ORT NO. UMTA-MA-06-0099-80-6

WAYSIDE NOISE OF ELEVATED RAIL TRANSIT STRUCTURES: ANALYSIS OF PUBLISHED DATA AND SUPPLEMENTARY MEASUREMENTS

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DECEMBER 1980

INTERIM REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
Transportation Systems Center
Cambridge MA 02142

Technical Report Documentation Page

1. Report No. UMTA-MA-06-0099-80-6	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle WAYSIDE NOISE OF ELEVATED RAIL TRANSIT STRUCTURES: ANALYSIS OF PUBLISHED DATA AND SUPPLEMENTARY MEASUREMENTS		5. Report Date December 1980
		6. Performing Organization Code DTS-331
7. Author(s) Unger, Eric E.; Wittig, Larry E.		8. Performing Organization Report No. DOT-TSC-UMTA-80-41
9. Performing Organization Name and Address Bolt Beranek and Newman Inc.* 50 Moulton Street Cambridge MA 02238		10. Work Unit No. (TRAIS) UM049/R0701
		11. Contract or Grant No. DOT-TSC-1531
12. Sponsoring Agency Name and Address U.S. Department of Transportation Urban Mass Transportation Administration Office of Technology Development and Deployment Office of Rail and Construction Technology Washington DC 20590		13. Type of Report and Period Covered Interim Report July 1978-Oct. 1980
		14. Sponsoring Agency Code UTD-30

15. Supplementary Notes

*Under contract to: U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Kendall Square, Cambridge MA 02142

16. Abstract

Elevated structures that carry rail traffic are classified in terms of their noise-radiating components and are compared to similar trains operating at grade, according to how much more noise results from trains running on elevated structures.

The mechanisms responsible for the generation of wayside noise are discussed, noise control concepts are reviewed, and the effectivenesses of noise-control means that have been reported in the technical literature are summarized. The noise-control means that are most suitable for the various major classes of structures are indicated.

In the appendices, results of measurements made on a MARTA structure to investigate the noise reductions resulting from a barrier and from damping applied to a steel box beam are presented, as well as the results of an investigation carried out on a NYCTA structure in order to evaluate the effects of replacement of standard by resilient rail fasteners. An extensive annotated bibliography of the world literature appears in a final appendix.

17. Key Words Noise, Rail transportation noise, Urban rail noise, Elevated structure noise, Noise barriers	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	126	

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

PREFACE

This report presents the results of one of five tasks in a program dealing with the reduction of noise from elevated structures in U.S. rail rapid transit systems. This report was prepared by Bolt Beranek and Newman Inc. (BBN) under Contract DOT-TSC-1531 as part of the Urban Rail Noise Abatement Program sponsored by the Office of Rail and Construction Technology of the Urban Mass Transportation Administration. This program, which is being managed for UMTA by the Transportation Systems Center, has the objectives of assessing the noise produced by urban rail transit operations and of appraising corresponding noise reduction methods and their associated costs.

First Dr. Leonard G. Kurzweil, and later Dr. Robert P. Kendig, served as the Transportation System Center's technical coordinator for the efforts leading to this report. Their cooperation, and the literature review contributions made by Dr. Istvan L. Ver of BBN, are gratefully acknowledged.

The measurements made on elevated structures of the New York City Transit Authority and of the Metropolitan Atlanta Rapid Transit Authority were carried out with the cooperation, respectively, of the Environmental Staff Division of NYCTA, under the direction of Mr. Anthony Paolillo, and of the engineering staff of MARTA, under direction of Mr. Morris Solomon. Their participation and assistance are greatly appreciated.

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

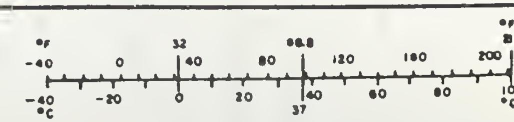

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

A recent inventory [Towers 80]* has shown that more than one-third of a million people living or working near the roughly 250 km (160 miles) of elevated structures of U.S. rail rapid transit systems are exposed to disturbing noise levels resulting from trains operating on these structures. Therefore, reduction of this noise may be expected to have a favorable and extensive environmental impact.

Observers in the vicinity of locations where trains make the transition from elevated structures to track at grade or on beams (or inversely, from at-grade to elevated track) can usually note that a train running on an elevated structure generates considerably more noise than the same train at grade. Comparison measurements have shown that the noise from trains on elevated structures in some instances exceeds the corresponding at-grade noise by as much as 20 dBA [Kurzweil 77], leading one to surmise that the noise associated with trains on elevated trackage can be reduced considerably if the elevated structure can be made to behave acoustically like track support structures at grade.

Accordingly, the U.S. Department of Transportation has embarked on a program of investigation aimed at the development of cost-effective means for reducing the environmental noise of elevated structures in rail rapid transit systems. The present report summarizes the results of one facet of this program.

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* Literature citations, given in terms of the (first-listed) author's name and the last two digits of the year of publication, appear in brackets and refer to the annotated bibliography at the end of this report.

The initial report produced under the current contract dealt with criteria for rating the noise radiated from elevated structures, in order to establish a basis for evaluation and comparison of the noise impacts of these structures on their neighborhoods [Schultz 79]. The second report applied the recommended noise rating criterion to information derived from noise and schedule data and from a physical inventory of elevated structures, so as to evaluate the noise impacts of structures in use in U.S. rapid transit systems and to identify the structure types responsible for the greatest impact [Towers 80]. The third report prepared under the current program [Remington 80] presents an analytical model of noise generation/radiation by the most prevalent type of elevated structure - namely, one in which the rail is fastened to wood ties that rest directly on steel plate girders - which consists of an improvement of a model that was developed earlier [Manning 75]. The present report summarizes the results of a study of literature and field measurements aimed at (1) delineating the effectiveness of noise-abatement means that have been implemented and tested, (2) ascertaining the existence of data against which the analytical model may be tested, and (3) developing an improved understanding of the most important contributors to wayside noise.

The first of the following sections (Section 2) presents an overview of the salient features of elevated structures and discusses their relative noisiness. Section 3 addresses noise generation and radiation, as well as corresponding noise control approaches. Section 4 summarizes the results of a literature search for definitive data and of supplementary field measurements that were undertaken. A discussion of some Japanese data, descriptions of the aforementioned field measurements, and an annotated bibliography appear in appendices.

2. ELEVATED STRUCTURES FROM THE NOISE STANDPOINT

In order to establish an organized framework for the discussion of noise reduction associated with train passages on elevated structures, the present section provides a general description and classification of elevated structures and discusses how noise generated on and by these structures reaches the wayside. The discussion also serves as a basis for consideration of noise control treatments presented hereafter.

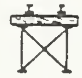
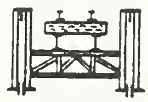
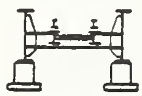
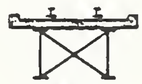
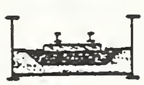
2.1 Classification of Structures

There exists a great variety of rail-carrying structures. Table 2.1 shows the cross-sections of some of the configurations for which noise data are available. In order to develop a classification system that is useful from the noise standpoint, it is helpful to consider the various structural elements and how these participate in the noise production process.

One may observe that any elevated structure incorporates two primary components, in addition to vertical supports (columns or bents):

1. Longitudinal supports -- primary load-carrying members that span longitudinally between vertical supports.
2. Decks -- structural elements that carry the tracks and generally are supported by parallel longitudinal members.

TABLE 2.1. WAYSIDE NOISE AT 25 m (82 ft) FROM CENTERLINE OF ELEVATED STRUCTURES OR TRACKS*

Description of structure		Adminis-tration¶	Measured wayside levels (dB(A))	Estimated levels for full train at 60 km/h‖ (dB(A))	Reference
1. Direct fixation of rail on orthotropic steel plate deck, steel plate (or box) girder	 Structure 1	DB	88†	93	[7]
		DB	92†	97	[7]
		DB	92†	97	[7]
2. Wood ties supported on steel plate girders	 Structure 2	JNR	105‡††	94††	[9]
3. Direct fixation of rail on flat plate which is integral with steel plate girders	 Structure 3	NS	87†	92	[7]
		NS	88†	93	[7]
4. Wood ties on rail bearers, steel plate girders	 Structure 4	CFF	86†	91	[7]
		SNCF	85†	90	[7]
		SNCF	88†	93	[7]
5. Wood ties, on rail bearer, lattice girder (or steel truss bridge)	 Structure 5	DB	81†	86	[7]
		SNCF	83†	88	[7]
		NS	85†	90	[7]
		DB	91§	91	[7]
		JNR	98‡	87	[9]
6. Direct fixation of rail on rail bearers, steel plate girders	 Structure 6	NS	82†	87	[7]
7. Direct fixation of rail on reinforced concrete deck, steel plate (or box) girders	 Structure 7	DB	82§	82	[7]
		SNCF	81†	86	[7]
		JNR	93‡	82	[9]
8. Direct fixation of rail on concrete viaduct	 Structure 8	JNR	92‡	81	[8]
9. Wood tie/ballast track on steel plate, steel plate (or box) girders	 Structure 9	DB	77†	82	[7]
		DB	78†	83	[7]
		DB	80†	85	[7]
		JNR	92‡	81	[9]
10. Wood tie/ballast track on reinforced concrete deck, steel plate girders	 Structure 10	SNCF	74†	79	[7]
		CFF	74†	79	[7]
11. Wood tie/ballast track on concrete viaduct	 Structure 11	JNR	88‡	77	[8]
12. At-grade track		DB	76†	81	[7]
		CFF	75†	80	[7]
		SNCF	75†	80	[7]
		NS	77†	82	[7]
		JNR	82‡	71	[8]

† Single locomotive coasting by at 60 km/h (37 mile/h); levels measured 25 m (82 ft) from near-track centerline, 1·6 m (5 ft, 3 in) above ground.

‡ Multicar train passby at 200 km/h (124 mile/h); levels measured 25 m (82 ft) from structure centerline, 1·2 m (4 ft) above ground.

§ Multicar train passby at 60 km/h (37 mile/h); same measurement location as †.

‖ $L_{train} - L_{single\ car} = 5$ dB(A) [7, 10]; $L_{200\ km/h} - L_{60\ km/h} = 11$ dB(A) (see text).

¶ CFF = Swiss Railways; DB = German Federal Railways; JNR = Japanese National Railways; NS = Netherland Railways; SNCF = French National Railways.

†† After this paper had gone to press, the author discovered that the values given were for a structure having corrugated rail (rail with periodic wear patterns along its running surface which cause higher noise levels). The appropriate measured and normalized values for the structure with typically worn rail should read 98 and 87 dB(A) respectively. Based on the revised data, structure type 2 has about the same wayside noise level as structure type 5.

*From [Kurzweil 76]
**[7] = [ORE 71]
[8] = [JNR 73]
[9] = [JNR 75]

Longitudinal supports typically are of one of the following five types:

Steel plate girders
Steel box beams
Steel lattice girders or trusses
Concrete girders
Concrete box beams,

and decks generally are of one of the following four types:

Ties of wood or concrete
Steel plate
Concrete slabs
Rail bearers and stringers.*

The upper surface of box beams serves both as the deck and as part of the longitudinal support structure. Similarly, the upper portion of concrete beam structures often serves both as a deck and as a beam component.

Where continuous deck structures are used, ballast (gravel) is often interposed between the deck and the rail-carrying ties, primarily to spread the relatively concentrated loads due to the wheels. Such structures therefore need to be classified further in terms of the presence or absence of ballast.

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*Rail bearers are secondary longitudinal beams that support the rails (with or without ties) and that are carried by stringers — i.e., by beams, trusses or plates spanning laterally between parallel longitudinal supports.

In addition, it is necessary to distinguish between two arrangements of the deck relative to the longitudinal supports; in one, the deck is directly atop the longitudinal supports; in the other, the deck is situated between the longitudinal supports, yielding a trough-like configuration.

It thus appears that elevated structures may be categorized in terms of the following five characteristics:

Longitudinal support type
Deck type
Presence of rail bearers
Presence of ballast
Deck/Longitudinals relation

However, not all combinations of components occur in practice. Open tie decks cannot be employed with ballast, of course, and are never used on concrete longitudinal support structures. Steel decks are not used in conjunction with concrete longitudinal supports, although concrete decks are employed on both concrete and steel longitudinal structures. It turns out that all commonly used elevated structures may be assigned to seven major classes, defined in terms of the deck type, the longitudinal support structure material, and the presence or absence of ballast. These classes may be subdivided conveniently in terms of the type of longitudinal support structure, the arrangements of track relative to the support structure, and the presence of rail bearers. The classification scheme for elevated structures is indicated in Table 2.2.

TABLE 2.2. CLASSIFICATION OF ELEVATED STRUCTURES.

Major Class	Deck[1]	Longitudinal Supports	Ballast
1	Open Tie	Steel Beams	No
2	Concrete	Steel Structure[2]	No
3	Concrete	Steel Structure[2]	Yes
4	Concrete	Concrete[3]	No
5	Concrete	Concrete[3]	Yes
6	Steel Plate	Steel Structure[2]	No
7	Steel Plate	Steel Structure[2]	Yes

Notes:

[1]Includes subclasses with and without railbearers.

[2]Includes subclasses A through E.

[3]Includes subclasses A through C.

Subclass	Structure Type	Rail Location
A	Box Beam	On Top
B	Solid-Web Beam	On Top
C	Solid-Web Beam	In Trough
D	Lattice Beam or Truss	On Top
E	Lattice Beam or Truss	In Trough

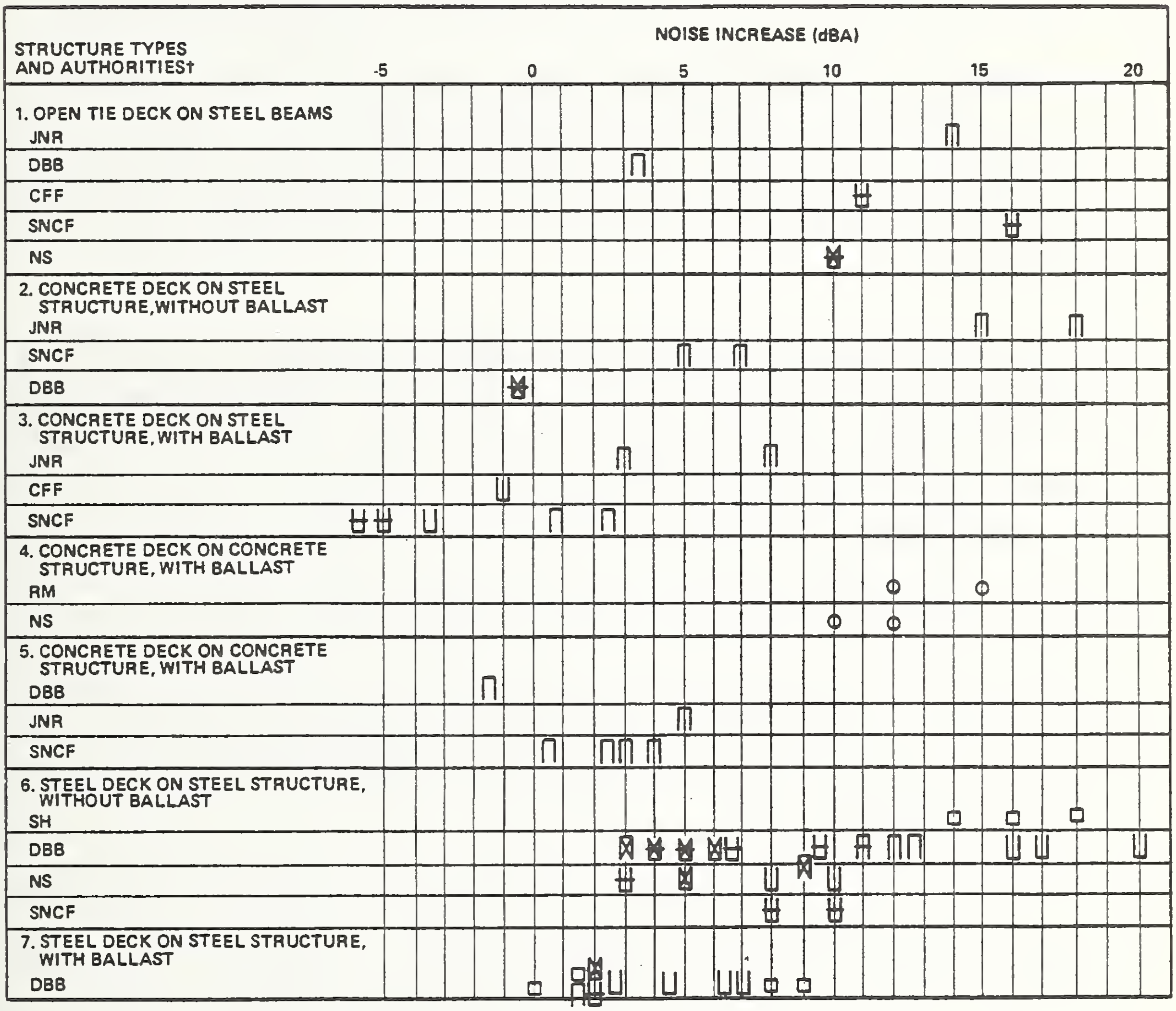
2.2 Noise Comparisons

Table 2.1 presents a compilation of results of European and Japanese measurements. The column headed "Measured wayside levels" indicates the average A-weighted sound pressure levels that were observed in the tests. However, because these test data pertain to different speeds and train lengths, some normalization was necessary in order to permit comparison. Accordingly, the reported data for each structure were extrapolated to a full train length (much longer than 25 m) passing at 60 km/h; the results appear in the right-hand data column of the table.

