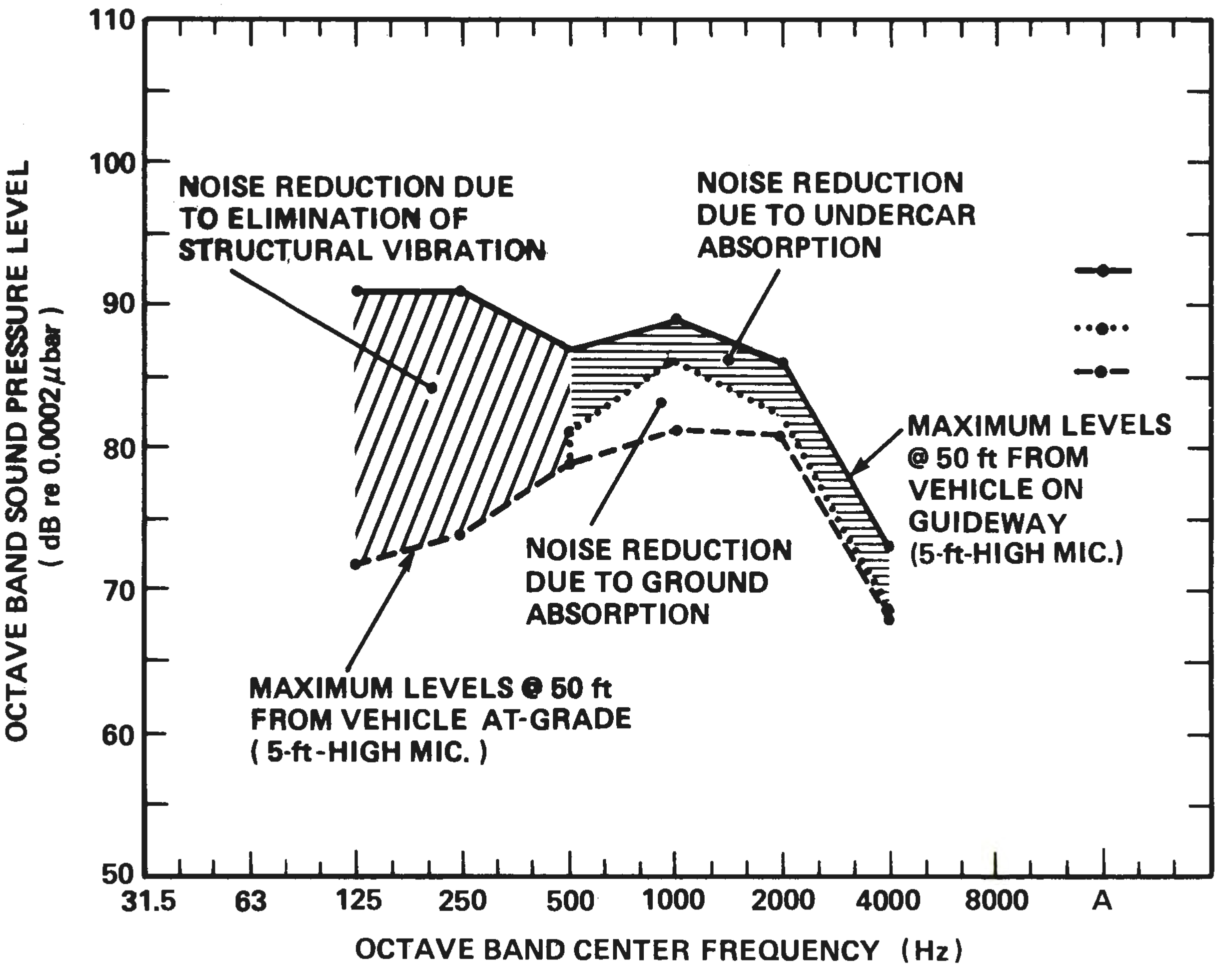


FIGURE 13. PATCO FAR-FIELD SOUND SPECTRA FOR ELEVATED AND AT-GRADE CONFIGURATIONS NORMALIZED TO 60 MPH (97 KM/H)

A-weighted sound levels were lower at the 5-ft (1.5 m) position by 2.3 dB and 5.6 dB for near- and far-track train passbys, respectively. These differences are likely due to shielding, directivity, and ground effects. Figure 14 provides comparative spectra for the two measurement positions for a vehicle on the far track.

Finally, Figures 15 and 16 provide narrowband (1/10-octave) sound pressure level spectra for near- and far-field measurements at the elevated and at-grade sites, respectively. The analysis has been performed for the 250- to 2000-Hz frequency range, which controls the A-weighted sound level for the vehicle. The spectra are indicative of propulsion motor fan noise rather than wheel/rail noise, with sharp peaks and harmonics. Thus, these results confirm that propulsion system noise dominated the A-weighted sound level at the sites chosen for this measurement program.