Although the data summary in Table 2.1 permits one to rank-order elevated structures in terms of the absolute wayside noise levels that occur in their vicinity, it does not enable one to draw any definite conclusion concerning the noise increases that are attributable to the elevated structures. For example, trains that are themselves noisy at grade also produce high wayside noise levels on elevated structures; thus, structures in systems with noisy trains would, in Table 2.1, be reported as resulting in high noise levels.

Table 2.3 was compiled in order to provide a clear indication of the noise increases that result from elevated structures. It shows how much more noise is observed near an elevated structure than near at-grade track for like trains passing at like speeds. This table, which is arranged according to the structure classification scheme indicated in Table 2.2, summarizes all of the pertinent data in the available literature (and identifies subclasses by means of symbols).

TABLE 2.3. INCREASE IN WAYSIDE NOISE NEAR ELEVATED STRUCTURES, COMPARED TO AT-GRADE TRACK.*



*Legend

⊓	Track on top of structure
⊔	Track in trough formed by beams
▢	Box beam, track on top
X	Lattice or truss beams
—	Rail bearers
O	Configuration not specified

†BART	Bay Area Rapid Transit (San Francisco)	NYCTA	New York City Transit Authority
JNR	Japanese National Railway	NS	Netherlands Railways
DBB	German State Railway	RM	Rotterdam Metro
CFF	Swiss Railways	SH	S-Bahn, Hamburg
SNCF	French National Railway	SL	Stockholm Lokal traffik
SEPTA	Southeastern Penn. Transit Authority	u	unspecified

From the data shown in Table 2.3 one may observe that ballastless steel-deck structures with steel longitudinals (Class 6) generally produce the greatest noise increases (up to 20 dBA) compared to at-grade track. Box-beam and trough configurations are generally noisier than average and truss beam structures are generally less noisy. Comparable structures with ballast (Class 7) tend to be of the order of 10 dBA quieter than the ballastless structures.

Elevated structures with open tie decks on solid-web steel longitudinal beams (Class 1) and ballastless concrete deck structures on steel longitudinals (Class 2) or on concrete longitudinal (Class 4) may be seen to result in noise increases, in some instances, of the order of 15 dBA. However, structures in the first two of these classes may also result in relatively small noise increases. On the other hand, the noise increases associated with structures that have ballast on concrete decks (Classes 3 and 5) may be seen typically not to exceed 5 dBA; in some instances these configurations even result in noise decreases of up to about 5 dBA.

Table 3.2, presented at the end of the next section of this report, indicates typical values of wayside noise associated with the various classes of structures, together with the average amounts by which noise from these structures exceeds that from comparable track installations at grade.

3. WAYSIDE NOISE GENERATION AND CONTROL

3.1 Generation of Wayside Noise

Figure 3.1 is a schematic representation of how noise from trains running on elevated structures reaches the wayside. This diagram reflects the currently available quantitative models [Remington 80, Manning 75], as well as qualitative information found in the literature.

There are two primary sources of wayside noise: (1) the propulsion and undercar equipment and (2) interaction between the wheels and rails. The unsteady wheel-rail interaction forces, particularly those resulting from the contacting surfaces not being perfectly smooth, cause the wheels and the rails to vibrate. These vibrations propagate to other components, and all vibrating components radiate sound (noise) into the air.

Noise from propulsion and undercar equipment, as well as noise radiated from wheels and rails, occurs also for trains running at grade. However, the propagation of vibrations and noise resulting from trains at grade may differ markedly from that for trains running on elevated structures.

The contribution to the overall wayside noise level, resulting from the airborne noise produced by propulsion and undercar equipment, often is approximately of the same magnitude as that caused by wheel-rail interaction. Wheel vibrations in the audio frequency range are poorly transmitted to the vehicle trucks and bodies, so that these vehicle components usually make no appreciable contribution to wayside noise. On the other hand, rail vibrations usually are transmitted easily to ties and to deck and longitudinal support structures; however, this transmission is inhibited if ballast or rail bearers are present. Because of their extended areas, deck and longitudinal support structures generally are good sound radiators and therefore often make major contributions to the radiated noise. The same has also been found to be the case for ties in open-deck structures [Remington 80].

Auxiliary structures (e.g., walkways and cable channels) that are attached to the primarily longitudinal supports act as significant sound radiators, particularly if they are relatively light and have considerable surface area. On the other hand, comparatively little vibratory energy tends to be transmitted to the generally massive and compact vertical supports, so that these usually make no significant noise contribution. Even less audio-frequency energy is transmitted to the ground; the corresponding sound radiation generally is insignificant, although lower-frequency ground vibrations in the immediate vicinity of vertical supports may be perceptible tactually.

As Figure 3.1 indicates schematically, the airborne noise radiated from the train equipment and from the structural components generally may be reflected and partly absorbed at structural and ground surfaces. Of course, only the larger surfaces produce significant reflection and absorption effects. The majority of the structural surfaces are essentially non-absorptive, and thus do not reduce the acoustical power radiated to the wayside. Nevertheless, they do affect the directional distribution of the noise, particularly in the vertical direction. This change in distribution usually is of relatively little interest,

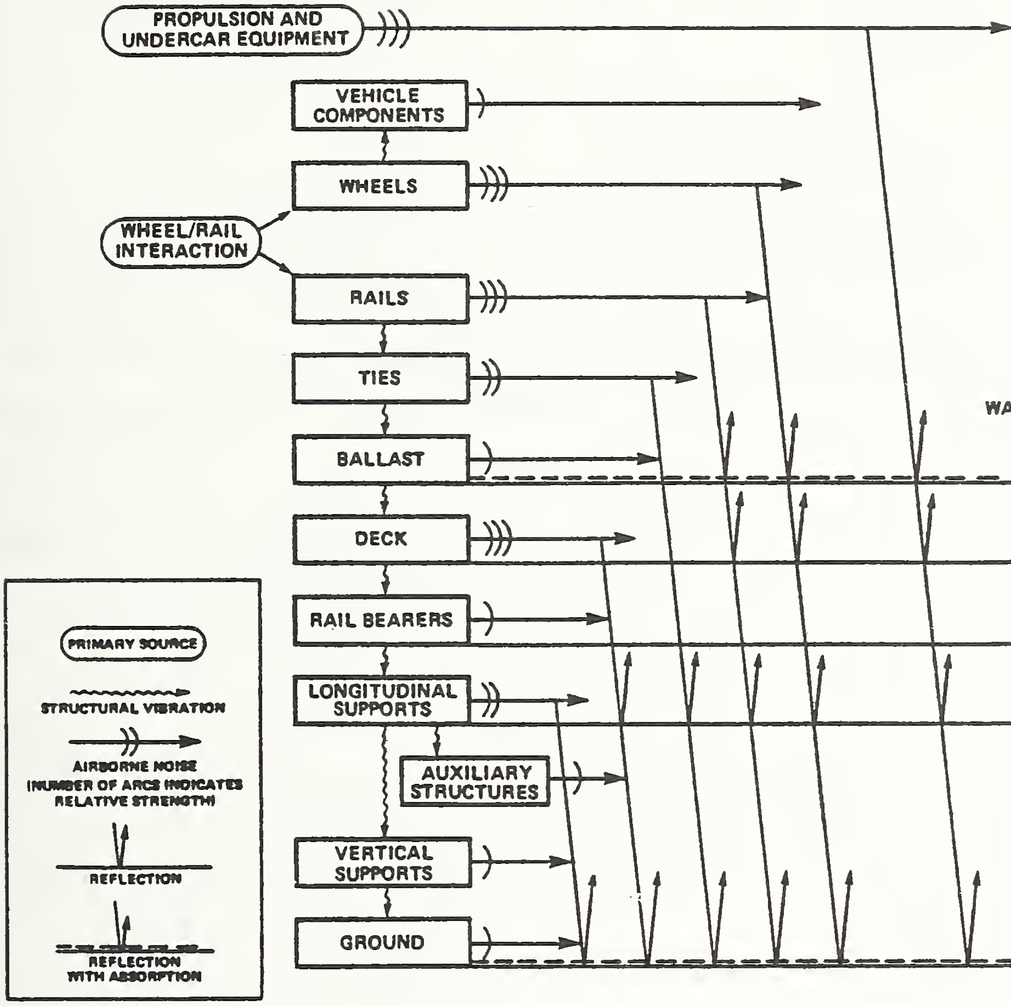


FIG. 3.1. SCHEMATIC REPRESENTATION OF WAYSIDE NOISE GENERATION BY ELEVATED STRUCTURES.

especially in "city canyon" areas, where acoustic reflection from building surfaces tends to contain sound energy in the street canyon.

3.2 Noise Control Concepts

In the light of Figure 3.1, it appears that the control of noise produced by trains operating on elevated structures may be considered in terms of (1) source reduction, (2) impeding the build-up and propagation of vibrations, (3) reduction of radiation from vibrating surfaces, and (4) impeding the propagation of airborne sound.

Because of the existence of two primary sources indicated in Figure 3.1, source reduction may involve quieting of the propulsion and undercar equipment, as well as reducing the unsteady wheel-rail interaction forces. The latter may be accomplished by replacing jointed by welded rail, by smoothing the wheel and rail surfaces (e.g., by wheel truing and rail grinding), and by using resilient wheels or rails. The build-up of vibrations in lightweight structural components may be reduced by the addition of mass (e.g., in the form of ballast), and the build-up of vibrations in lightly damped structures may be limited by the addition of damping treatments (e.g., viscoelastic sandwich configurations). The propagation of vibrations along extended structures or from substructure to substructure may be inhibited by the introduction of impedance discontinuities (generally in the form of resilient components) and/or by use of vibration isolation systems consisting essentially of resiliently supported masses.

In practical terms, vibration isolation may be accomplished by such means as resilient rail fasteners, resilient pads under ties, or ballast mats (between decks and ballast beds). The reduction of radiation from the surface of a vibrating structure can be accomplished by reducing its radiating surface area (e.g., by replacing solid by perforated metal sheets). Of course, the previously mentioned means for reducing the vibrations of a component also reduce the associated radiation.

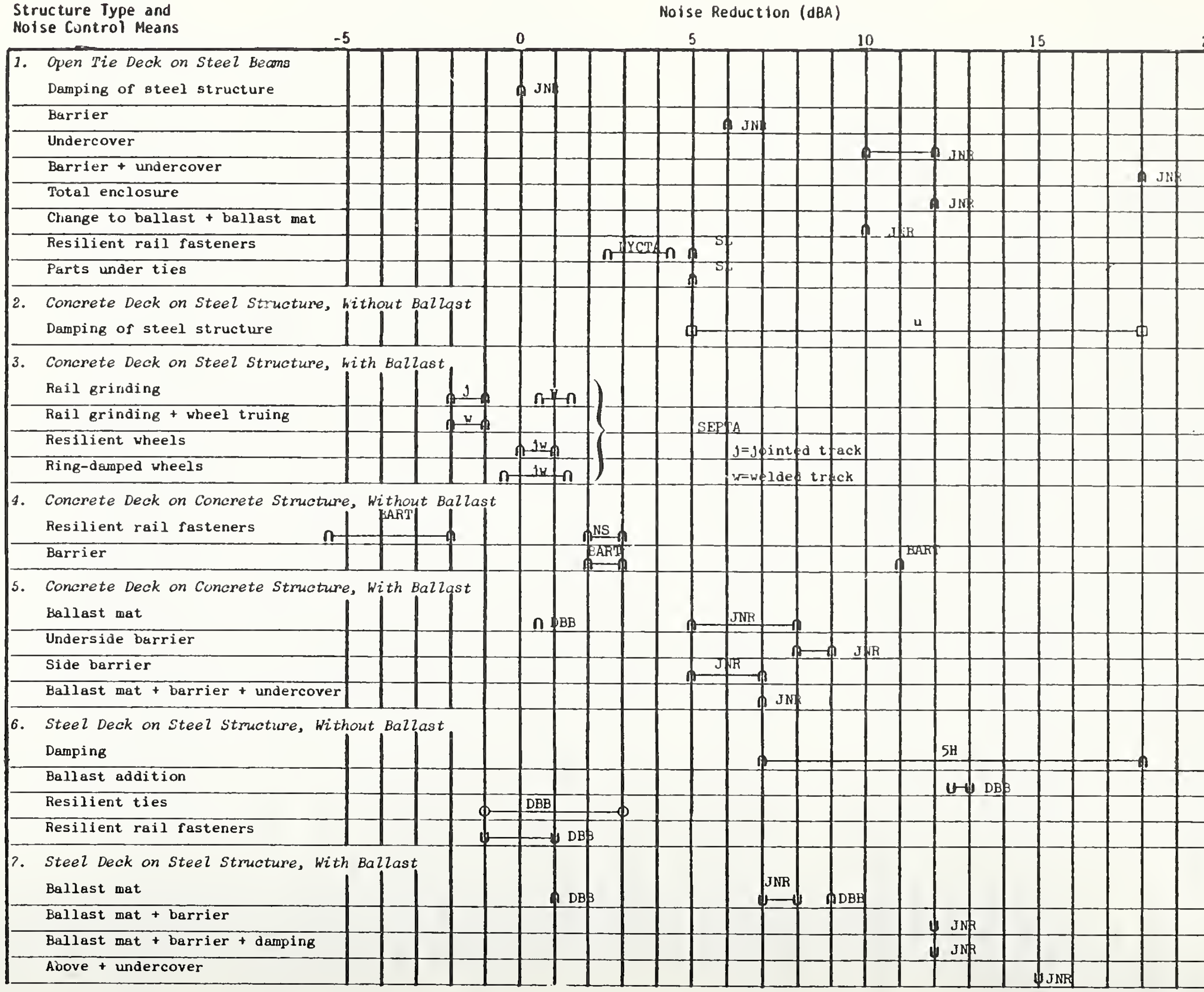
Means for impeding the propagation of airborne sound include various barriers (shields), partial and full enclosures, and also acoustical absorption. Absorption placed on the source-side of barriers or enclosures increases their effectiveness, and absorption on surfaces responsible for significant sound reflection reduces the reflected noise component.

3.3 Reported Noise Reductions

There exist only a limited number of instances in which noise reduction means have been implemented and in which directly comparable noise measurements taken before and after implementation of these means have been documented. The reductions in wayside noise achieved by various means that have been tried, as reported in the available literature, are summarized in Table 3.1. The corresponding literature references are listed in Table 4.1 and cited in detail in the annotated bibliography of Appendix D.

For structures of the type that generally produce the greatest noise increase as compared to track at-grade, namely ballastless steel deck structures on steel longitudinal supports (Class 6), the installation of damping treatments and the addition

TABLE 3.1. WAYSIDE NOISE REDUCTIONS DUE TO VARIOUS MODIFICATIONS.*



*See Table 2.3 for definitions of symbols.

Note: Symbols connected by line indicate spread of data.

of ballast have been found to produce noise reductions of the order of 15 dBA; whereas the use of resiliently supported ties only produce a few dBA of noise reduction.

For structures with open tie decks on longitudinal steel beams (Class 1), which are considerably noisier than comparable track at-grade, major noise reductions (10 dBA or more) have been achieved only by means of barriers that shield the wayside from noise coming from the sides and the underside of the elevated structure. A noise reduction of 6 dBA was reportedly achieved by use of only side barriers, and a reduction of 10 dBA was reported due to a modification that permitted the installation of ballast on a ballast mat. Resilient rail fasteners or the insertion of rubber pads between the ties and the longitudinal beams were found to produce noise reductions of 3 to 5 dBA. In the one instance documented, the addition of structural damping to the steel beams of an open tie deck structure resulted in no measurable reduction in wayside noise. On the other hand, such a damping addition to the steel of a composite structure consisting of a ballastless concrete deck atop a steel trough-beam (Class 2) was reported (though without full documentation) to result in noise reductions of 5 to 18 dBA.

Reductions in excess of 10 dBA in the noise from ballastless all-concrete structures (Class 4) were reportedly achieved by use of a barrier, although in another instance a barrier produced only a 2 to 4 dBA reduction. The use of resilient rail fasteners on such a structure resulted in a 2 to 4 dBA noise reduction in one case and a 2 to 6 dBA increase in another case.

Significant noise reductions (5 to 9 dBA) of ballasted concrete deck structures (Classes 3 and 5), which are relatively quiet even without noise control treatments, have been reported only for barriers both on the sides of the structures and underneath them. Resilient mats placed under the ballast have also proven useful in some cases. The results of rail grinding and wheel truing here have been mixed, ranging from 2 dBA reductions to 2 dBA increases in noise.

3.4 Summary; Noise Levels and Control Means

Table 3.2 presents a concise summary of the data indicated in Tables 2.1 and 2.3, together with a listing of the noise control means that are most suitable for the various classes of structures.

The average wayside noise levels indicated in Table 3.2 were obtained simply by averaging all of the data of Table 2.1 that pertain to each class of elevated structures. These data indicate the typical noise levels observed at 25 m (82 ft) at the side of an elevated structure due to passage of a full-length train at 60 km/h (37 mi/h). The values indicated in Table 3.2 for the average noise increases over at-grade track similarly were obtained by averaging over all data points indicated in Table 2.3 for each structure class.

If it is kept in mind that the aforementioned broad-brush averaging, together with the estimations involved in delineation of some of the original data, probably make class-to-class differences of less than 3 dBA meaningless, it may be observed that the various structures can be rank-ordered as follows in terms of their noisiness:

TABLE 3.2. SUMMARY OF NOISE LEVELS AND APPLICABLE NOISE CONTROL MEANS.