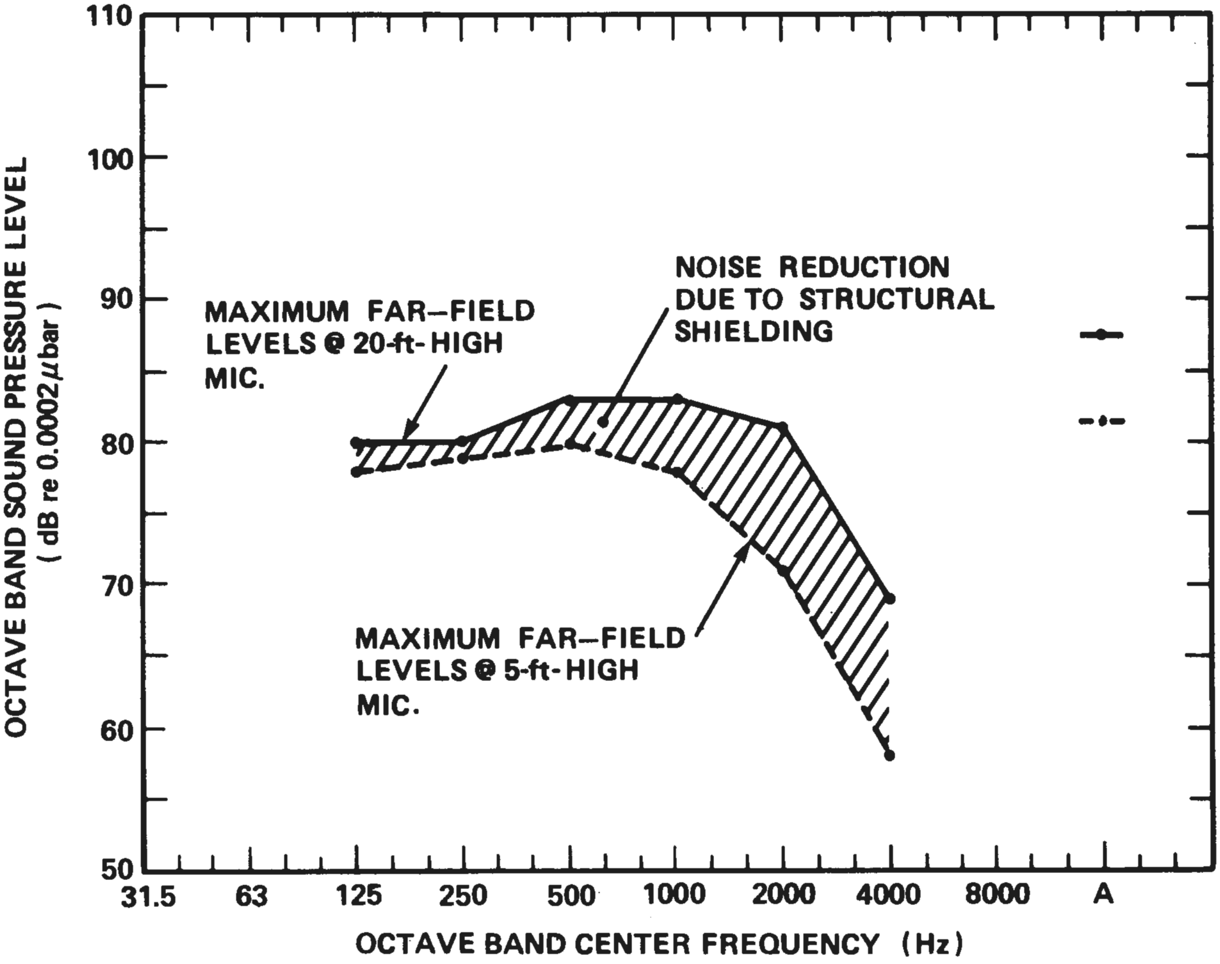


FIGURE 14. A COMPARISON OF SOUND SPECTRA BETWEEN A 5-FT-HIGH MICROPHONE POSITION AND A 20-FT-HIGH MICROPHONE POSITION FOR FAR-TRACK PATCO VEHICLE SOUND SPECTRA

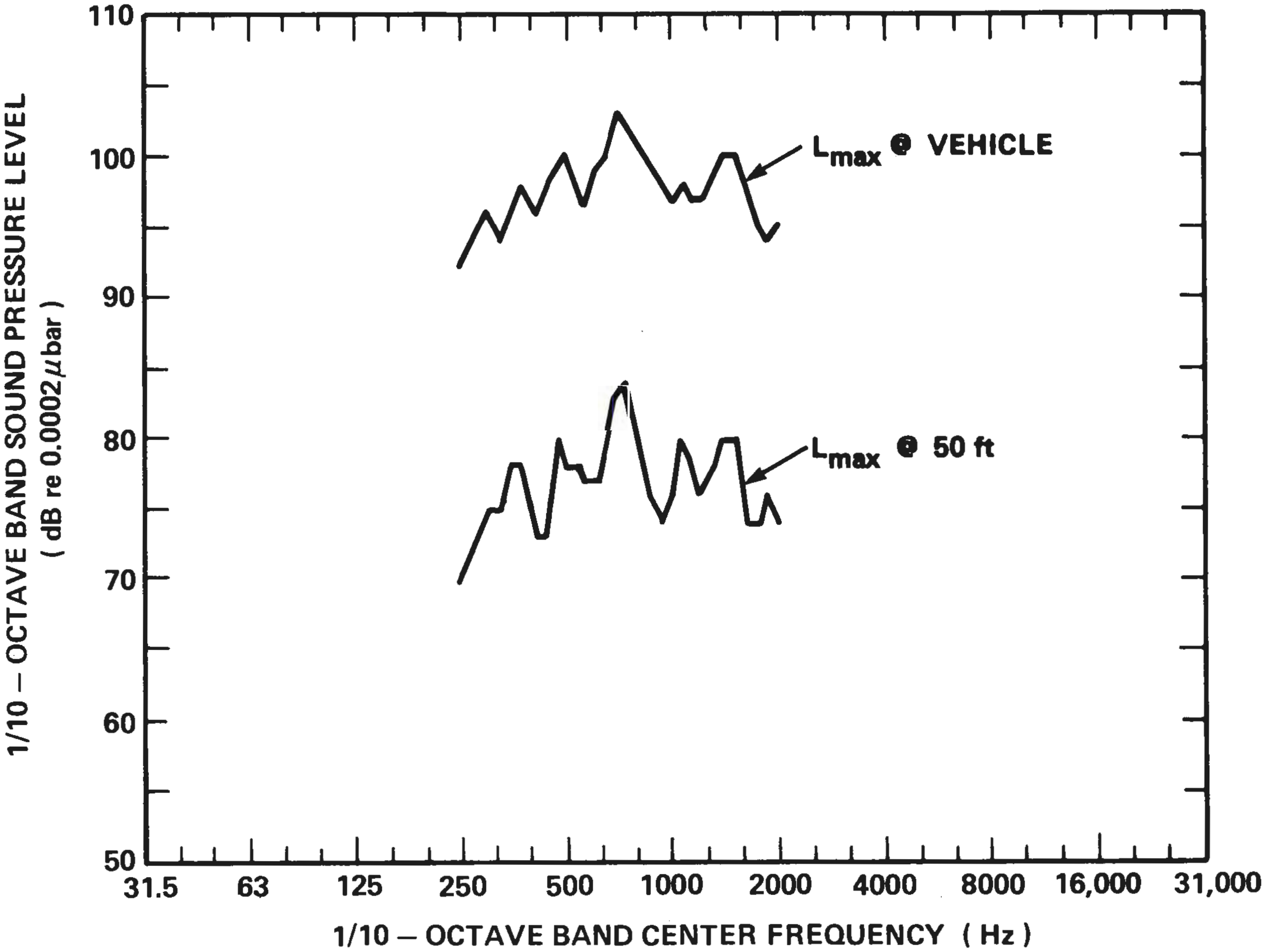


FIGURE 15. NARROWBAND SOUND SPECTRA FOR PATCO ELEVATED STRUCTURE

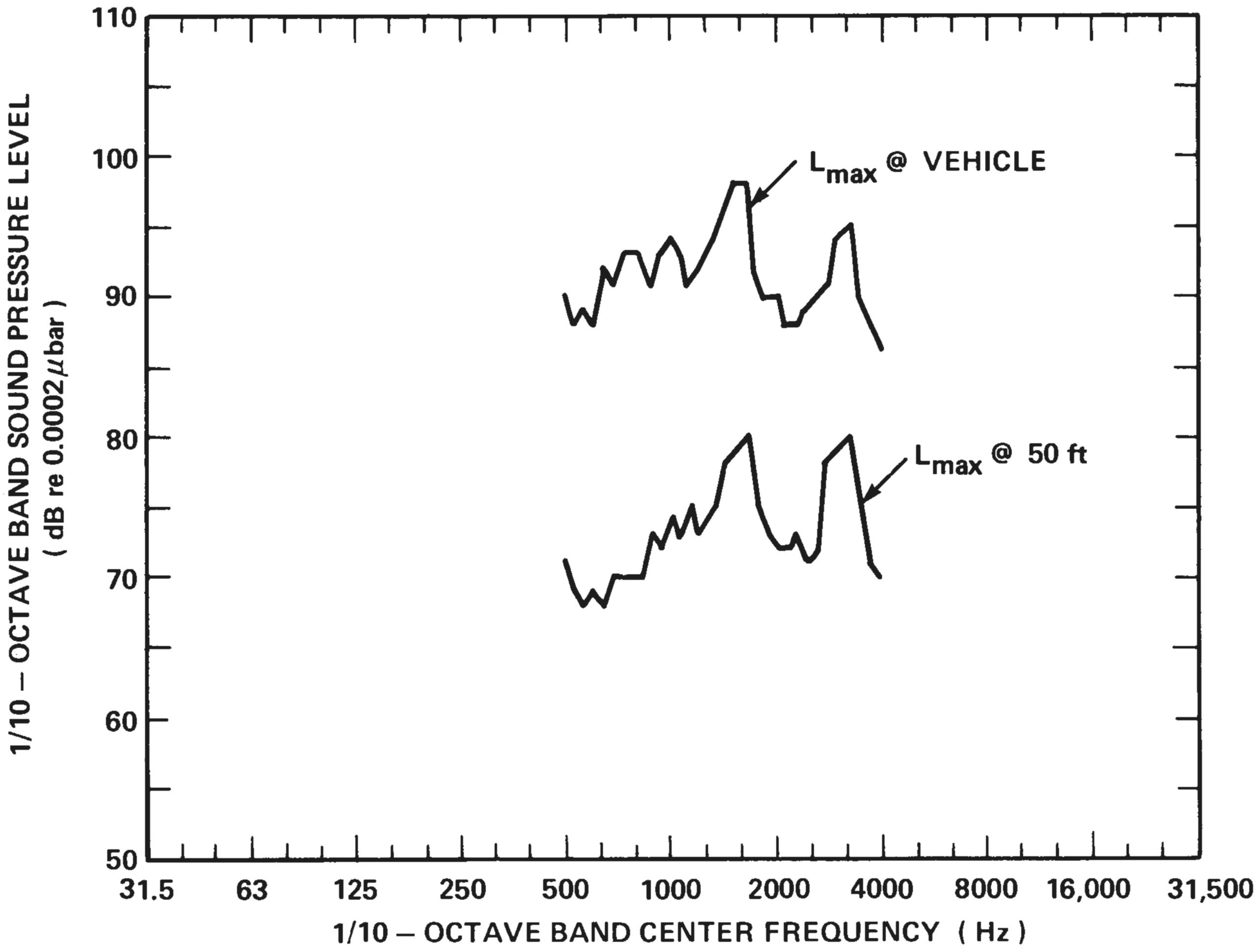


FIGURE 16. NARROWBAND SOUND SPECTRA FOR PATCO AT-GRADE TRACK

4. CONCLUSIONS

4.1 NOISE REDUCTION

The scale model results are only approximate and must be verified by full-scale demonstration tests. However, the potential value of the results can be demonstrated by applying the measured noise reductions in octave bands to the actual measured noise spectrum of the PATCO vehicle.

Figure 17 shows the expected noise reduction from the application of various treatments to the PATCO vehicles at speeds where propulsion system noise dominates wheel/rail noise. The reductions drawn from the scale model experiments will not be as high if significant wheel/rail noise is present. Also, the results do not necessarily imply that vehicle skirts are an effective procedure to reduce wheel/rail noise. Nevertheless, the results show that vehicle treatments reduce A-weighted noise levels by 5 to 10 dB, depending upon skirt height and the amount of undercar absorptive material used. Guideway barriers provide 10 to 20 dB of noise reduction, depending upon height. These results are important because noise criteria are often exceeded by only 5 to 10 dB, seldom as much as 15 dB.

4.2 SOUND PROPAGATION

The findings of the full-scale measurement program are extremely important in documenting the difference between transit operations at-grade and elevated structures. In general, the noise level is 7.3 dB greater for trains on an elevated structure than for trains at-grade on tie and ballast track. Two key elements cause this increase. First, due to loss of ground effects, a 2.8-dB increase results from raising the train to an elevated structure. The second factor is the 4.5-dB increase from the lack of ballast absorption on elevated structures. It is important to note that noise specifications for rapid transit vehicles are generally based on ballast and tie track at-grade. These results

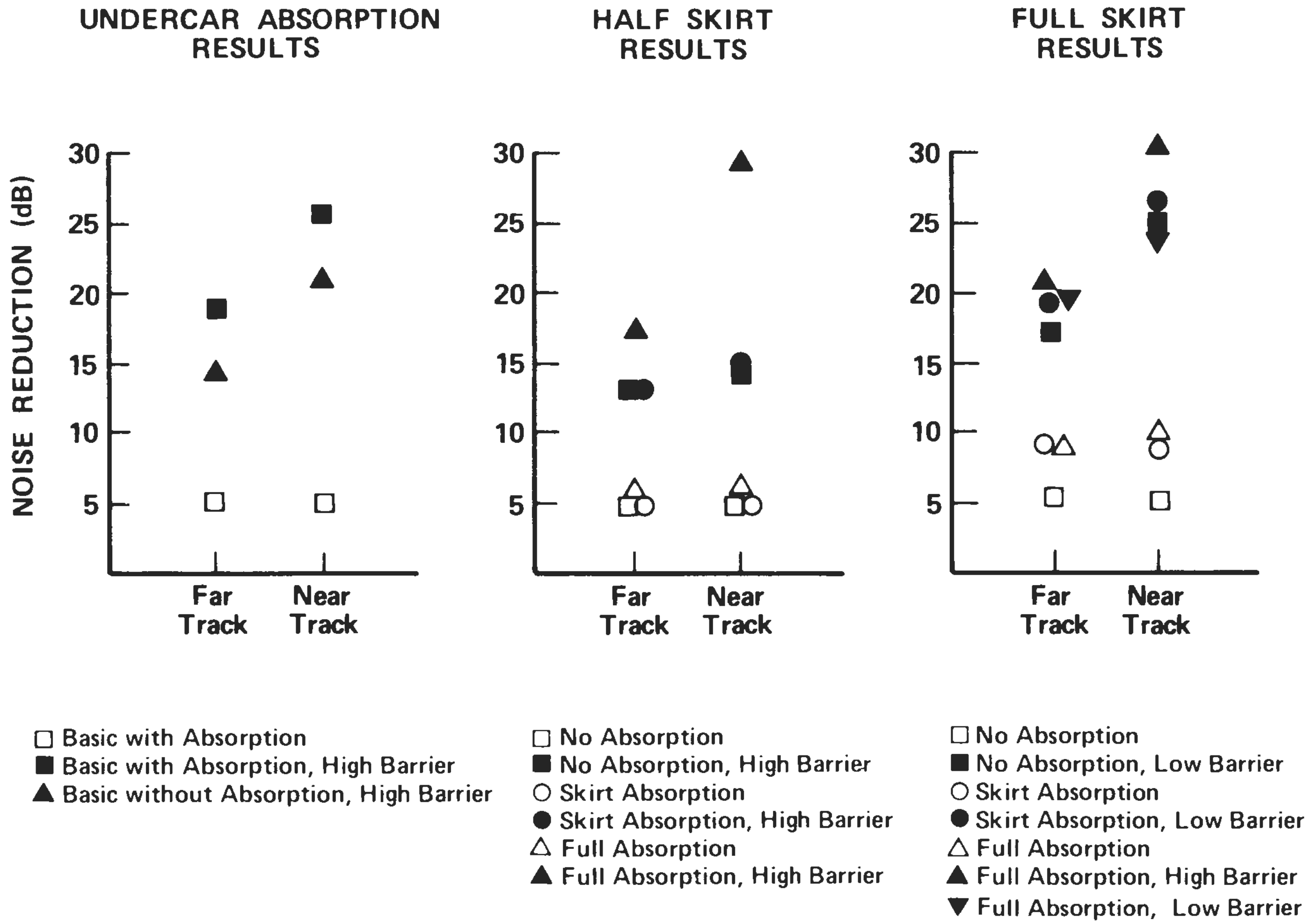


FIGURE 17. PERFORMANCE OF NOISE CONTROL TREATMENTS. SCALE MODEL RESULTS APPLIED TO PATCO VEHICLE A-WEIGHTED NOISE. REDUCTIONS ARE RELATIVE TO THE VEHICLE WITHOUT SKIRTS OR UNDERCAR ABSORPTION ON AERIAL STRUCTURE WITHOUT A BARRIER

quantify the considerable increase in noise for systems with significant elevated structure.