STRUCTURE				NOISE CHARACTERISTICS		APPLICABLE NOISE CONTROL MEANS TO ACHIEVE:	
CLASS	DECK	LONGIT. SUPPORTS	BALLAST	AVG. WAYSIDE NOISE (dBA)*	AVG. NOISE INCR. OVER AT-GRADE (dBA)	AT-GRADE NOISE LEVELS	SOME REDUCTION
1	Ties	Steel	No	89	11	Barriera	Resilient Fasteners
2	Concr.	Steel	No	83	7	Ballast	Damping**
3	Concr.	Steel	Yes	79	0	-	-
4	Concr.	Concr.	No	81	12	Ballast	Resilient Fasteners
5	Concr.	Concr.	Yes	77	2	Barriera	Ballast Mat**
6	Steel	Steel	No	91	10	Ballaat	Damping**
7	Steel	Steel	Yes	83	4	Barriers	Ballast Mat**

*At 25m, full train at 60 km/h; data from [Kurzweil 76].
**May also be used to achieve at-grade levels, but maybe more difficult to implement.

1. The noisiest category includes open tie deck steel structures (Class 1) and ballastless all-steel structures (Class 6). These structures are responsible for high absolute noise levels and also for large noise increases compared to track at grade.

2. Ballastless structures with concrete decks (Classes 2 and 4) and steel deck structures with ballast (Class 7) fall into an intermediate category, in terms of either the absolute noise levels or the noise increases, or both.

3. Concrete deck structures with ballast (Classes 3 and 5) belong to the quietest category, both in terms of absolute levels and levels relative to track at grade.

In the right-hand portion of Table 3.2 the noise control means that appear most applicable for each class of structures are indicated. The noise control means shown as applicable to achieving noise levels comparable to those obtained for track at grade were chosen on the basis of the data appearing in Table 3.1, with an eye toward proven performance and ease of installation. Thus, although damping may result in as much noise reduction of Class 2 and Class 6 structures with the addition of ballast, damping has been listed in the secondary "Some Reduction" category, because damping technology is not as widely accepted as ballast addition, and because for some structures the noise reduction due to damping has not been fully established. Similarly, barriers are listed in preference to ballast mats for Class 5 structures, because barriers may be more acceptable in practice.

The noise control means shown as applicable to achieving some noise reduction also were chosen on the basis of the data shown in Table 3.1. These means generally provide less reduction than required to reduce the elevated structure noise levels to those associated with trains operating at grade, but may be acceptable in many circumstances, particularly where use of the first-listed noise control means is ruled out.

4. INVESTIGATIONS OF NOISE SOURCES AND PATHS

4.1 Literature Study

A literature review was undertaken as part of the present project, not only for the purpose of compiling the information presented in the foregoing sections, but also in order to locate data that may be useful for validating analytical models of noise produced by trains on elevated structures.

Table 4.1 presents an overview of the relevant literature that includes quantitative data. (A complete annotated bibliography appears in Appendix D). This table indicates the structure types with which the various references deal, lists the corresponding average amounts by which the A-weighted wayside noise levels near elevated structures exceed those near track at grade, indicates the observed noise reductions achieved by various means,* and also shows the type of data that is reported.

It may be observed that only three of the references listed present all three types of data needed for analytical model validation, namely: noise spectra, vibration spectra, and quantitative descriptions of the structures. Of these three references one [Hanel 77] pertains to a steel box-beam bridge and one [ORF D105/RP2] pertains to a heavy railroad bridge - both configurations of little interest in relation to elevated structures used in U.S. rapid transit systems. The third of these references, [Manning 75] deals with development of an analytical model and with its validation; this information should also be useful for evaluation of other analytical models.

* The A-weighted noise level and noise reduction values listed here were used in the development of Tables 2.3 and 3.1.

TABLE 4.1. LITERATURE SOURCES OF QUANTITATIVE DATA.

Reference	Structure						Noise Increase Over Track At-Grade (dBA)	Noise Reduction (dBA) Due To Noise Control Means[6]		Data Type[7]	Notes
	Deck[1]	Ballast[2]	Support[3]	Rail Placement[4]	Rail Bearers[2]	Property[5]					
Abe 76	O	A	G	T	U	JNR	14	10	b+M	N	Also see JNR
	u	u	B	T	A	JNR	u	0	D	-	
	u	u	B	T	A	JNR	u	7	D+W	-	
	S	P	G	U	A	JNR	u	3	M	-	
	O	A	G	T	A	JNR	u	6	W	N	
	O	A	G	T	A	JNR	u	6	W+D	N	
	O	A	G	T	A	JNR	u	18	W+D+U	N	
	O	A	G	T	A	JNR	u	12	T	-	
	S	P	G	U	A	JNR	u	8	M	N	
	S	P	G	U	A	JNR	u	12	M+W	N	
	S	P	G	U	A	JNR	u	12	M+W+D	N	
	S	P	G	U	A	JNR	u	15	M+W+D+U	N	
Arai 78	u	P	u	u	u	JNR	u	-3	t	-	
Ban 75	C	P	Cb	T	A	JNR	u	7	M	-	
	C	u	Cb	T	A	JNR	u	3-9	U	-	
Betzhold 78	S	A	B	T	A	SH	u	14 to 18	D	N	
Buchta 75	S	A	TG	u	u	DD	-	2 to 3	G	-	
	S	A	TG	u	u	DD	-	2	R	-	
Grunewald 78	S	A	G	U	A	DB	20	13	b	N	
	S	P	G	U	A	DB	7			N	
	O	A	G	T	A	DB	3.5			N	
	S	P	B	T	A	DB	1.5	1	M	N	
	S	A	L	U	A	DB	6.5			N	
	S	A	L	U	P	DB	5			N	
	S	A	L	T	P	DB	11.5			N	
	C	A	L	U	P	DB	-0.5			N	
	C	P	Cb	T	A	DB	-1.3	0.5	M	N	
	S	A	G	T	A	DB	12			N	
	S	A	G	T	A	DB	12.5			N	
	S	P	L	U	A	DB	2			N	
	S	A	G	U	P	DB	0.5			N	
	S	P	G	T	A	DB	1.5			N	
	S	A	L	U	A	DB	5			N	
	S	A	L	T	A	DB	3			N	
	S	A	L	U	P	DB	4			N	
	S	A	L	T	A	DB	9			N	
	S	P	B	T	A	DB	9	9	M	N	
	S	P	G	U	P	DB	2			N	
	S	P	G	U	A	DB	4.5			N	
Hanel 77	S	A	B	T	A	SH	17	7 to 17	D	N,V,gm	See Volberg 77

TABLE 4.1. *(Cont.)*

Reference	Structure						Noise Increase Over Track At-Grade (dBA)	Noise Reduction Due To Noise Control Means[6]		Data Type[7]	Notes
	Deck[1]	Ballast[2]	Support[3]	Rail Placement[4]	Rail Bearers[2]	Property[5]					
JNR	u	A	u	u	u	JNR	9-10			-	Also see Abe 76
(Shinkansen)	C	P	G	T	A	JNR	3-8			N	
	C	A	G	T	A	JNR	15-18			N	
	C	P	Cb	T	A	JNR	u	5 to 7	W	N	
	u	u	u	u	u	JNR	u	0 to 1	R	N	
	O	A	G	T	A	JNR	u	10 to 12	U	N,V	
	C	P	Cb	T	A	JNR	u	7	M+B+U	V	
Kirschner 65	C	A	B	T	A	u	u	5 to 18	D	-	Artificial excitation (by hammer)
Lindholm 72	O	A	G	T	A	SL	u	5	f or rt	N	
Manning 75	O	A	G	T	A	MBTA	u			N,V,gm	
Nimura 76	C	P	Cb	T	A	JNR	5	7	M	N,V	With barrier
Oleson 65	C	A	B	T	A	BART	u			N	
Ore D105/RP1	S	P	B	T	A	DB	0			N	
	S	A	G	U	A	DB	17			N	
	S	P	G	U	A	DB	6.5			N	
	S	P	G	U	A	DB	2.5			N	
	O	A	L	U	P	DB	4			N	
	S	A	G	U	A	NS	10			N	
	S	A	G	U	A	NS	8			N	
	O	A	L	U	P	NS	10			N	
	S	A	G	U	P	NS	3			N	
	O	A	G	U	P	CFF	11			N	
	C	P	G	U	A	CFF	-1			N	
	O	A	G	U	P	SNCF	16.5			N	
	C	P	G	U	A	SNCF	-3.5			N	
Ore D105/RP2	S	A	G	U	P	DBB	5-8	-1 to 1	e	N,V,gm	Locomotive coastby
Paolillo 78	O	A	G	T	A	NYCTA	u	3 to 5	f	-	
Sodo 74	C	P	Cb	T	A	JNR	u	5 to 8	M	-	
Satoh 72	u	u	G	T	u	JNR	u	5	rr	-	
SNCF 466	S	A	G	U	P	SNCF	8-10			N,V	
	C	A	G	T	A	SNCF	5-7			N,V	
SNCF 925	C	P	G	U	P	SNCF	-5 to -5.5			N	
	C	P	G	U	A	SNCF	-1			N	
	O	A	L	U	P	SNCF	10.5 to 11			N	
	C	P	Cb	T	A	SNCF	3 to 4			N	
	C	P	G	T	A	SNCF	1 to 2.5			N	
	C	D	Cb	T	A	SNCF	0.5 to 2.5				

TABLE 4.1. *(Cont.)*

Reference	Structure: Deck[1]	Ballast[2]	Support[3]	Rail Placement[4]	Rail Bearers[2]	Property[5]	Noise Increase Over Track At-Grade (dBA)	Noise Reduction (dBA) Due To Noise Control Means[6]		Data Type[7]	Notes
Saurenman 79	C	P	G	T	A	SEPTA	u	0.5 to 1.5	G	N	Welded rail
	C	P	G	T	A	SEPTA	u	-1 to -2	G+t	N	Welded rail
	C	P	G	T	A	SEPTA	u	-1 to =2	G	N	Jointed rail
	C	P	G	T	A	SEPTA	u	0 to 1	R	N	Both types of rail
	C	P	G	T	A	SEPTA	u	-.5 to 1.5	dw	N	Both types of rail
Stüber 65	S	A	G	U	A	DBB	17	12.5	b	N,V	Locomotive coastby at 60 km/h
Swanson 66	C	A	Cb	T	A	BART	u	-2 to -6	f	N,V	Various fasteners
	C	A	Cb	T	A	BART	u	2 to 4	W	N,V	
vanOs 65	C	A	Cb	u	u	RM	12-15			N	
	C	A	Cb	u	u	NS	10-12			N,V	
	C	A	Cb	u	u	NS	u	2 to 4	f	N,V	
Venema 74	O	A	G	T	A	CTA	u			V	
Towers 79	C	A	Cb	T	A	PATCO	u			V	
Volberg 77	S	A	B	T	A	SH	16	7 to 17	D	N,V	See Hanel 77
Wilson 66	C	A	Cb	T	A	BART	16	-3 to -5	f	N,V	See Swanson 66
						BART	u	11	W	N,V	

LEGEND

(1) O Open tie deck
- C Concrete slab
- S Steel plate

(2) P Present
- A Absent
- u Unspecified

(3) G Solid Web Steel Girder
- B Steel Box-Beam
- Cb Concrete Beam or Box
- L Lattice Girder or Truss
- TG Track at Grade

(4) T Track on Top
- U Track in trough
- u Unspecified

(5) JNR Japanese National Railroad
- SH S-Bahn, Hamburg
- DD D-Bahn, Dusseldorf
- DBB German State Railway
- SL Storstockholms Lokaltrafik
- BART Bay Area Rapid Transit
- NS Netherlands Railways
- CFF Swiss Railways
- SNCF French National Railways
- NYCTA New York City Transit Authority
- SEPTA Southeastern Pennsylvania Transportation Authority
- RM Rotterdam Metro
- CTA Chicago Transit Authority
- PATCO Port Authority Trans. Co. (NJ)
- MBTA Massachusetts Bay Trans. Authority (Boston)

(6) b Ballast
- M Ballast Mat
- W Barrier (wall) side
- D Damping – Main Support Structur
- U Underside Barrier
- T Total Enclosure
- t Wheel Truing
- G Rail Grinding
- R Resilient Wheel
- f Resilient Fasteners
- e Elastic (Resilient) Tie
- rr Resilient Rail
- dw Ring-Damped Wheels
- rt Resilient Support Under Ties

(7) N Noise Spectra
- V Vibration Spectra
- \- No Spectra
- gm Geometry and Materials

Because of the dearth of fully documented data relevant to rapid transit structures, the Japanese data for a particular structure that appeared to be similar to one in common use in U.S. transit systems were reviewed carefully and supplemented by information obtained by correspondence. Although the data collection here still is inadequate for full analytical model validation, it does permit the conclusion that directly generated wheel-rail interaction noise predominates over noise radiated from the structure. (See Appendix A.)

4.2 Field Measurements

Two investigations, taking advantage of particular measurement opportunities, were carried out in order to provide additional data of potential utility for analytical model validation or for evaluation of the effectivenesses of some noise reduction approaches. Measurements made in Atlanta, on structures of the newly operational MARTA system, served to investigate the noise reductions due to barriers and due to damping added to steel box beams, as well as providing data on the impedance of rail and on ground reflection effects. Measurements on a structure of the New York City Transit Authority served to determine the noise reductions achieved from an installation of resilient fasteners and to clarify the relative noise contributions made by the structure and by wheel-rail interaction.

The MARTA investigation, which is described in Appendix B, deals with a ballastless composite structure consisting of a concrete deck atop a steel trough-beam. Comparison measurements of wayside noise and structure vibrations were carried out on two spans that were essentially identical, except that a damping treatment had been installed in the trough-beam of one. These structures had a noise barrier installed on only one side, thus making it possible also to evaluate the effect of the barrier.

It was found* that this barrier produced wayside noise reductions of about 9 dBA and that the damping was responsible for noise reductions of 1 to 2 dBA, although it produced greater reduction of the vibrations of the steel trough-beam walls. It appears that for this structure directly radiated wheel-rail noise generally predominates over that radiated from the structure.

The study carried out in New York pertains to a typical NYCTA elevated structure, which has wood ties supported directly on steel plate girders. This study, which is described in Appendix C, involved measurement of noise and vibration made before and after conventional steel plate rail fasteners were replaced by resilient fasteners. It was concluded that this fastener replacement resulted in a noise reduction of 3 to 4 dBA for train speeds below 25 mph and in lesser reductions at higher speeds. This lesser reduction may be attributed to the greater noise contributions made by the propulsion system at these speeds - with propulsion system noise, of course, not being affected by rail fastener changes. In view of a recent analytical model study [Remington 80], it appears

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*The values reported here pertain to measurements made at rail height, at 25 ft from the centerline of the structure, and thus probably are relevant for community noise. Somewhat different values may be observed under the structure or at street level near it. At such locations, where the observer is exposed more directly to radiation from the structure and less directly to radiation from the wheels and rails, the barrier may be expected to produce less, and damping may be expected to produce more noise reduction than indicated by the aforementioned values.

that the primary noise reduction effect of the resilient fasteners is due to the damping they provide for the rail; their vibration isolation effectiveness is relatively small, because their stiffness is greater than the local stiffness of the ties that support them.

It is instructive to compare the noise levels measured at MARTA and at NYCTA at locations at rail height, 25 ft from the track centerline, where the noise may be expected to be largely due to the rail. The noise levels at NYCTA were found to exceed comparable levels at MARTA by about 18 dB. Most of this difference (roughly 15 dB) may be attributed to differences in the rail vibration levels resulting primarily from wheel roughness differences; the remaining difference is likely to be due to the use of relatively smooth welded rail at MARTA, versus the comparatively rough jointed rail present at NYCTA.

APPENDIX A
ANALYSIS OF JNR YAMASHINAGAWA BRIDGE DATA

The Yamashinagawa Bridge is of an open tie deck configuration employing solid-web steel longitudinal beams, and thus is similar to the type of structure that is responsible for the greatest noise impact in U.S. rapid transit systems [Towers 80]. Data pertaining to this bridge appear in the Japanese National Railways report entitled "Shinkansen Noise (II)."

Supplementary information* indicates that the aforementioned bridge is made up of two spans of different lengths consisting of different girders, with the following dimensions:

Span	30 m (98.4 ft.)	35 m (114.8 ft.)
Girder upper flange	48 x 5.7 cm (18.9 x 2.24 in.)	53 x 6 cm (20.9 x 2.36 in.)
Girder lower flange	48 x 12 cm (18.9 x 04.7 in.)	52 x 5 cm (20.5 x 1.97 in.)
Girder Web	190 x 1.2 cm (74.8 x 0.47 in.)	210 x 1.4 cm (82.7 x 0.55 in.)

It is clear that this structure is considerably more substantial than typical NYCTA elevated structures, for example, which have spans of about 15m (50 ft).

The train speed to which the published data pertain is 100 km/h. For this speed, the contribution made by aerodynamic noise is found not to be significant [King 77], and the noise due to auxiliaries may be expected to be less than that produced by wheel-rail interaction.

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*Obtained with the assistance of Dr. Yasuo Tokita of the Kobayasi Institute of Physical Research, Tokyo (Personal correspondence, 15 October 1979).

It was reported that the addition of non-absorptive noise barrier sidewalls and of shields on the underside of the structure, just below the top flanges of the girders, resulted in a 5 dB reduction in the noise observed directly underneath the structure. In view of the fact that these barriers and shields did not obstruct the noise radiated from the girders, this result implies that wheel-rail noise here predominates over noise radiated from the structure.