For transit systems with significant tie and ballast track, the effect of ballast absorption may be even more enhanced by the use of train skirts, in much the same way that undercar absorption is enhanced when complemented by train skirts.

4.3 DESIGN CONSIDERATIONS

This study has shown that train skirts and undercar absorption are effective noise reduction treatments, in combination with or in lieu of guideway barriers. The true advantage comes from cost considerations.

Noise reduction treatments applied to the vehicle can yield direct cost benefits. For example, the noise assessment in the Environmental Impact Statement (EIS) [2] for the proposed Dade County Rapid Transit System shows that with the vehicle design specified, approximately 22 miles (35.2 km) of noise barrier will be required on the elevated structure in order to meet the noise control criteria adopted. With 4.5 miles (7.2 km) of split guideway in noise-sensitive areas, an additional 9 miles (14.4 km) of barrier would be required. Analysis shows, however, that with an additional 5 dB of vehicle quieting obtained from the use of undercar absorption and vehicle skirts, the barrier requirements are reduced by half, to 16 miles (25.6 km). Assuming a cost of $35 per linear foot for sound barrier walls attached to concrete guideway, the potential cost savings amounts to $3.0 million. This savings could be used to offset the additional vehicle costs for the noise control treatment.

A rough estimate of the initial cost for vehicle skirts and undercar absorption is $12,000 per vehicle. This figure is obtained by assuming requirements of 2 skirts per vehicle and assuming each skirt is 75 ft (22.5 m) long and 2 ft (.6 m) wide. A surface density of 4 lb/ft (6 kg/m) is enough to provide acoustical transmission loss and retain structural rigidity with stiffeners. Installation of fabricated noise control enclosures is assumed to cost $40 per square foot ($420 per square meter) of external surface.

With an initial vehicle order of 130 cars for Dade County, the additional cost for this treatment is estimated to be $1.6 million, or a $1.4 million savings to the overall system. While this analysis is only a crude estimate and does not account for increased maintenance costs, it does illustrate the advantages in cost tradeoff for emphasizing noise control on the vehicle.

REFERENCES

1. U.J. Kurze and G.S. Anderson, "Sound Attenuation by Barriers," *Applied Acoustics* 4(1971):35-53.

2. U.S. Department of Transportation, Urban Mass Transit Administration, *Final Environmental Impact Statement: Metropolitan Dade County Rail Rapid Transit Project,* UMTA Project No. FL-03-0036, May 1978.

APPENDIX A: PRINCIPLES OF ACOUSTIC SCALE MODELING

The fundamental principle behind acoustical scale modeling is that physical size may be scaled down to any convenient dimensions provided that the wavelengths of sounds are scaled accordingly. For example, if a 20:1 scaling is used, then a 10-ft (3.1-m)-wide transit car is scaled to 6 in. (15.2 cm) in width; a 50-ft (15.3-m) distance becomes 2 1/2 ft (.76 m), etc. Accordingly, a 250-Hz tone becomes a 5000-Hz tone; the 500 Hz octave band, from 355 Hz to 710 Hz, scales to 7.1 kHz to 14.2 kHz.

Several factors influence the choice of the exact ratio by which size is reduced. The smaller the size of the model, the less the cost of materials and construction. However, the higher frequencies required in a smaller model are more difficult to produce, propagate, and detect.

In order to produce sounds rich in high-frequency energy, one of two specialized sources may be employed. One is the air jet (or cross jet), which produces continuous high-frequency noise through turbulence of high-velocity air streams impinging upon a surface or upon one another. The other source is a high-voltage spark discharge device. A broadband noise pulse with significant high-frequency energy is produced as the spark fires across a gap between two electrodes.

Once the sound is produced within the model, it propagates to a microphone through the air. Air absorbs high frequencies more than it does low frequencies; this fact must be taken into account when determining propagation path losses.

Objects that reflect, scatter, or absorb sound in full-scale measurements must be accurately represented in small scale. The difficulty here comes in finding model materials that sufficiently imitate full-scale acoustic characteristics.

The microphone used within the scale model must be small in order to be as acoustically unobtrusive as possible. Using a 1/4-in. (.64-cm)-diameter microphone in a 1:40 scale model is equivalent to using a 10-in. (25-cm)-diameter microphone for full-scale measurements. This may be too large in critical applications. However, as the size of a microphone decreases, its sensitivity and omnidirectional properties deteriorate. This problem is especially acute for the high frequencies needed in scale model applications.

Finally, the instrumentation employed for analysis of microphone signals must be capable of operating in the ultrasonic region above 20,000 Hz, sometimes as high as 100,000 Hz.

APPENDIX B: SCALE MODEL CONSTRUCTION

SCALE

For this experimental program, the following factors influenced the choice of a scale factor;

- The full-scale frequencies of interest were in the 250-, 500-, 1000-, and 2000-Hz octave bands, the dominant bands in spectra of propulsion noise from high-speed transit vehicles.
- The maximum floorspace available in the testing room was approximately 7 x 11 ft (2.1 x 3.4 m).
- The model was required to represent at least 120 ft (36.7 m) of elevated guideway, and measurements were to be taken at a distance of 50 ft (15.3 m) from the centerline of the near track.

A 20:1 scale factor met the requirements. At this scale, the frequency range for the model scaled from 250-, 500-, 1000-, and 2000-Hz octave bands to the 5-, 10-, 20-, and 40-kHz octave bands, which are easily within the limits of the instrumentation available. The 20:1 scale also permitted the representation of 140 ft (42.8 m) of guideway deck within the test chamber.

MATERIALS

Concrete and steel surfaces, of the guideway and car body, for example, need to be modeled by a hard reflective material. This study used 1/2-in. (1.27-cm) medium-density overlay plywood, which has smooth, dense paper glued to both sides of the plywood.

The gound impedance in the neighborhood of elevated structures varies from reflective (e.g., asphalt parking lots) to absorptive (e.g., tall grass). These changes in ground surface impedance have a pronounced effect on noise propagation. To investigate these changes, tests were conducted with either a perfectly reflective plane surface between the structure and the microphone, or a totally absorptive one. Overlay plywood was used as the reflective plane, and the cable mesh "floor" suspended in the anechoic test chamber simulated the absorptive ground condition.

Modeling absorptive surfaces, such as the proposed undercar treatments, was done using various thicknesses of Owens-Corning PF-105 fiberglass insulation. This material has an absorption coefficient of 0.97 in the frequency region of interest.

FABRICATION

The dimensions of the scale model were taken from cross sections and plans of the proposed Metropolitan Dade County rapid transit system provided by Kaiser Transit Group (Figs. B-1 and B-2). Detailing included the elevated structure supports, transit car dimensions, wheel-truck positions, and undercar equipment positions.

The model was assembled using nails and glue. The car itself was filled with fiberglass to prevent a reverberant sound field inside the car shell. All open joints or cracks were sealed with tape or glue.

The guideway noise barrier and the transit car skirt models were constructed of 18-gauge aluminum sheeting. When absorptive skirts or barriers were required, a 0.1-in. (.25-cm) layer of Owens-Corning PF-105 glass fiber was glued to the sheeting. The skirt and/or barriers were attached to the model using heavy tape to insure a tight seal.

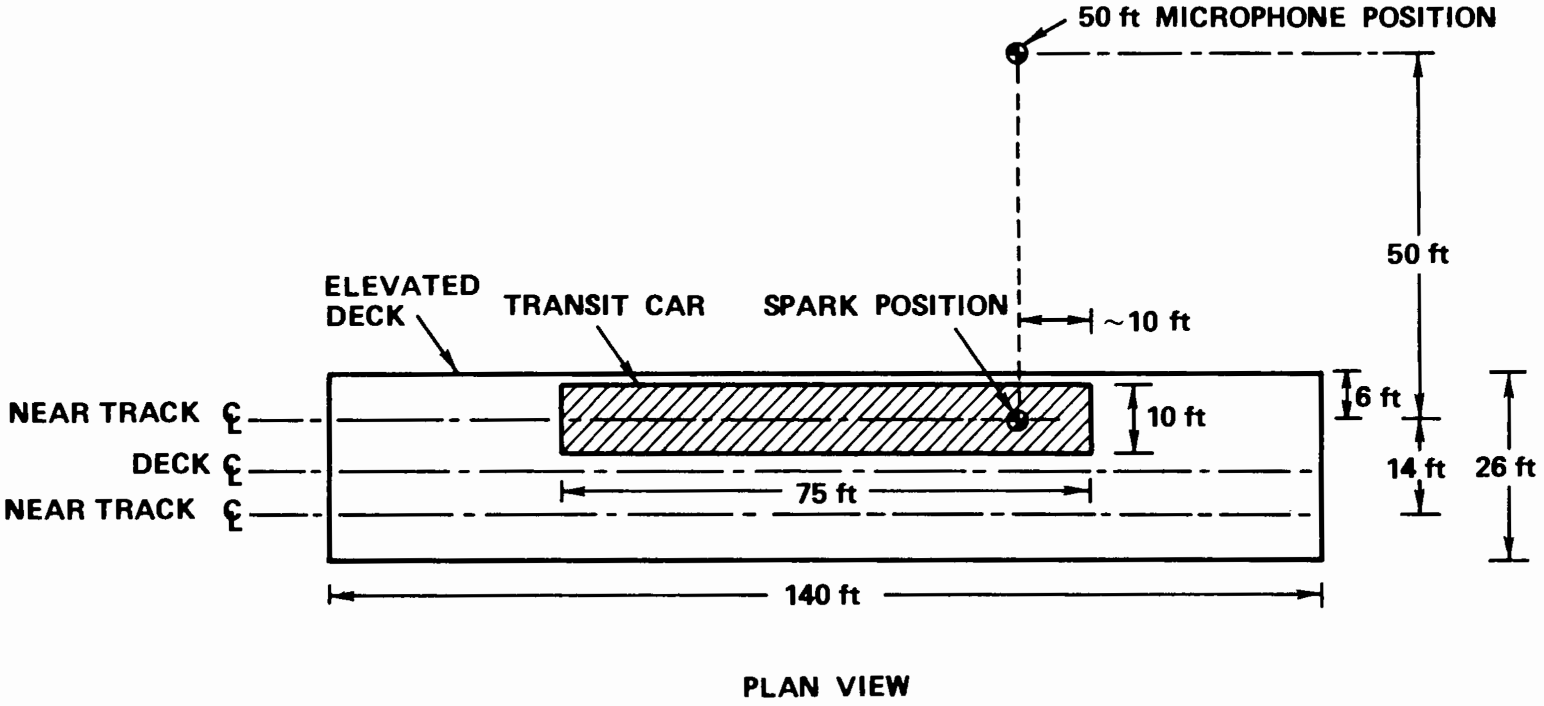


FIGURE B-1. MODEL GENERAL ARRANGEMENT. (DISTANCES ARE FULL SCALE)

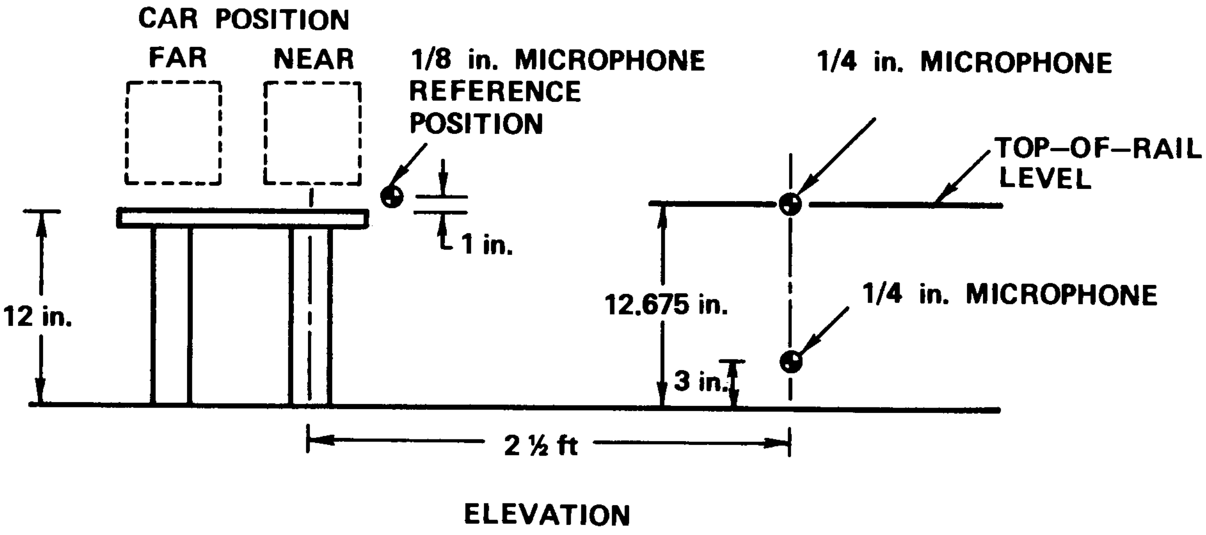


FIGURE B-2. MODEL GENERAL ARRANGEMENT. (DISTANCES ARE MODEL SCALE)

APPENDIX C: SCALE MODEL INSTRUMENTATION

The acoustical scale model study required specialized instrumentation and a test room with sound-absorbing walls (Fig. C-1).

SOUND SOURCE

An electric spark discharge (10,000 V) was used as a sound source (Fig. C-2). This impulsive sound source provided significant energy in the frequency regions of interest. It could also be conveniently supported from within the model transit car. The spark gap itself could be accurately positioned and easily aligned. The position chosen for the spark was just above axle height near the center of the truck, representing a position somewhere between the two traction motors.

The spark was triggered by an external firing unit, designed to fire repeatedly at a precise rate, with a high degree of uniformity from one discharge to the next. The triggering unit also sent timing pulses to the analysis instrumentation, in order to provide accurate synchronization.

MICROPHONES

One of two microphones was used, depending upon the measurement to be taken. Close-in reference measurements, for near-field propagation tests, were taken with a 1/8-in. (.318-cm)-diameter microphone (B & K 4138). This microphone was chosen because of its smaller size and its ability to withstand the high sound pressure levels near the spark source [≃160 dB @ 3 in. (7.6 cm)]. The far-field measurements were taken with a 1/4-in. (.64-cm)-diameter microphone (B & K 4135), which has higher sensitivity than the B & K 4138. The microphones were connected to battery-powered microphone preamplifiers (GenRad P42), which increased the system signal-to-noise ratio.