An additional noise reduction of about 3 dB was reported as the result of damping of the girders. The Shinkansen noise report indicates that there were some gaps in the bottom shields, which may have limited the noise reductions that were achieved. The report also shows that the sidewalls and shields vibrated considerably, and thus may have been responsible for some noise radiation. When an absorptive layer was added between the tracks, the barrier walls were covered with absorptive material, and an isolated bottom shield was added that completely enclosed the girders, an additional 20 dB of noise reduction was realized.

APPENDIX B

MEASUREMENTS ON STRUCTURES OF THE METROPOLITAN ATLANTA RAPID TRANSIT AUTHORITY (MARTA)

Sites and Structures

Noise and vibration measurements were carried out on 21 and 22 April 1979 at two locations along MARTA's east-west line that parallels DeKalb Avenue:

1. Station 77, near the Bradley Street intersection, and
2. Station 100, near the Spruce Street intersection.

Both of these locations are between the King Memorial and the Moreland Avenue stations.

At both test sites, the elevated structure consists of an approximately 30 ft wide concrete slab deck (varying in thickness from 1 ft. at the center to 8 in. at the edges), supported on a steel box beam that is 4 ft high and 7 ft wide. The sides of this box beam are 3/16 in. thick, and its bottom is 3/4 in. thick.

The north edge of the concrete slab is provided with a 5 ft high non-absorptive acoustical barrier. The south edge, which faces a railroad switching yard, has no such barrier, only a hand rail. The gap between the barrier and the sidewall of a car is about 2 ft. Figures B.1 and B.2 show the elevated structure as seen from the barrier and nonbarrier sides.

The rail used on this structure weighs 115 pounds per yard and is continuously welded. It is fastened directly to the concrete deck by means of resilient rail fasteners of the Hixson type (with a nominal static stiffness of 100,000 lb/in.), spaced 30 in. apart. At the first measurement site, the box-beam had been provided with damping. At the second site, the box-beam was not damped.

Transducer Locations and Instrumentation

Figure B.3 is a sketch of the cross-section of the structure and indicates the locations of the accelerometers and microphones that were used. All of these were located in a plane situated at about one fourth of the (approximately 70 ft long) span distance from a vertical support.

The instrumentation arrangement that was used is shown in Figure B.4. Different accelerometers with suitable preamplifiers and power supplies were used at different locations, in order to accommodate the different expected vibration levels. Additional (Ithaco Type 453) preamplifiers with rms meters and high-pass filters were used in each channel; the filters were set at 10 Hz for all measurements. A switch box permitted the operator to display the signal from one channel at a time on an oscilloscope, for monitoring purposes.

Test Train and Runs

A two-car test train was driven past the measurement sites in both directions at speeds between 20 and 60 mph, as measured by on-board speedometers. The wheels were inspected before the tests to insure that they were in good condition. However, the rail vibration data show that the wheels on the lead truck had flats that caused 5 dB higher rail vibration levels than the other three trucks.

Speed-Variation of Maximum Noise Levels

For all sound signals from each test run, strip charts were prepared showing the time variation of the A-weighted noise level. The maximum noise levels were read from these charts and plotted as a function of speed. All test trains ran on the westbound track. The resulting graphs for the test site near Spruce Street are shown in Figs. B.5 to B.10. The straight lines fitted "by eye" to these data points were found to represent all of the observed data within 1 or 2 dB; these lines correspond to noise level variations at between 26 and 29 times the logarithm of the speed (except for position 13, where the factor is only 21).

Effects of Barrier and of Box-Beam Damping on Maximum Noise Levels

Figure B.11 summarizes the speed-variations of the maximum noise levels observed at rail height, at 25 ft from the center-line of the two tracks (one with and one without a barrier) at the two test sites (one with and one without damping added to the box beam). This particular observation position was chosen for analysis, because it may be expected to be representative of the noise radiated to locations at distances from the structure that are relevant for environmental impact on the community*.

One may observe that the barrier by itself (in absence of damping) produced a reduction of about 9 dBA at all speeds, and that the barrier and damping together resulted in a noise

*Somewhat different results than those indicated in Fig. B.11 may be expected for other locations, e.g., those nearby and under the structure. However, the data for these locations were not closely analyzed, because of their limited interest for the present community noise impact study.

reduction of approximately 10 dBA at all speeds. On the other hand, it may be noted that damping by itself (in absence of a barrier) reduced the peak noise level by 1.5 dBA at 20 mph and essentially not at all at high speeds (45 to 60 mph).

Spectra; Effects of Box-Beam Damping

One-third octave band spectra of the tape-recorded data were obtained by use of a General Radio Model 1921 Real Time Analyzer. The averaging times used for these frequency analyses were chosen to be somewhat greater than the durations within which the overall A-weighted noise levels at microphone position 12 were within 10 dBA of their greatest values. For the 20 mph runs, the averaging time used was 16 sec, for 30 and 45 mph runs it was 8 sec, and for 60 mph runs, 4 sec. However, to simplify comparison, all spectra reported here have been normalized to an averaging time of 8 seconds (by shifting the spectra obtained for 4 second averaging times downward by 3 dB and shifting those obtained for averaging times of 16 seconds upward by 3 dB).

The data reduction approach using these extended averaging times was employed because the irregular time-variations of the overall signals did not permit one to select an analysis interval during which the signals were at a relatively steady plateau level. Furthermore, because time-averaging of a signal observed at a single point in essence averages the contributions of noise sources that move with the train, the extended averaging used here corresponds in a sense to integrating the contributions that are made by source locations along the track to the noise observed at a distance.

Figures B.12 through B.24 present the acceleration and sound pressure spectra obtained with the various transducers at the two sites for 45 mph train passages. The spectra are paired so as to enable one to judge the effect of the damping. One may observe that the damping applied to the box beam reduced the vibrations of the box beam by about 15 dB in the mid-frequency range, with somewhat lesser reductions at the high frequencies and only small reductions at low frequencies. On the other hand, this damping may be seen to have had only minor effects on the vibrations of the rail and deck, producing typically 3 dB reductions in the mid-frequency vibrations of the deck. One may also observe that at essentially all microphone positions the noise produced by the structure with the damped box-beam is between 2 and 5 dB less in the mid-frequency range than is the noise from the structure with the undamped box-beam. As evident from Figs. B.19 and B.22, which include A-weighted spectra for the sake of comparison, the mid-frequency (400 to 1000 Hz) components typically predominate in the overall A-weighted levels.

Figure B.25 indicates how the noise spectra at one observation location change with train speed. One notes that the most significant changes occur in the 400 to 1000 Hz range (in which the signals in essence control the overall A-weighted level), and also at frequencies below about 80 Hz.

Noise Increase Due To Gap In Barrier

In order to investigate how much the observed noise may increase due to the 2 to 3 inch gaps that exist in the barriers where adjacent spans come together (Fig. B.26), these gaps were covered with leaded vinyl for several 45 mph runs on the westbound track (the track nearer the barrier). Noise variations that occur from train passage to train passage, independently of what is done to the barrier, were taken into account by scaling the noise levels measured on the barrier-side according to levels observed with microphone no. 3, on the barrier-less side of the structure.

The noise level changes obtained in this manner were found not to exceed the experimental error, leading to the conclusion that the gaps in the barriers have no significant effect on the noise.

Effect Of Ground Reflection

At site 2, microphone no. 11 was placed at 50 ft from the structure, at about 1.5 in. (the radius of the microphone's windscreen) above a concrete sidewalk. This microphone thus was located in the pressure-doubling region for almost the entire frequency range; at a comparable free-field location, a measure of 6 dB levels lower than those obtained at microphone no. 11 may be expected.

Nevertheless, the levels obtained at microphone no. 10 which was located at 5 ft above the ground, at the same distance from the structure as microphone no. 11, typically were only 3 dB lower than those measured by microphone 11. This difference indicates that microphone no. 10 did not measure the free-field levels, but rather recorded the combined effect of the free-field and an incoherent image source of essentially the same strength as the actual source.

At site 1, microphone no. 11 was atop soft ground, with uncertain acoustical reflection characteristics. Therefore, no similarly conclusive comparison could be made for this site.

Rail Impedance

Direct measurements of vertical rail impedance were carried out at site 2, for the purpose of providing data for the eventual inclusion in an analytical model of elevated structure noise. The rail was driven via a Wilcoxen Type Z602 impedence head by means of a Goodmans Type V-50 electrodynamic shaker; the resulting accelerations were measured by means of BBN model 507 accelerometers mounted immediately adjacent to the impedance head and at 5 and 10 ft from it along the top of the rail. The signal input to the shaker consisted of broadband noise filtered in one-third octave bands; force and acceleration measurements were made in the same bands.

Figure B.27 presents the measured driving-point impedance values, in terms of their magnitude and phase. Figure B.28 compares the magnitudes of the vibrations measured at two distances from the driving point to those measured directly at the driving point.

FIG. B.1. MARTA STRUCTURE NEAR SPRUCE STREET, AS SEEN FROM NORTH SIDE. NOTE NOISE BARRIER.

FIG. B.2. MARTA STRUCTURE NEAR SPRUCE STREET, AS SEEN FROM SOUTH SIDE. NOTE HANDRAIL, BUT NO NOISE BARRIER.

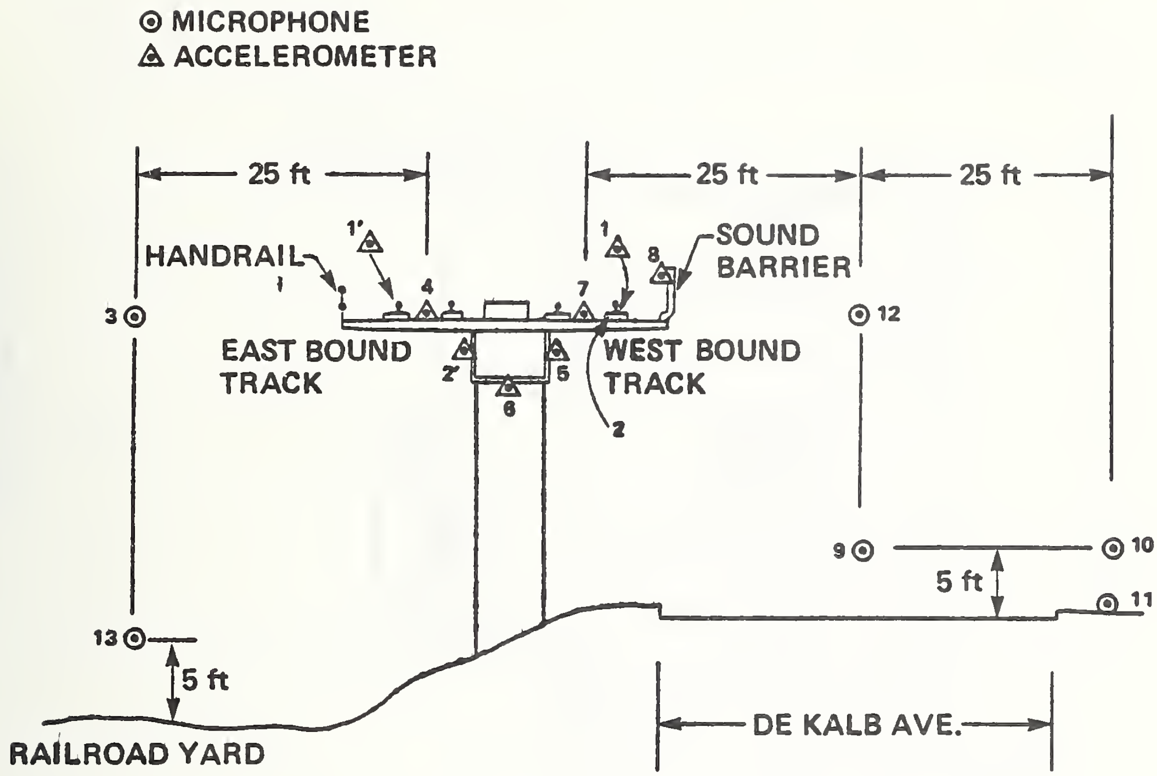

FIG. B.3. SKETCH OF MARTA CROSS-SECTION STRUCTURE, LOOKING WEST, SHOWING TRANSDUCER LOCATIONS.

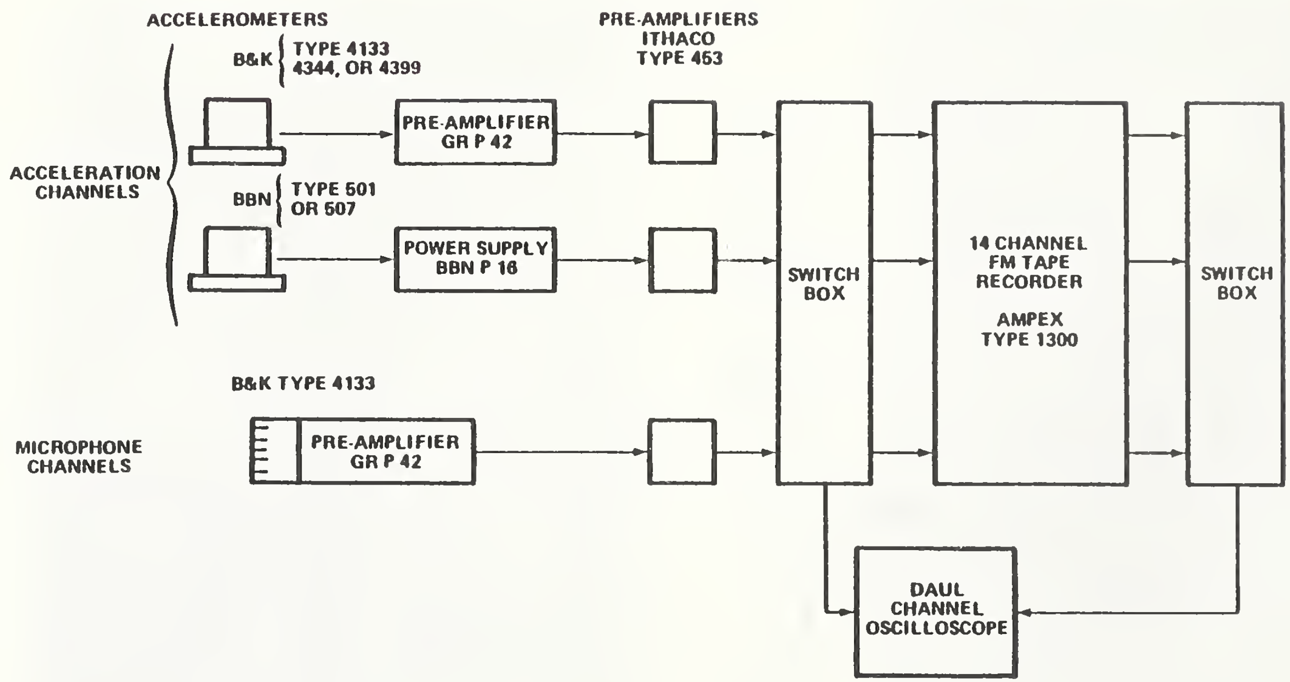

FIG. B.4. INSTRUMENTATION.

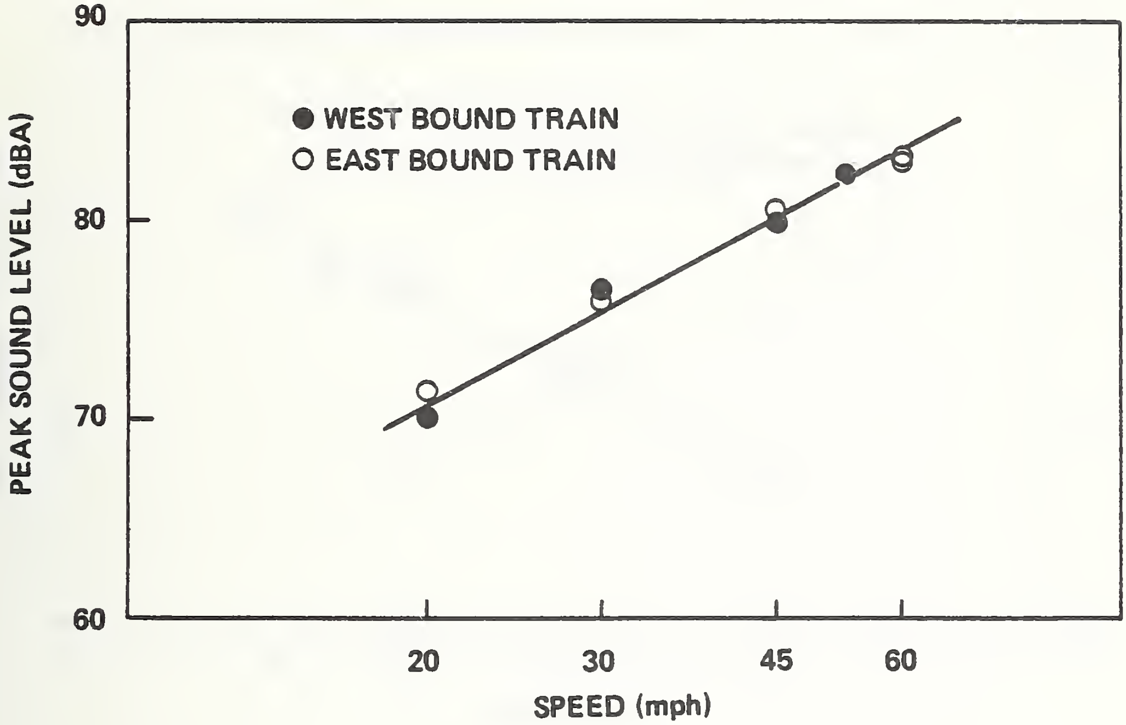

FIG. B.5. PEAK A-WEIGHTED SOUND PRESSURE LEVEL vs SPEED, AT MICROPHONE LOCATION NO. 3 (RAIL HEIGHT, 25 ft SOUTH OF THE CENTERLINE OF THE EASTBOUND TRACK).