Both microphones had good directional and frequency response characteristics in the frequency range of interest. A grazing

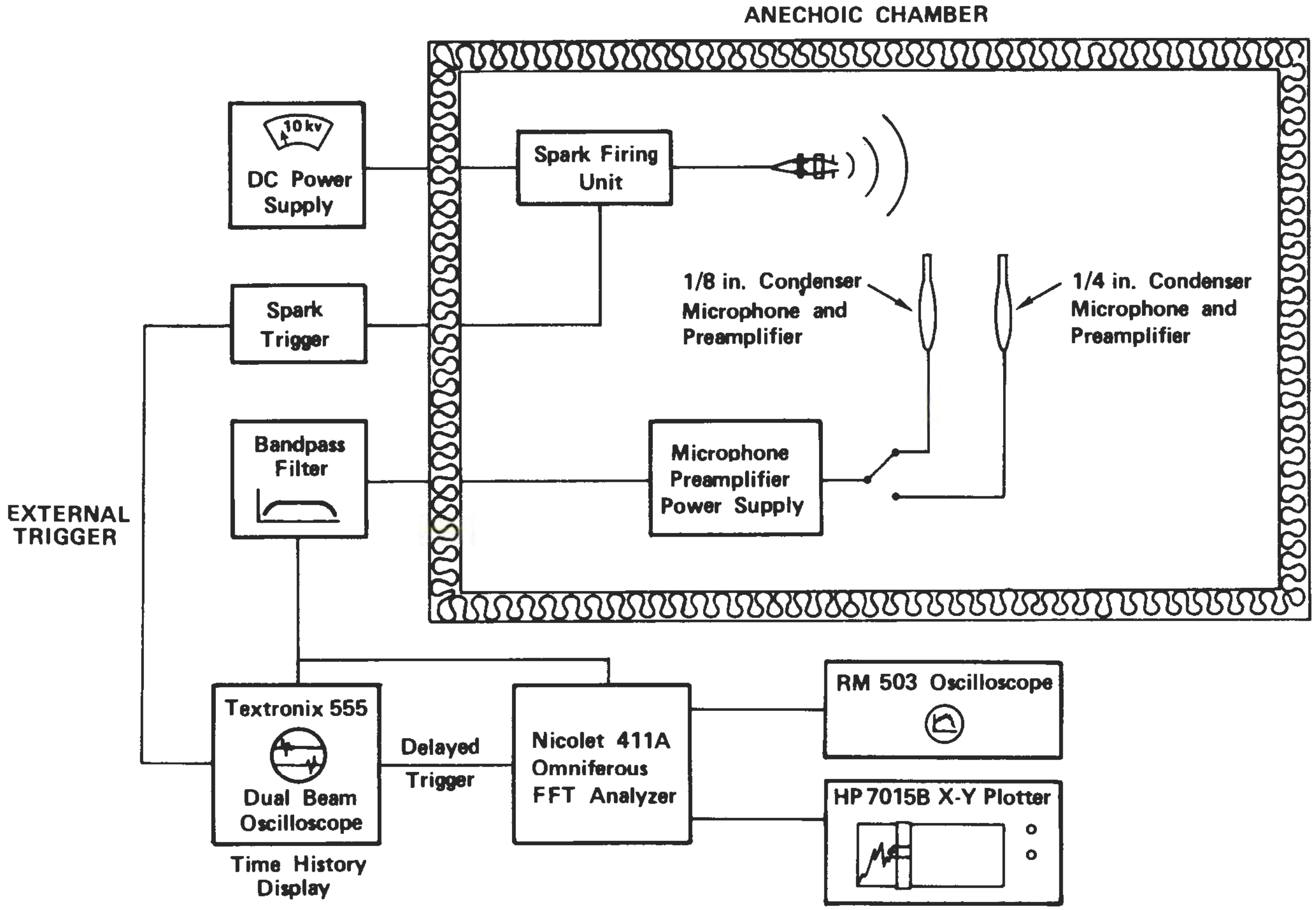


FIGURE C-1. INSTRUMENTATION BLOCK DIAGRAM OF ACOUSTICAL SCALE MODEL

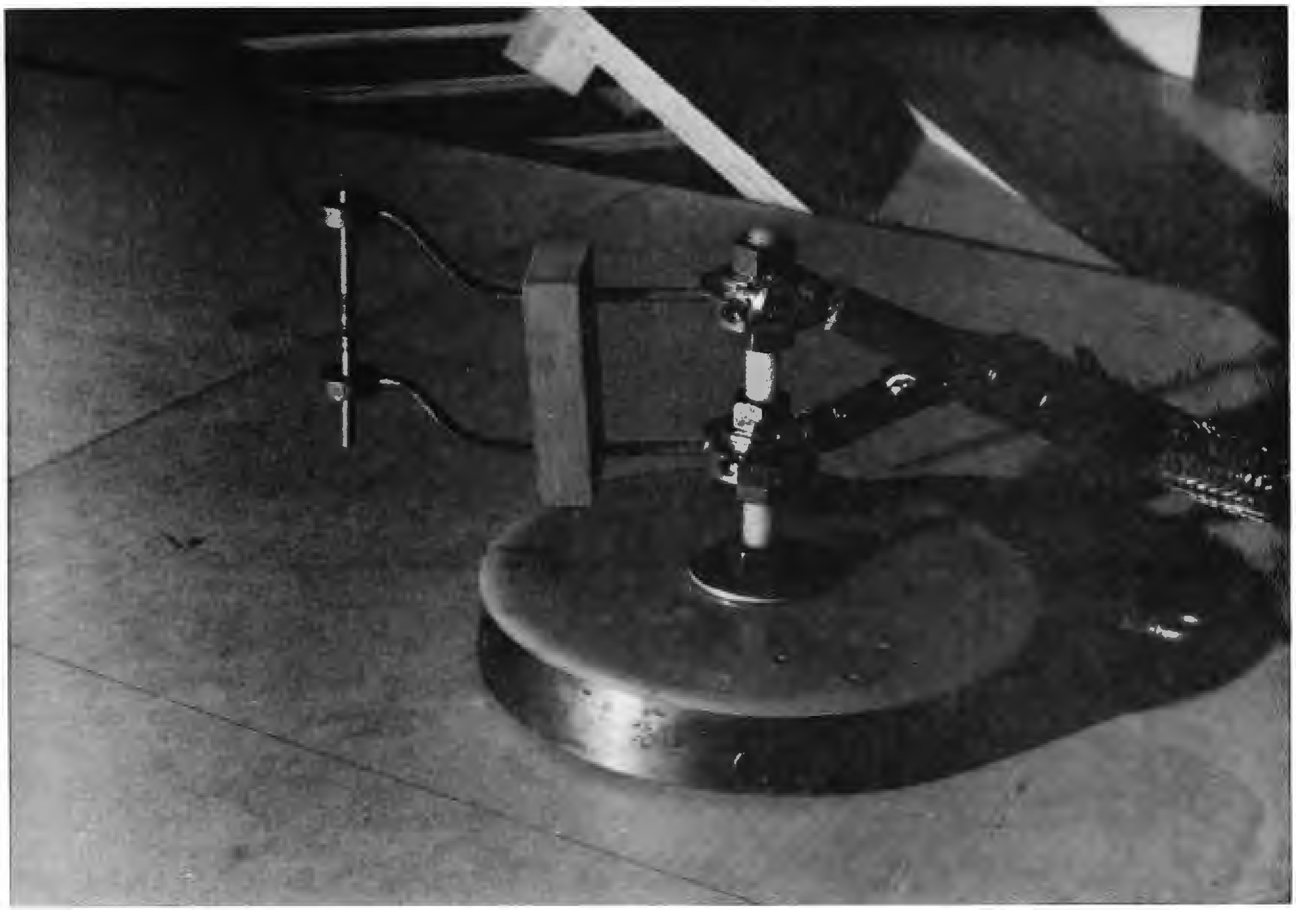


FIGURE C-2. NOISE SOURCE PROVIDED BY ELECTRIC SPARK DISCHARGE: 1/16 ft (.24 mm) GAP incidence orientation was used to insure the most uniform frequency response.