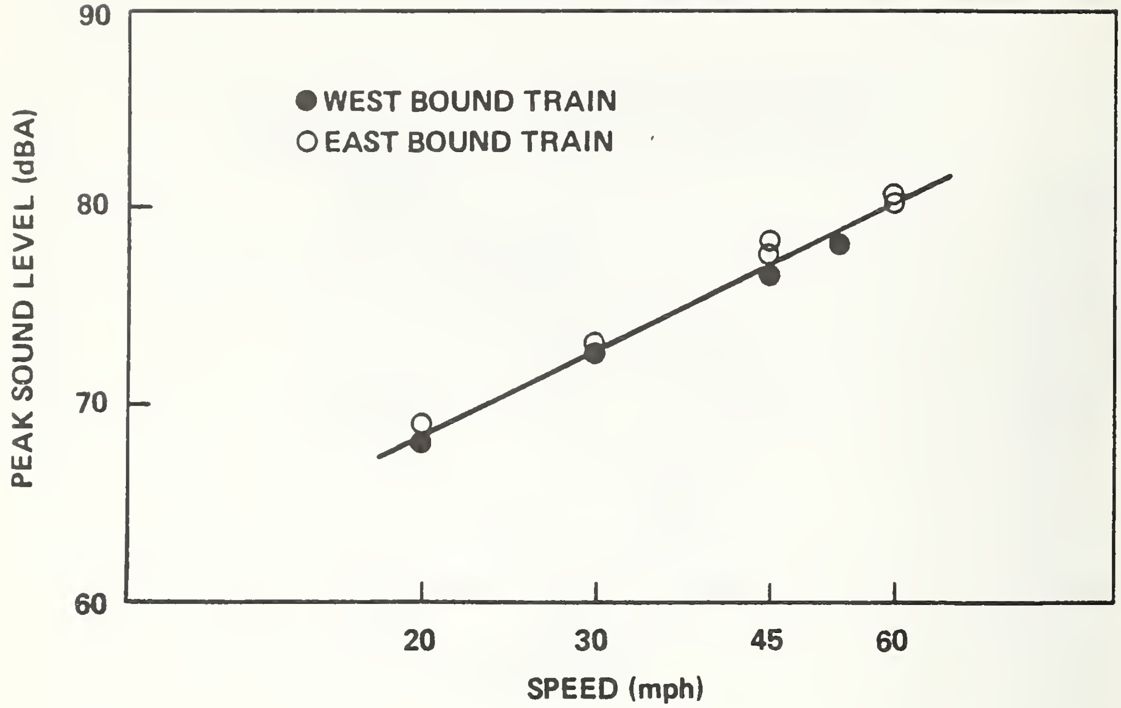

FIG. B.6. PEAK A-WEIGHTED SOUND PRESSURE LEVEL vs SPEED AT MICROPHONE LOCATION NO. 9 (5 ft ABOVE GROUND, 25 ft NORTH OF THE CENTERLINE OF THE WESTBOUND TRACK).

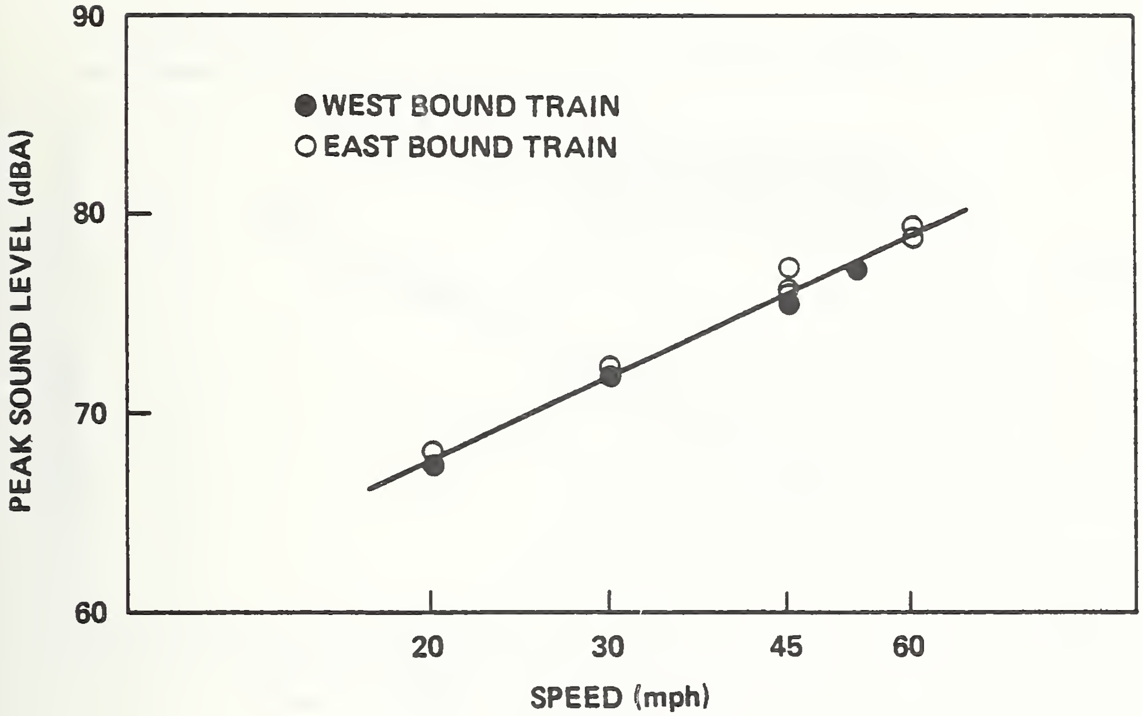

FIG. B.7. PEAK A-WEIGHTED SOUND PRESSURE LEVEL vs SPEED AT MICROPHONE LOCATION NO. 10 (5 ft ABOVE GROUND, 50 ft NORTH OF THE CENTERLINE OF THE WESTBOUND TRACK).

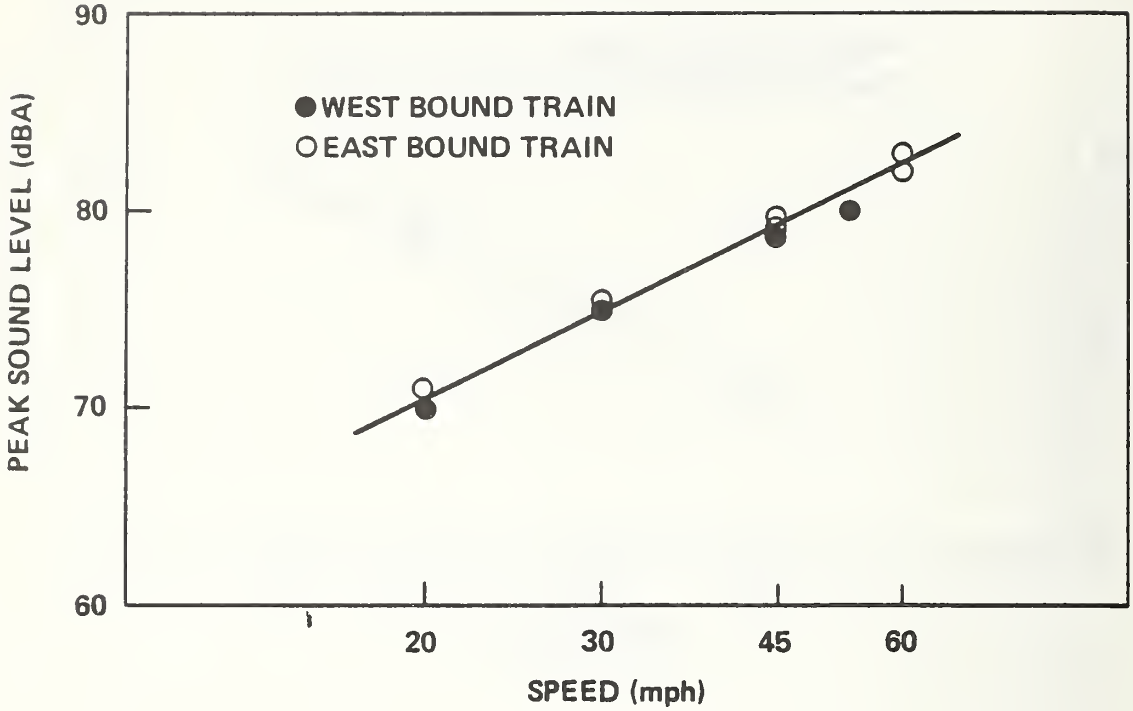

FIG. B.8. PEAK A-WEIGHTED SOUND PRESSURE LEVEL vs SPEED AT MICROPHONE LOCATION NO. 11 (1-1/2 in. ABOVE GROUND, 50 ft NORTH OF THE CENTERLINE OF THE WESTBOUND TRACK).

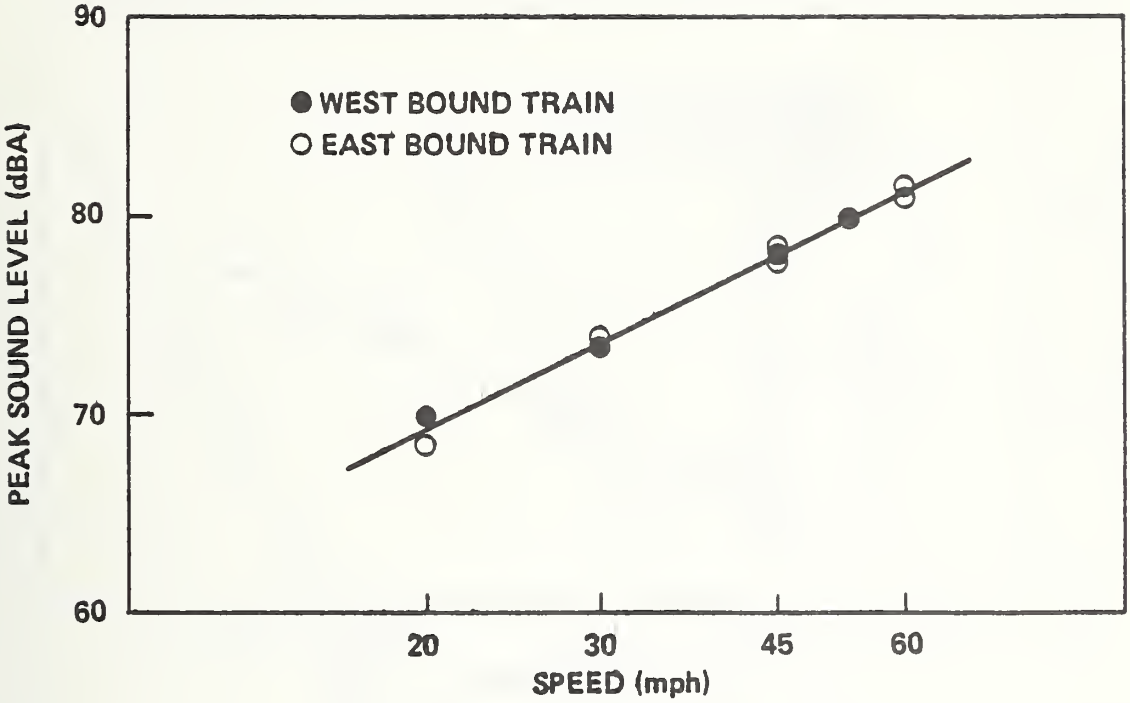

FIG. B.9. PEAK A-WEIGHTED SOUND PRESSURE LEVEL vs SPEED AT MICROPHONE LOCATION NO. 12 (RAIL HEIGHT, 25 ft NORTH OF THE CENTERLINE OF THE WESTBOUND TRACK).

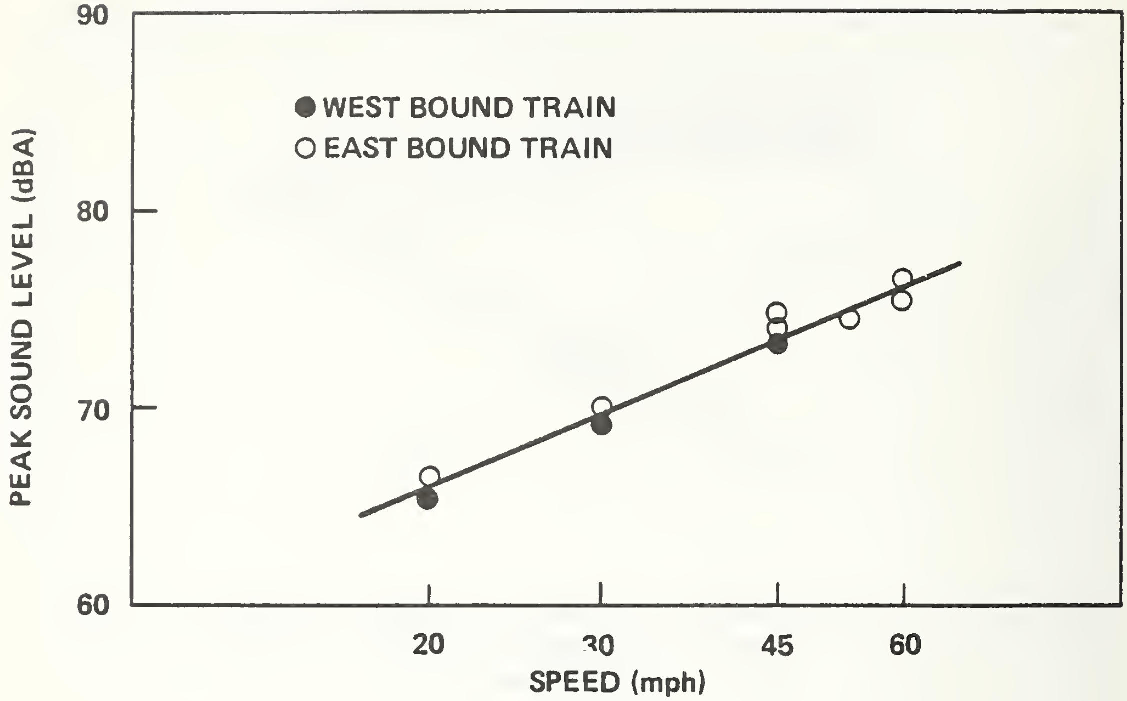

FIG. B.10. PEAK A-WEIGHTED SOUND PRESSURE LEVEL vs SPEED AT MICROPHONE LOCATION NO. 13 (5 ft ABOVE GROUND, 25 ft SOUTH OF THE CENTERLINE OF THE EASTBOUND TRACK).

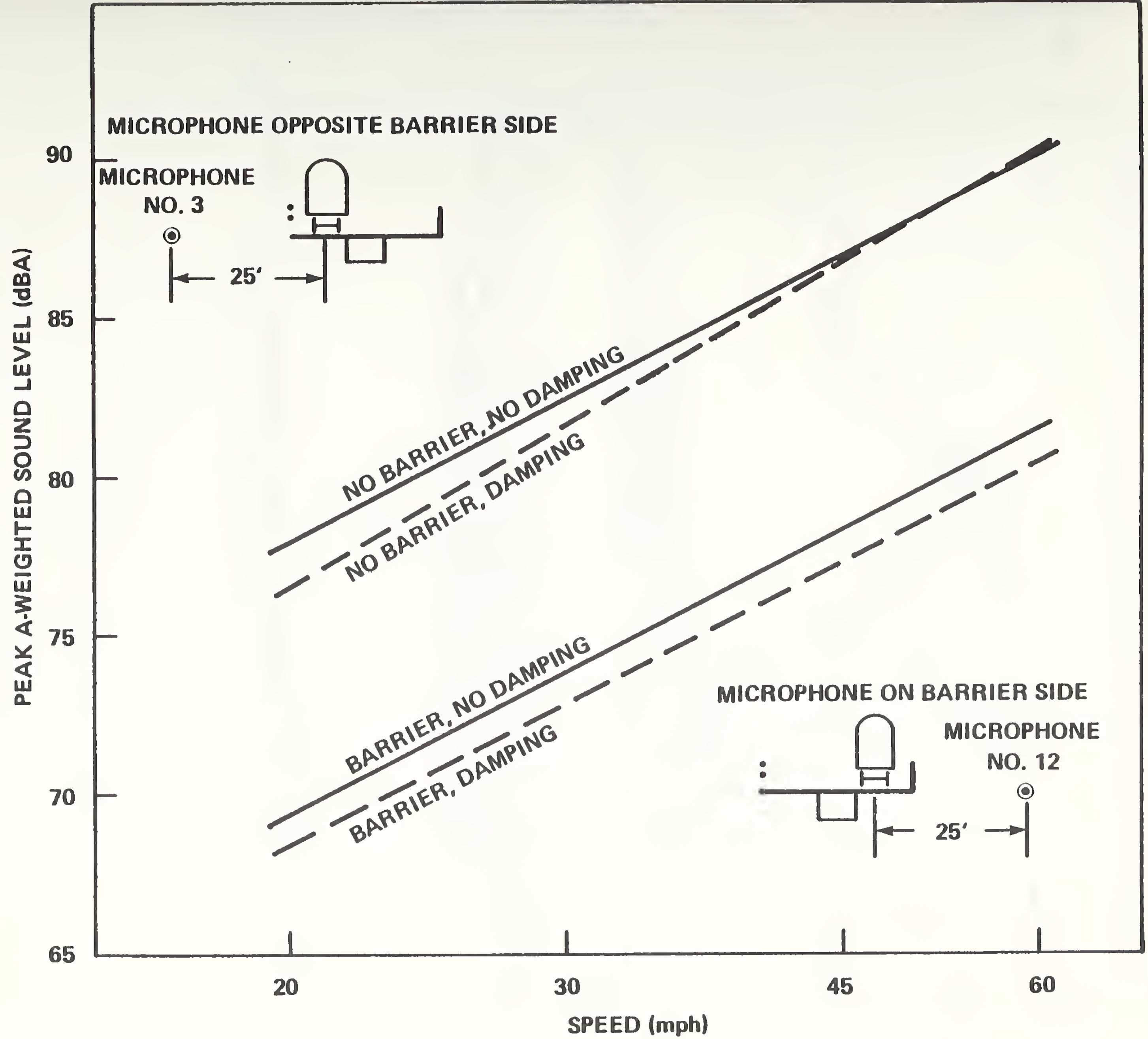

FIG. B.11. COMPARISONS OF PEAK A-WEIGHTED NOISE LEVELS OBSERVED WITH AND WITHOUT BARRIERS AND BOX-BEAM DAMPING.