A "band-pass" filter was used both to decrease the low-frequency energy received, which was of no use in this study, and also to roll-off the highest frequencies to help reduce interference.

ANALYSIS INSTRUMENTATION

To capture and analyze the spark source signal, a Nicolet Omniferous 411A FFT real-time spectrum analyzer was used. This instrument is capable of capturing the time history and frequency spectrum information of an implusive event such as a spark. This unit was triggered by a Textronix type 555 dual-beam oscilloscope. The oscilloscope, triggered synchronously with the spark source, produced a delayed pulse, which in turn triggered the Omniferous and allowed a variable temporal starting point of the frequency analysis. This variability of the "time-history window" is the key to the process. The delayed trigger makes possible the "gating out" of unwanted or spurious signals, such as the electromagnetic spike from the spark discharge. Thus, only the acoustically significant signals are analyzed.

The frequency spectra were continuously displayed on another oscilloscope and plotted on an X-Y recorder (Fig. C-3).

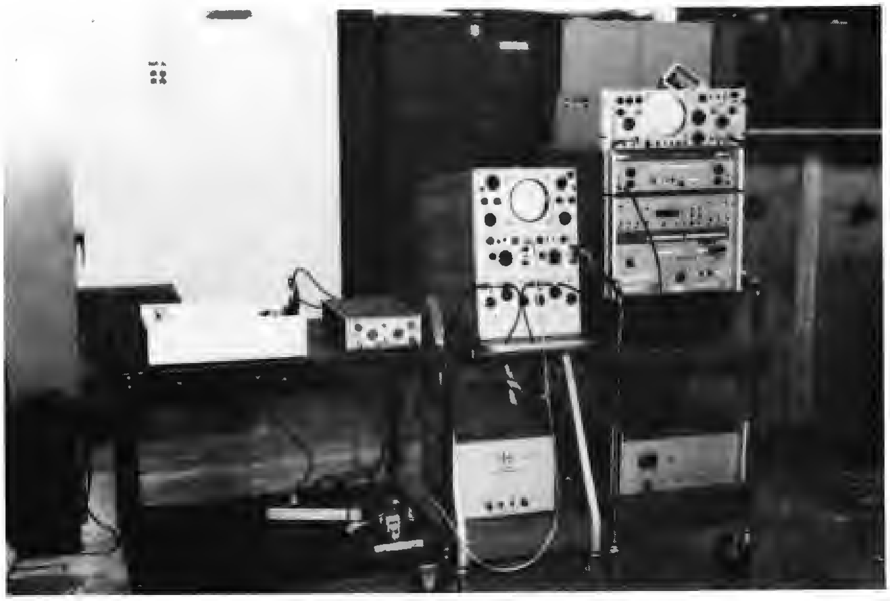


FIGURE C-3. INSTRUMENTATION USED IN THE SCALE MODEL STUDY

APPENDIX D: FULL-SCALE INSTRUMENTATION USED WITH PATCO VEHICLES ON AT-GRADE TRACK AND ON ELEVATED STRUCTURES

DATA ACQUISITION SYSTEM

Noise from passing trains was picked up by microphones, amplified, and then recorded on dual-track magnetic tape for laboratory analysis (Fig. D-1).

MEASUREMENT PROCEDURE

Microphone locations included a near-field position close to the vehicle (midway between the car skirt and top-of-rail), and a far-field reference position located 50 ft (15 m) from the center of the near track and 5 ft (1.53 m) above the ground (Fig. 10). Noise at these two positions was measured and recorded simultaneously for the elevated structure as well as for the at-grade alignment configuration. Measurements at the elevated structure site were also made 50 ft (15 m) from the track at the same height above ground as the near-field position. Another set of measurements was taken 6 in. (15.24 cm) beneath the concrete viaduct. All measurements were made simultaneously with the 5-ft (1.53-m)-high reference measurement. Data were recorded for both near- and far-track vehicle passbys. Speed was monitored with a portable traffic radar unit.