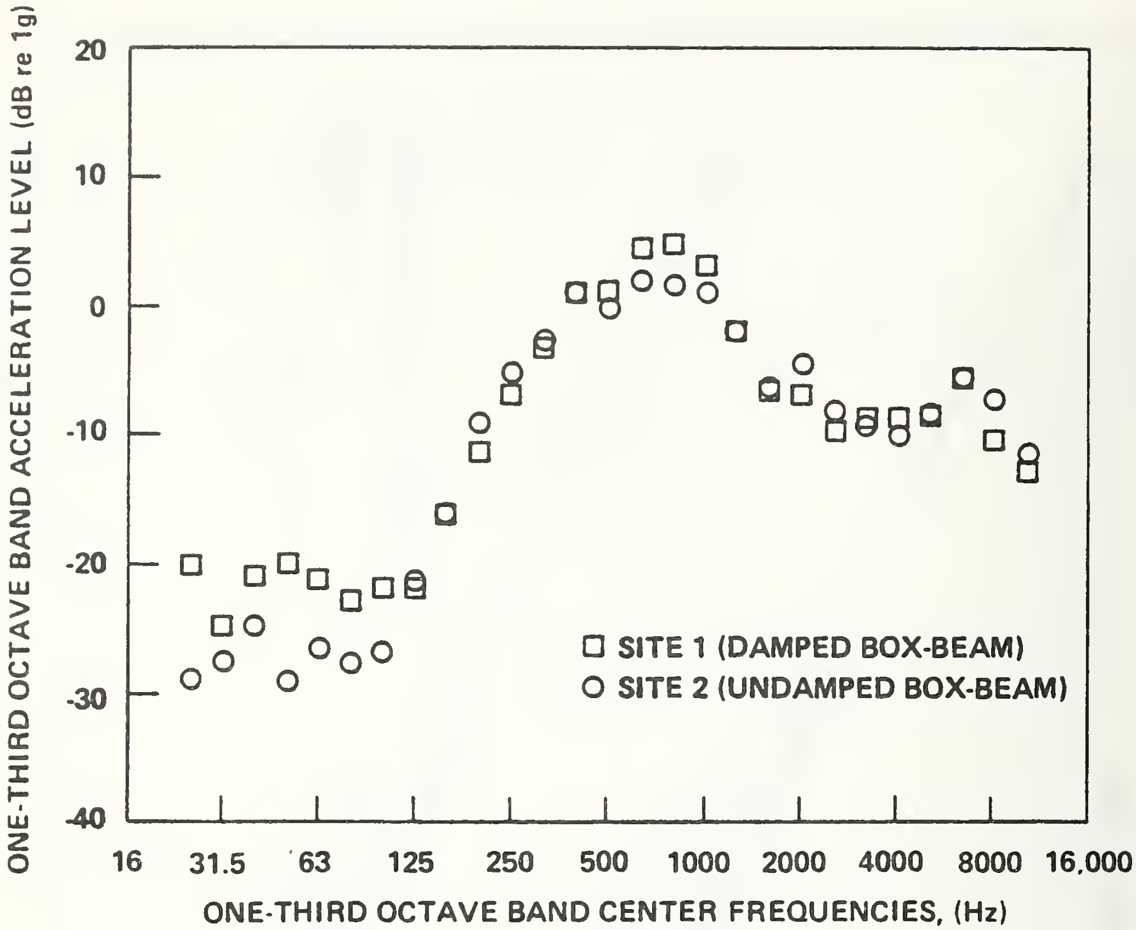

FIG. B.12. RAIL ACCELERATION SPECTRA (TRANSDUCER LOCATION NO. 1).

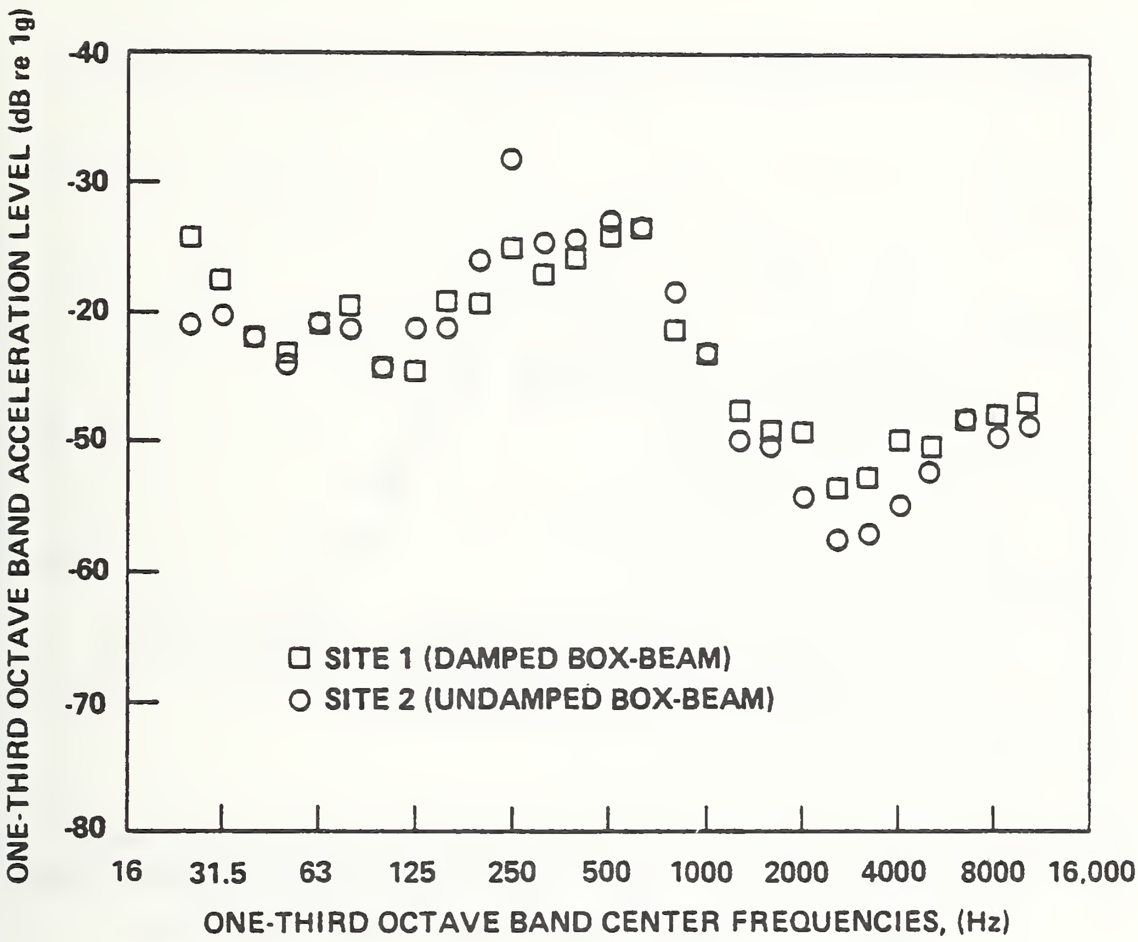

FIG. B.13. SPECTRA OF DECK ACCELERATION IMMEDIATELY BELOW RAIL (TRANSDUCER LOCATION NO. 2).

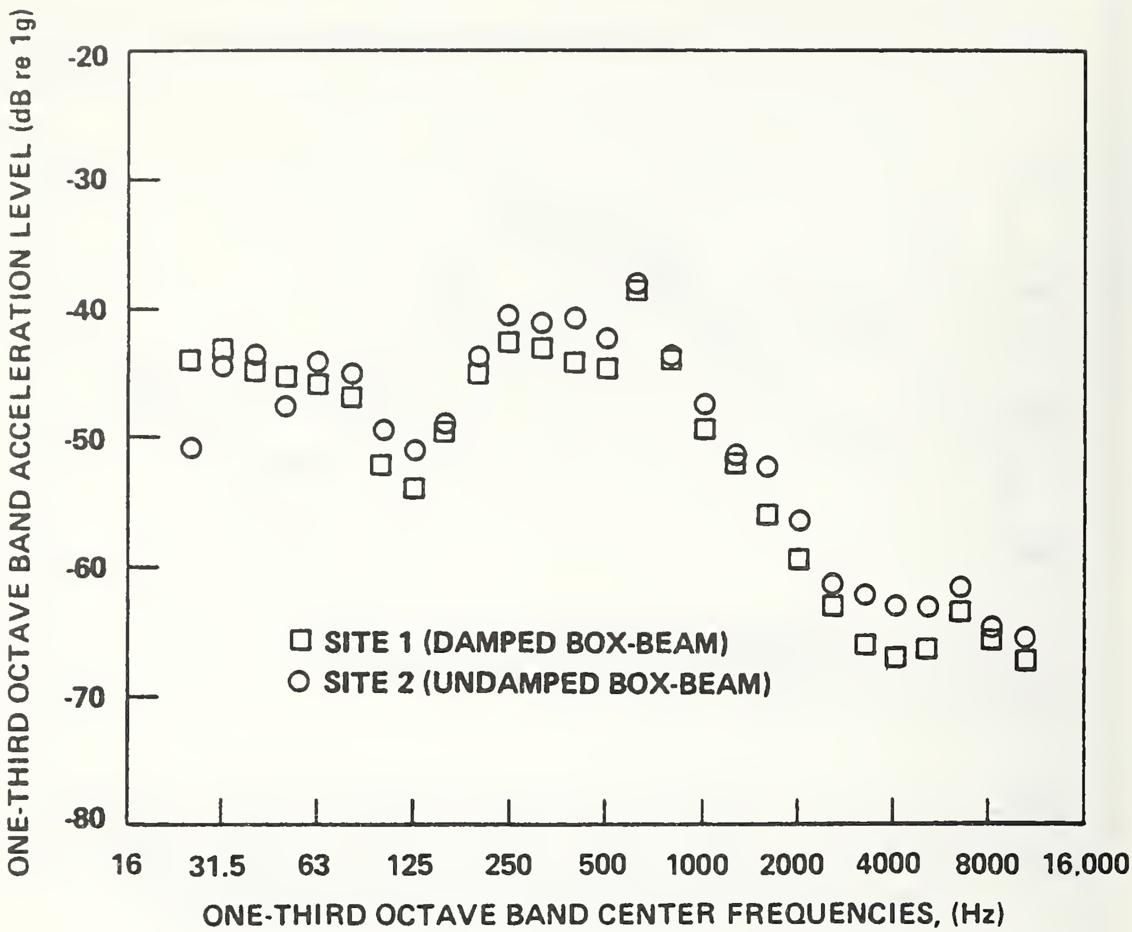

FIG. B.14. SPECTRA OF DECK ACCELERATION AT CENTERLINE OF EAST-BOUND TRACK (TRANSDUCER LOCATION NO. 4).

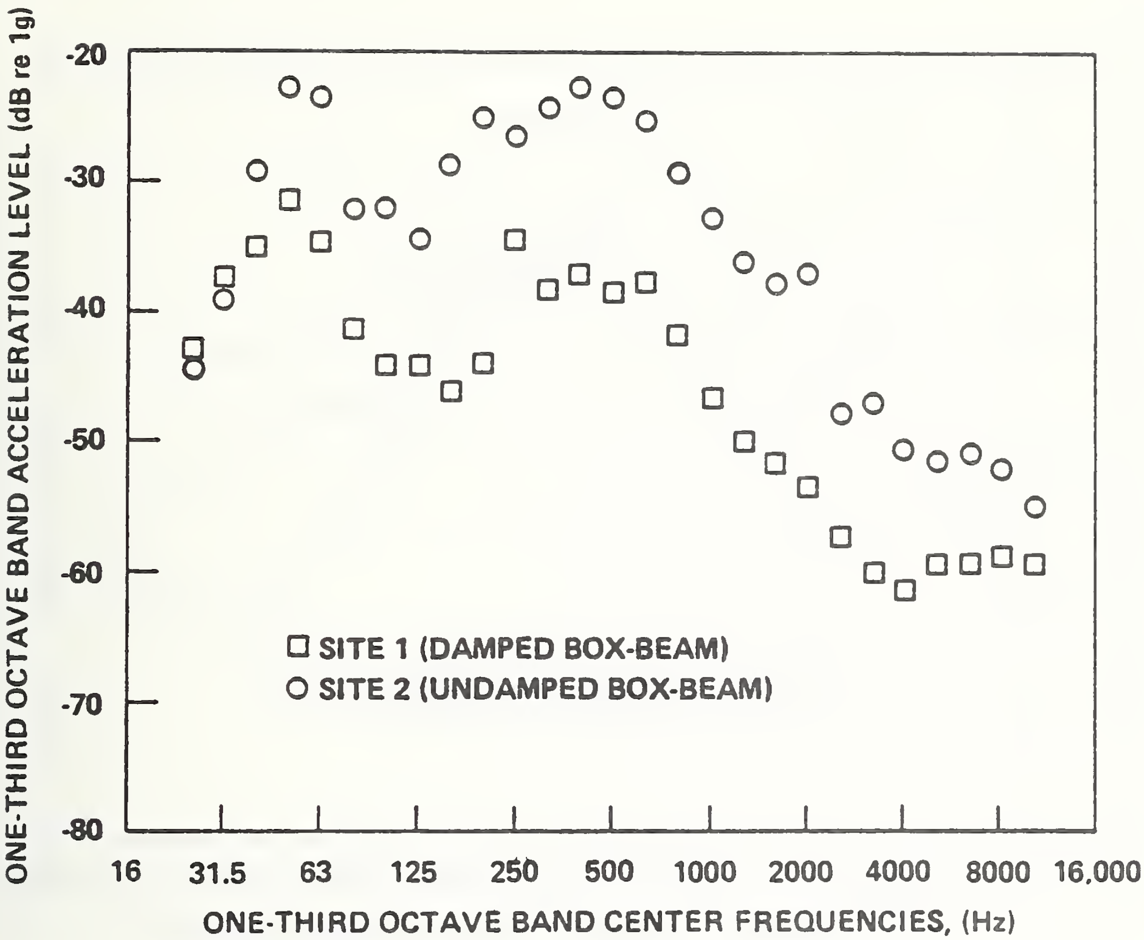

FIG. B.15. SPECTRA OF ACCELERATION OF SIDE OF BOX-BEAM (TRANSDUCER LOCATION NO. 5).

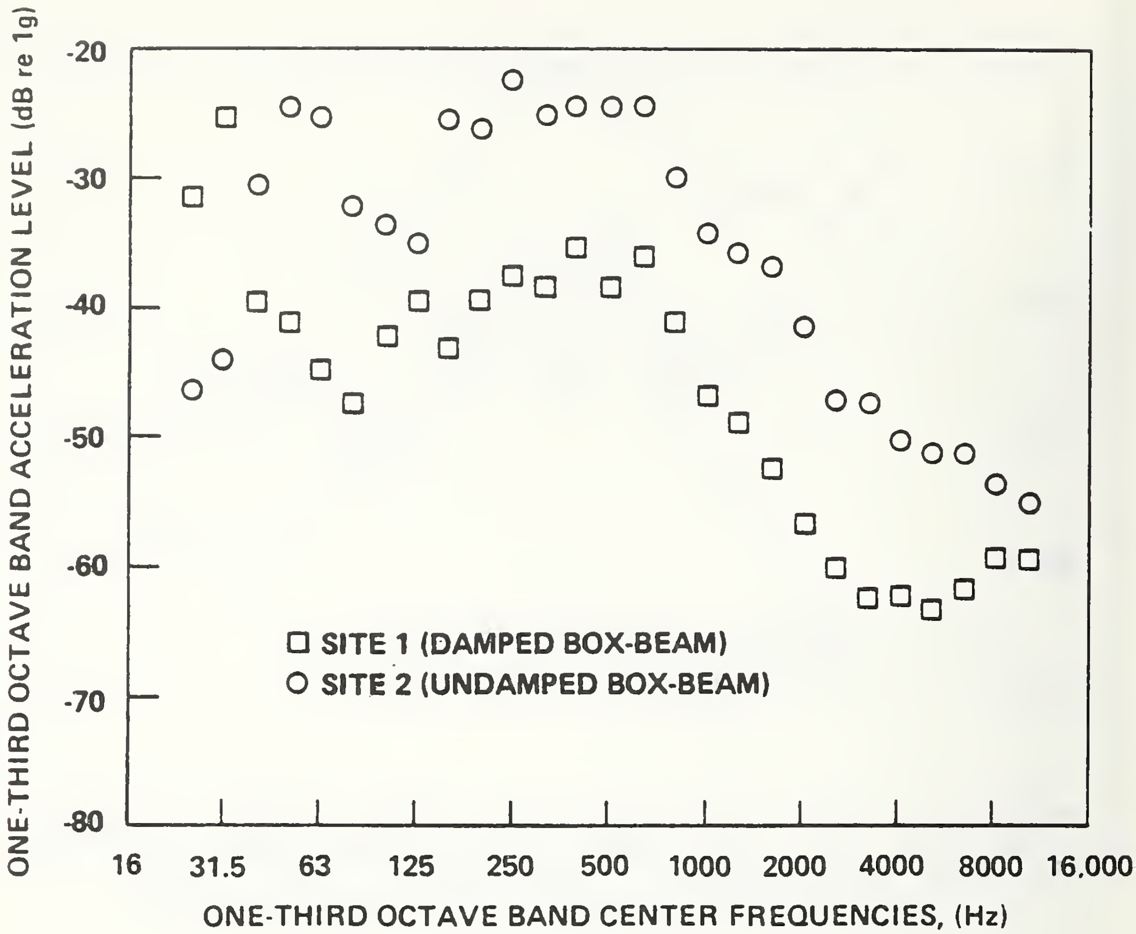

FIG. B.16. SPECTRA OF ACCELERATIONS OF SIDE OF STEEL BOX-BEAM (LOCATION NO. 2) AT SITE II, AND OF BOTTOM OF STEEL BOX BEAM (LOCATION NO. 6) AT SITE I.