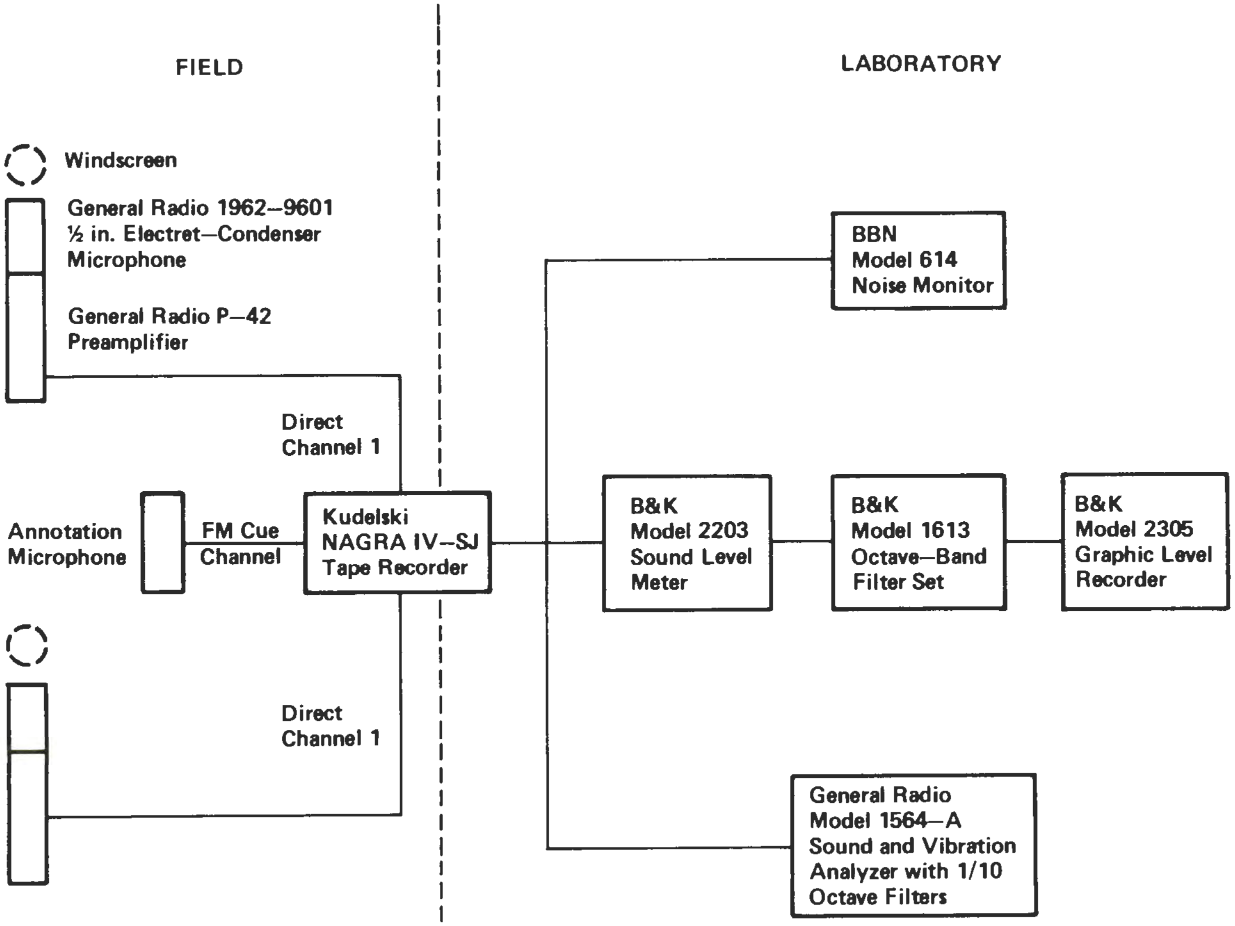


FIGURE D-1. FIELD AND LABORATORY DATA ACQUISITION AND REDUCTION SYSTEM

APPENDIX E: MEASUREMENT DATA FROM PATCO TEST RESULTS

TABLE E-1. PATCO NOISE MEASUREMENT DATA

Track Configuration/ Train Position	Maximum Sound Level (L_{max}, in dBA)				Train Speed (mph)	SINGLE EVENT LEVEL (SEL, in dBA)			
	Mic. Pos. 1	Mic. Pos. 2A	Mic. Pos. 2B	Mic. Pos. 2C		Mic. Pos. 1	Mic. Pos. 2A	Mic. Pos. 2B	Mic. Pos. 2C
Elevated/Near	90.1	102.9			55	92.4	102.5		
"	91.6	104.4			55	93.9	103.1		
"	90.0	100.6			55	91.1	102.1		
"	88.6	101.4			55	*	102.0		
"	90.1	103.5			55	92.6	102.7		
"	87.9	101.4			55	90.1	100.8		
"	89.4	102.7			55	91.8	102.5		
"	90.1	103.6			55	92.4	102.9		
"	93.1	105.1			55	94.5	105.0		
"	90.9		93.3		55	93.3		93.0	
"	91.6		93.9		55	93.9		93.9	
"	88.6		90.9		55	90.9		90.9	
"	89.4		91.5		55	91.5		91.6	
"	*			93.9	55	*			94.6
"	*			95.4	55	*			95.8
"	*			99.1	55	*			99.0
Log. Average	90.3	103.1	92.6	96.7	55	92.6	102.8	92.5	96.9
Corr. to 60 mph	+2.3	+2.3	+2.3	+2.3		+1.9	+1.9	+1.9	+1.9
Normalized Avg	92.6	105.4	94.9	99.0	60	94.5	104.7	94.4	98.8
At-Grade/Near	85.6	*			60	87.5	*		
"	86.4	102.9			60	88.1	101.8		
"	84.1	99.9			60	86.0	99.1		
"	84.9	99.9			60	87.0	99.5		

*Invalid data.

TABLE E-1. PATCO NOISE MEASUREMENT DATA *(Cont.)*

Track Configuration/ Train Position	Maximum Sound Level (L_{max}, in dBA)				Train Speed (mph)	Single Event Level (SEL, in dBA)			
	Mic. Pos. 1	Mic. Pos. 2A	Mic. Pos. 2B	Mic. Pos. 2C		Mic. Pos. 1	Mic. Pos. 2A	Mic. Pos. 2B	Mic. Pos. 2C
At-Grade/Near	85.6	102.1			60	88.1	101.0		
"	84.9	97.6			60	86.6	*		
Log Average	85.3	100.9			60	87.3	100.5		
Elevated/Far	81.0	99.0			60	84.5	99.5		
"	83.4	99.0			60	86.0	99.1		
"	78.1	95.4			60	82.6	96.3		
"	78.9	96.7			60	84.3	96.9		
"	82.6		87.9		60	86.2		90.9	
"	78.7		84.9		60	82.5		87.5	
"	80.4		86.4		60	84.9		88.5	
"	84.9		88.6		60	87.5		91.1	
"	*			88.5	60	*			90.5
"	*			93.1	60	*			93.7
"	*			88.6	60	*			88.6
"	*			95.2	60	*			94.3
Log Average	81.6	97.8	87.2	92.3	60	85.1	98.2	89.8	92.4
At-Grade/Far	84.1	94.6			55	86.6	95.6		
"	81.0	92.4			55	83.6	93.0		
"	82.6	92.4			55	85.6	93.0		
"	83.4	90.7			55	86.0	93.3		
"	80.4	90.7			55	83.6	92.0		
Log Average	82.5	92.8			55	85.3	93.6		
Corr. to 60 mph	+2.3	+2.3				+1.9	+1.9		
Normalized Avg	84.8	95.1			60	87.2	95.5		

*Invalid data

TABLE E-2. OCTAVE BAND INSERTION LOSS OF TREATMENTS TESTED*

	Octave Band Insertion Loss							
	Near Track Position				Far Track Position			
Treatment Description	250 Hz	500 Hz	1000 Hz	2000 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz
Basic, Full Undercar Absorption	1.9	4.6	5.3	4.0	3.0	3.2	2.7	4.6
Basic, Full Undercar Absorption, High Barrier	25.8	23.9	31.0	25.4	11.1	18.1	18.7	22.3
Basic, High Barrier	15.7	23.6	21.4	20.5	9.1	15.0	11.3	22.0
Half Skirt	1.7	5.3	4.9	2.9	1.2	6.1	3.5	3.2
Half Skirt, Low Barrier	13.2	11.9	15.1	13.0	5.1	12.0	13.9	11.9
Half Skirt, Skirt Absorption	2.1	6.3	4.7	3.1	1.3	6.3	3.4	2.9
Half Skirt, Skirt Absorption, Low Barrier	14.6	13.4	16.0	12.0	4.9	11.2	12.8	12.2
Half Skirt, Full Undercar Absorption	4.7	11.1	7.3	4.5	6.0	12.0	7.2	5.4
Half Skirt, Full Undercar Absorption, High Barrier	22.4	32.6	32.5	26.8	8.2	14.6	17.4	23.7
Full Skirt	3.3	4.5	6.2	5.8	2.8	3.1	4.6	7.0
Full Skirt, High Barrier	16.1	23.4	29.2	24.0	11.1	17.3	16.9	15.7
Full Skirt, Skirt Absorption	4.6	8.0	8.9	7.4	4.6	7.2	8.1	9.3
Full Skirt, Skirt Absorption, High Barrier	15.8	23.5	33.2	24.5	10.5	17.3	18.4	20.3
Full Skirt, Full Undercar Absorption	10.0	14.6	12.3	8.4	4.8	13.4	10.1	8.5
Full Skirt, Full Undercar Absorption, Low Barrier	21.2	24.8	26.6	21.7	10.3	17.3	22.7	20.6
Full Skirt, Full Undercar Absorption, High Barrier	20.1	31.3	33.6	28.3	13.4	19.7	20.8	20.1

*Microphone position is top-of-rail height, 50 ft (15 m) from structure centerline.

Numbers are insertion loss in dB with respect to "Basic, No Treatment" octave band noise levels.

APPENDIX F: REPORT OF NEW TECHNOLOGY

During this investigation, experimental techniques for acoustical scale modeling were refined and then applied in order to simulate noise propagation from Urban Rail Transit propulsion systems. There were no discoveries or innovations that represent patentable inventions.

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