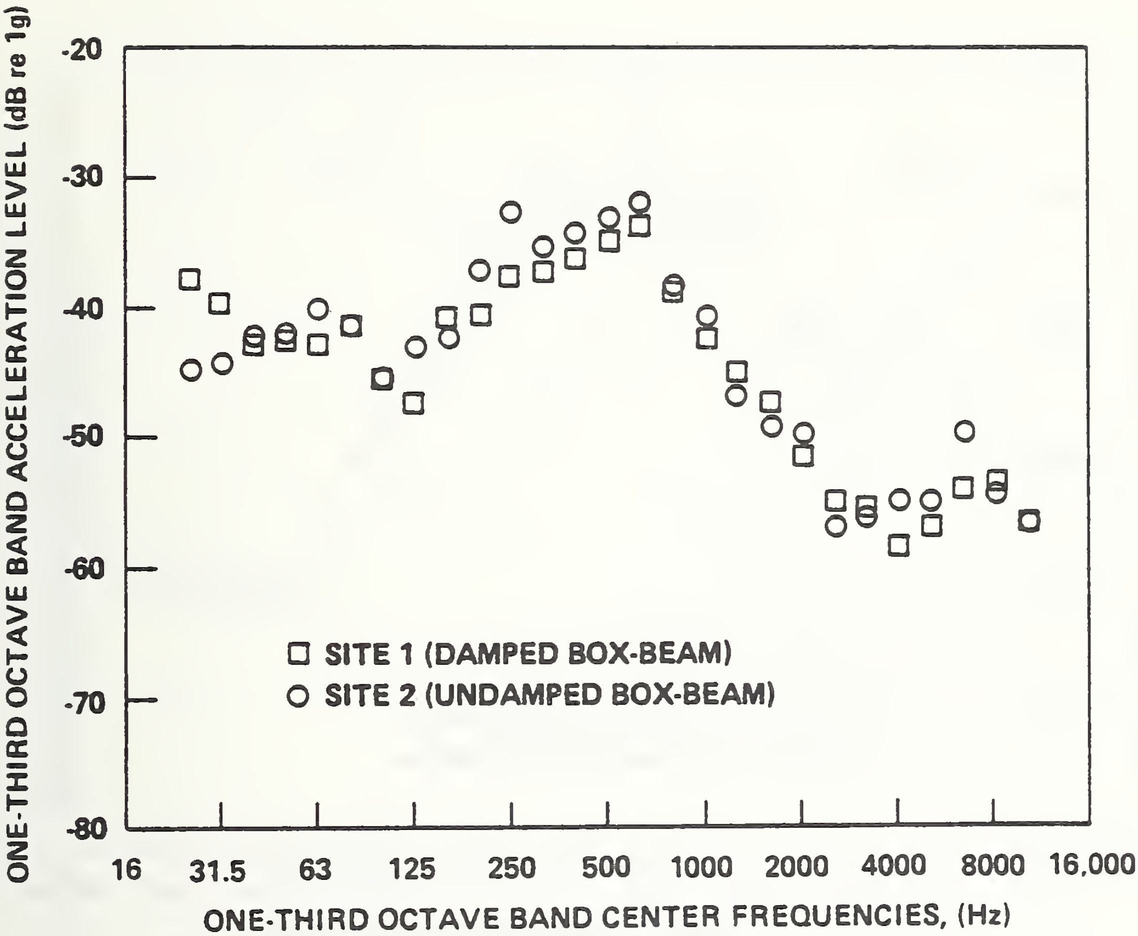

FIG. B.17. SPECTRA OF DECK ACCELERATION AT CENTERLINE OF WESTBOUND TRACK (TRANSDUCER LOCATION NO. 7).

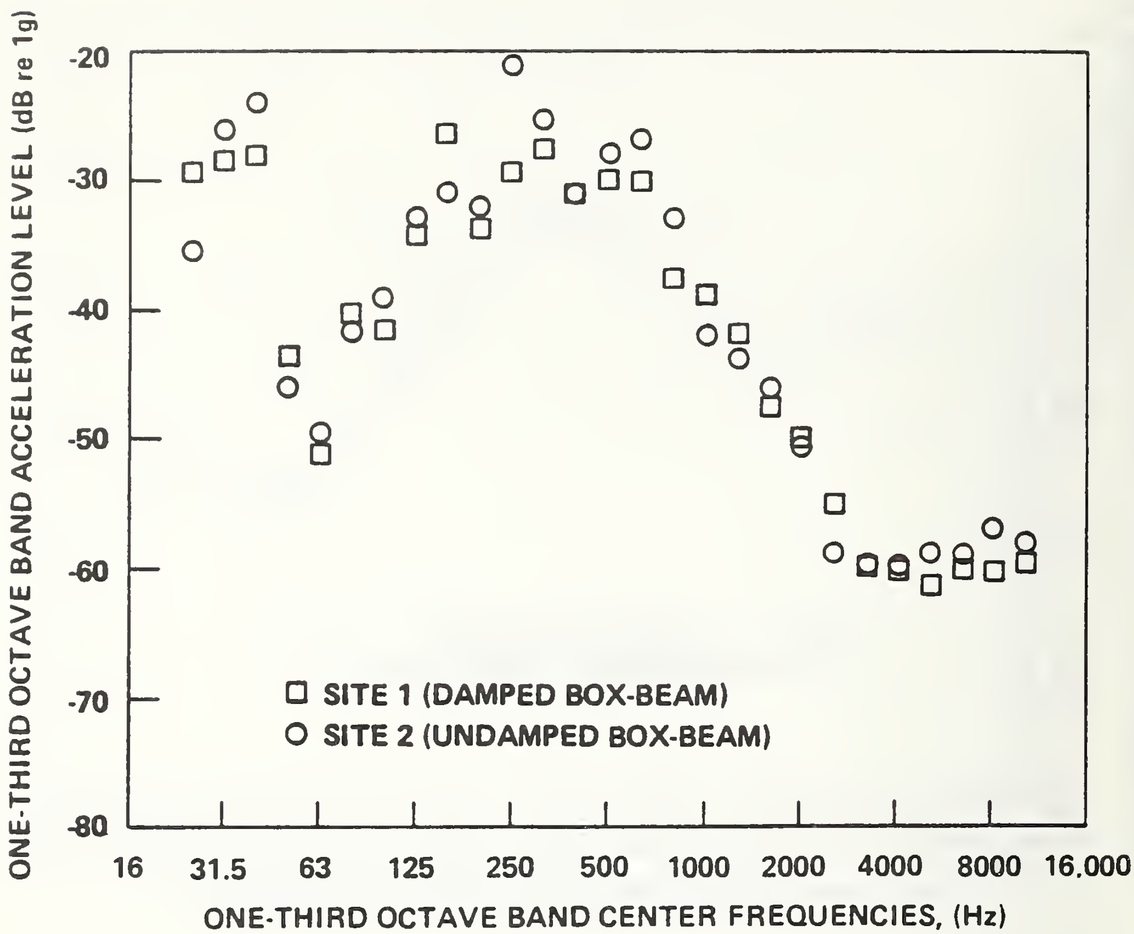

FIG. B.18. SPECTRA OF ACCELERATION OF SOUND BARRIER (TRANSDUCER LOCATION NO. 8).

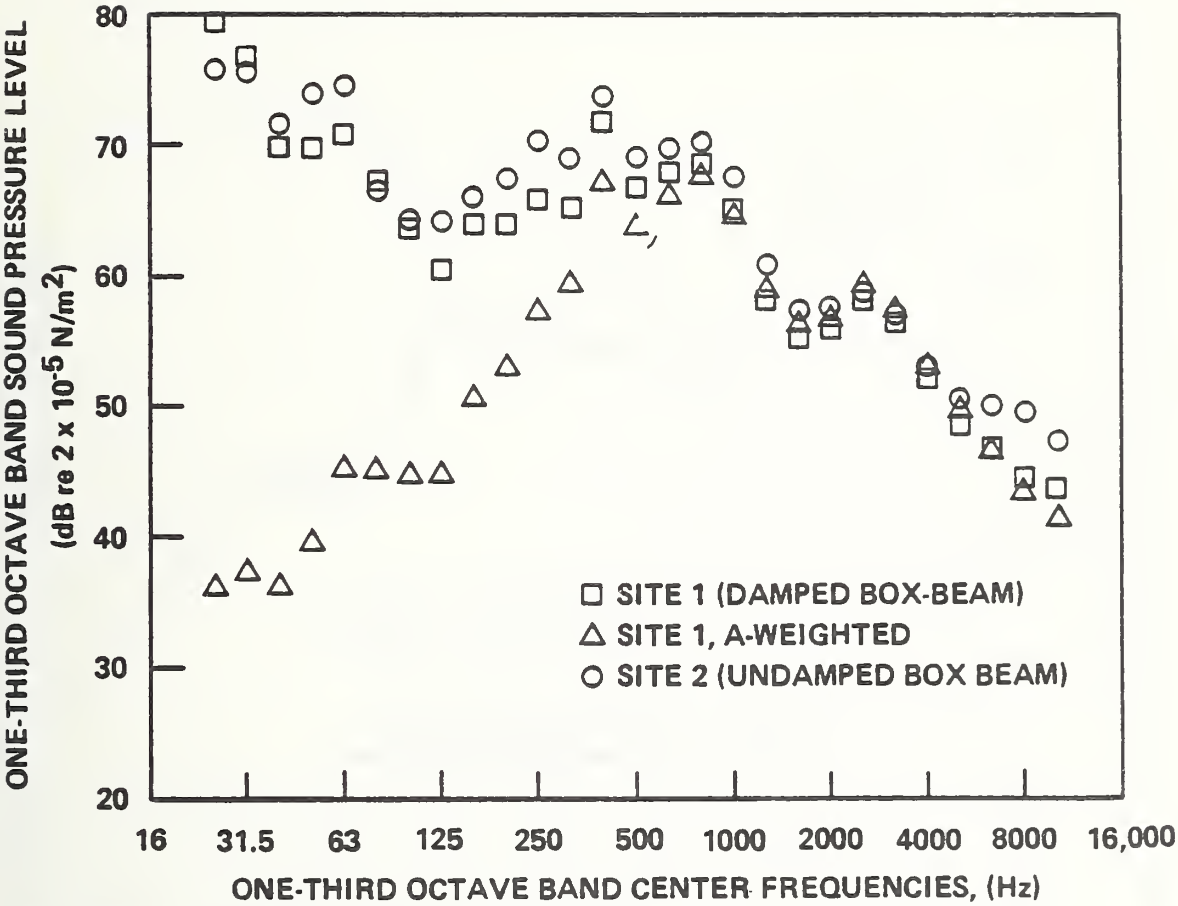

FIG. B.19. SOUND PRESSURE SPECTRA AT RAIL HEIGHT 25 ft SOUTH OF CENTERLINE OF EASTBOUND TRACK (ON BARRIER-LESS SIDE, MICROPHONE NO. 3).

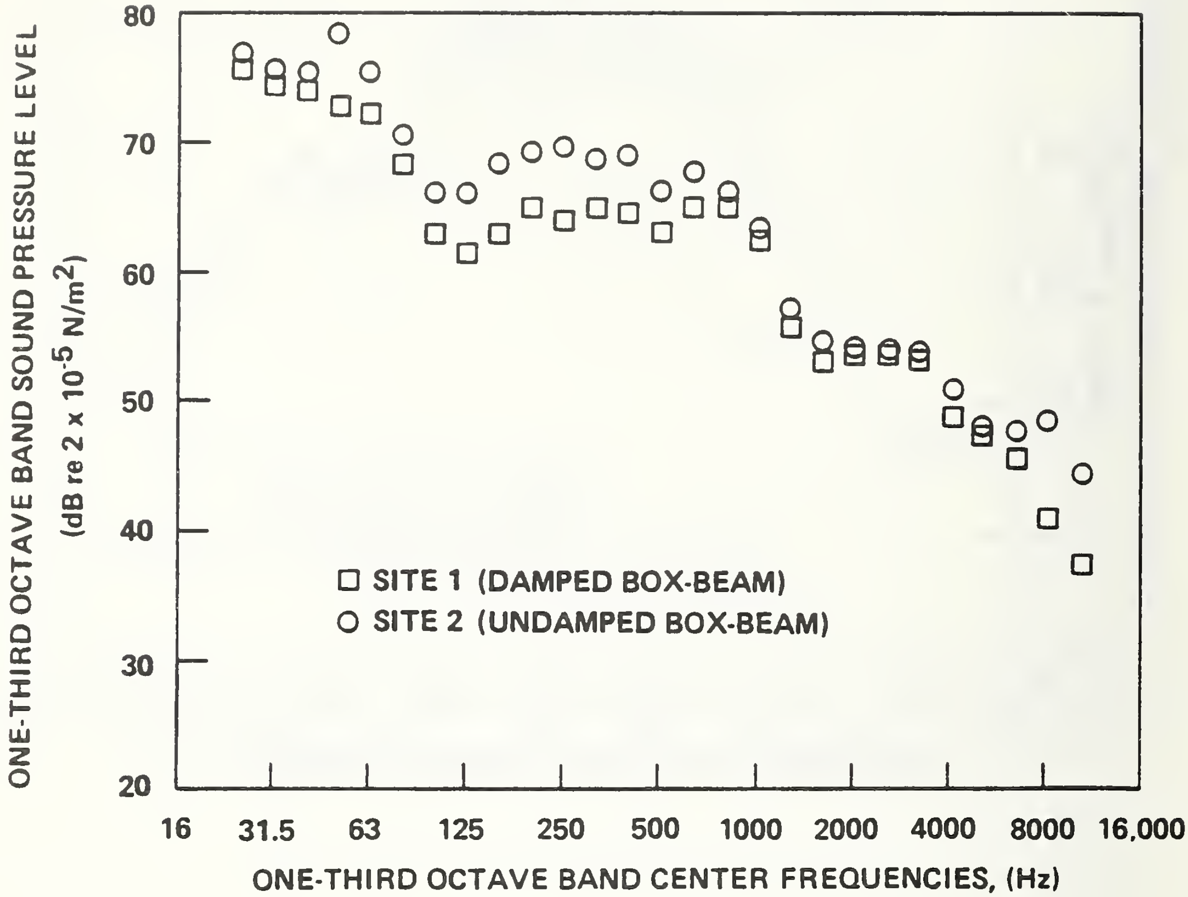

FIG. B.20. SOUND PRESSURE SPECTRA AT 5 ft ABOVE GROUND, 25 ft NORTH (ON BARRIER SIDE) OF THE CENTERLINE OF WEST-BOUND TRACK (MICROPHONE NO. 9).

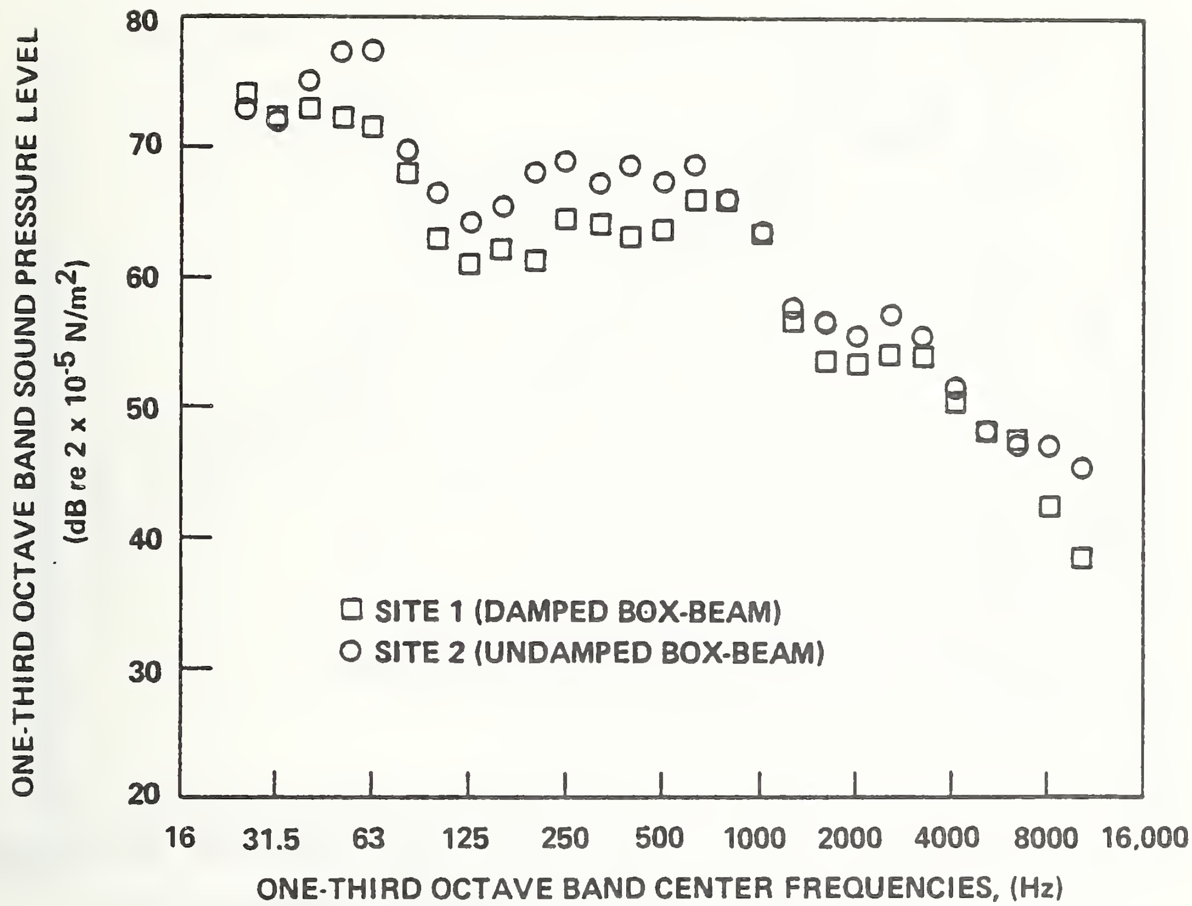

FIG. B.21. SOUND PRESSURE SPECTRA AT 5 ft ABOVE GROUND, 50 ft NORTH (ON BARRIER SIDE) OF CENTERLINE OF WESTBOUND TRACK (MICROPHONE NO. 10).

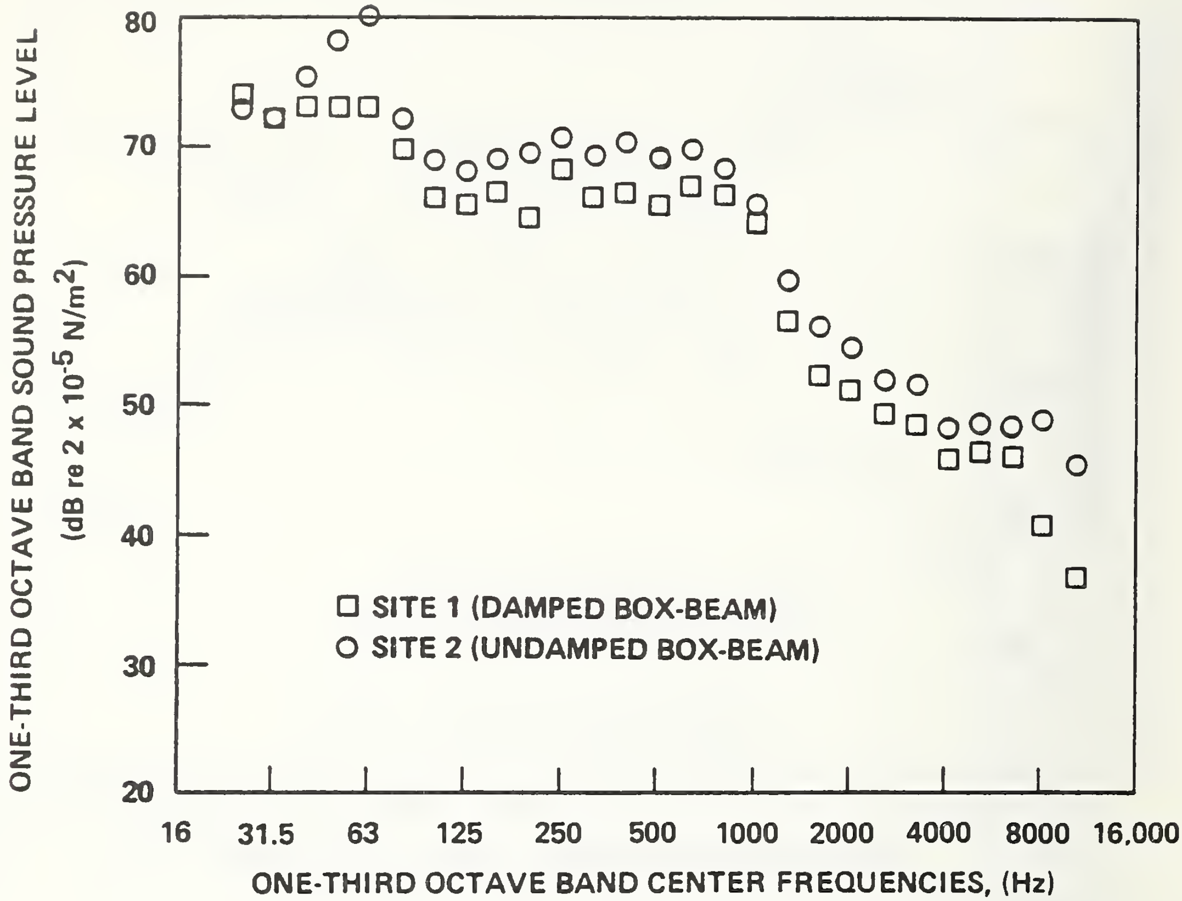

FIG. B.22. SOUND PRESSURE SPECTRA 1-1/2 in. ABOVE GROUND, 50 ft NORTH (ON BARRIER SIDE) OF CENTERLINE OF WESTBOUND TRACK (MICROPHONE NO. 11).

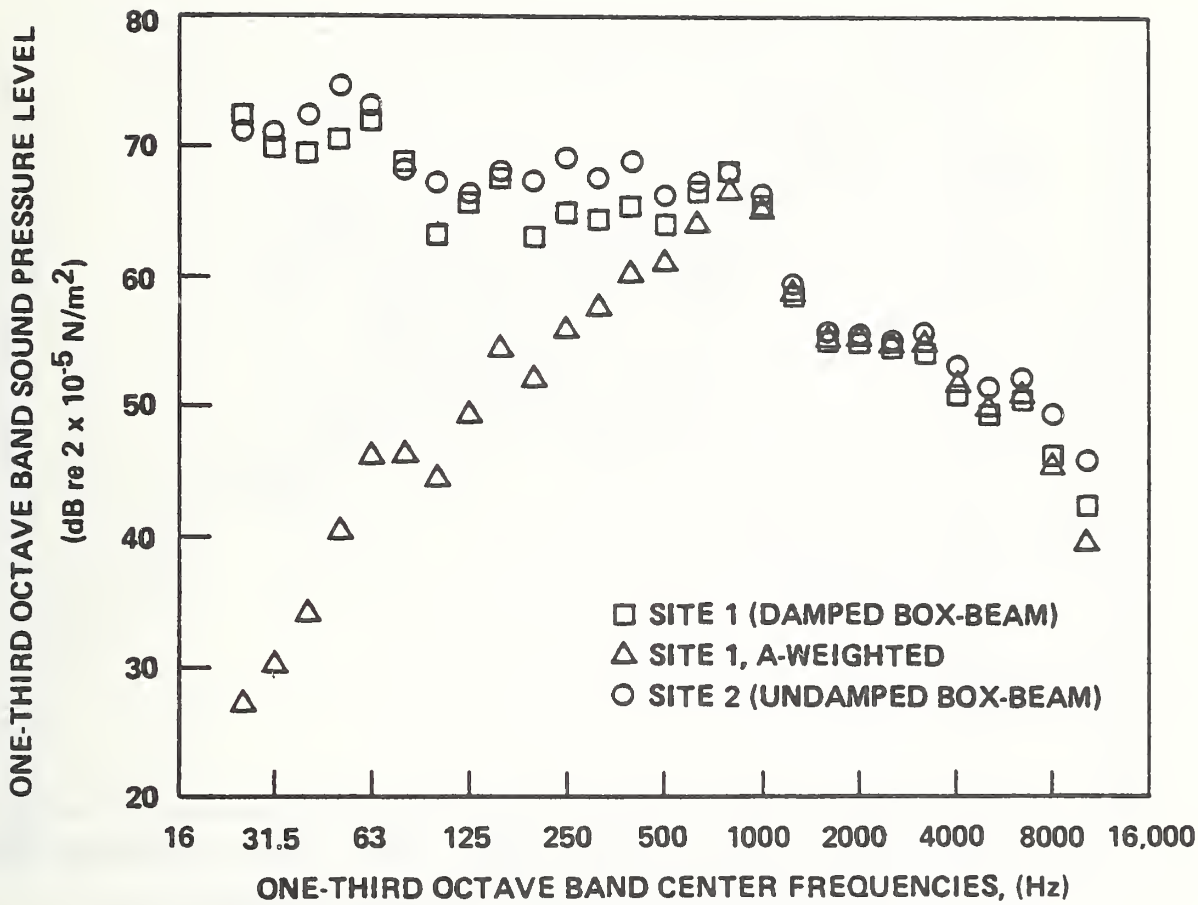

FIG. B.23. SOUND PRESSURE SPECTRA AT RAIL HEIGHT, 25 ft NORTH (ON BARRIER SIDE) OF CENTERLINE OF WESTBOUND TRACK (MICROPHONE NO. 12).

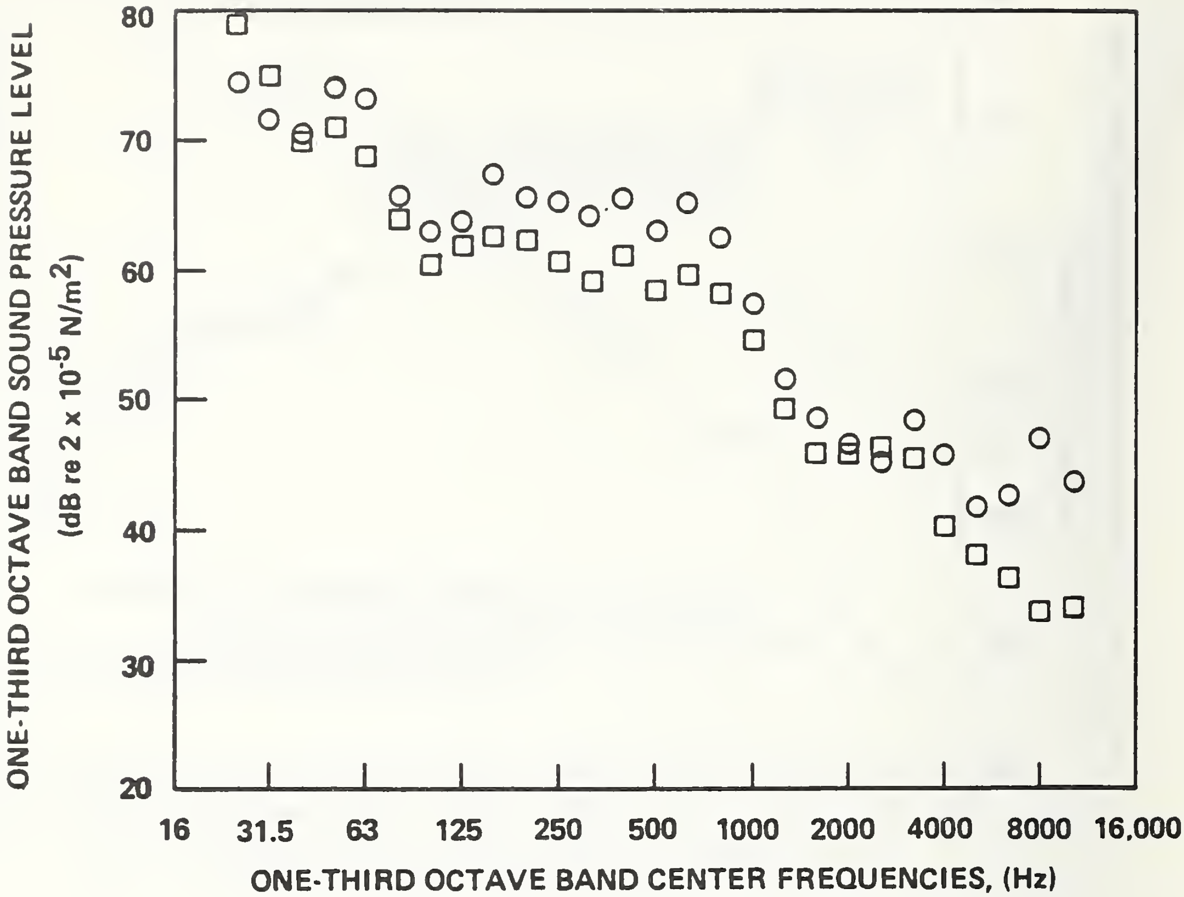

FIG. B.24. SOUND PRESSURE SPECTRA AT 5 ft ABOVE GROUND, 25 ft SOUTH (ON BARRIER-LESS SIDE) OF CENTERLINE OF EAST-BOUND TRACK (MICROPHONE NO. 13).

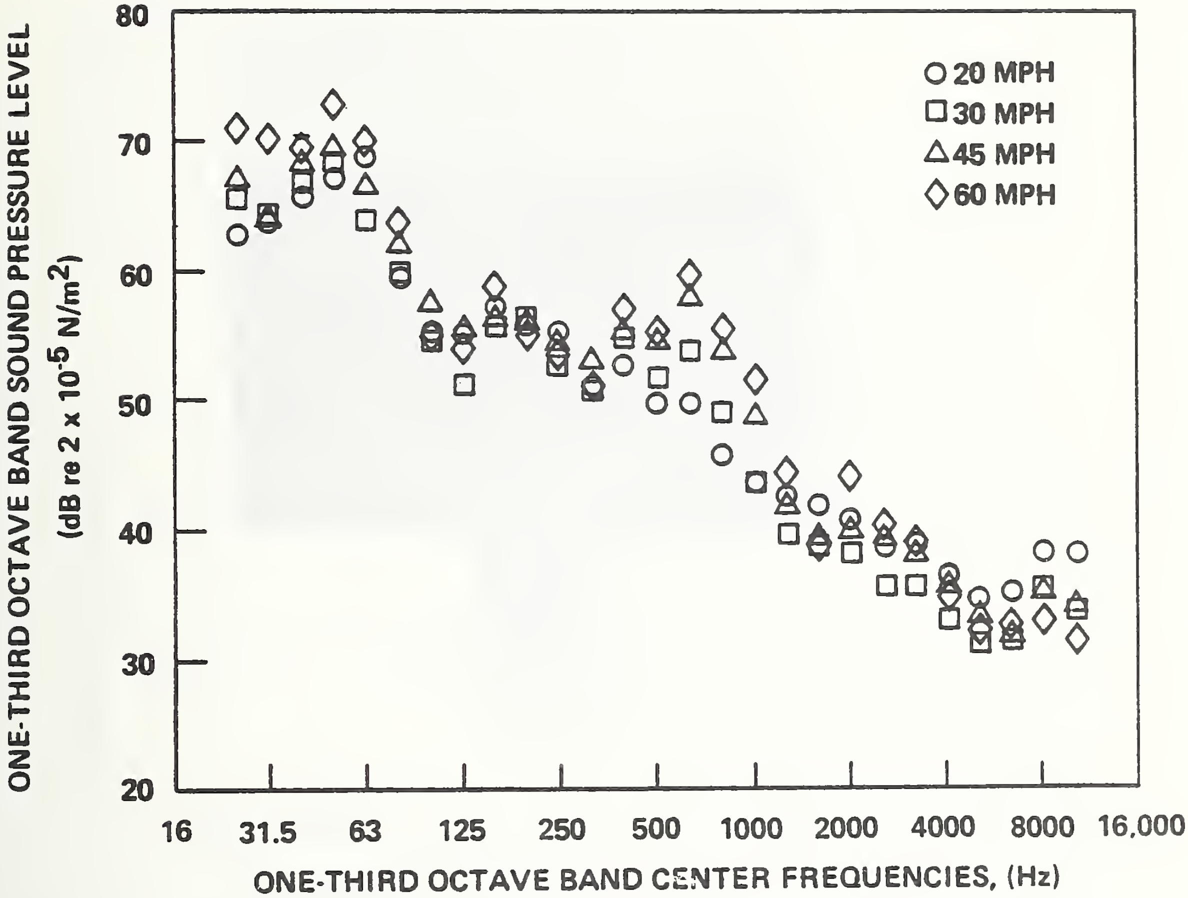

FIG. B.25. SOUND PRESSURE SPECTRA FOR FOUR TRAIN SPEEDS, OBSERVED AT SITE II (UNDAMPED BOX-BEAM), AT 5 ft ABOVE GROUND, 50 ft NORTH (ON BARRIER SIDE) OF CENTERLINE OF WEST-BOUND TRACK (MICROPHONE NO. 10).

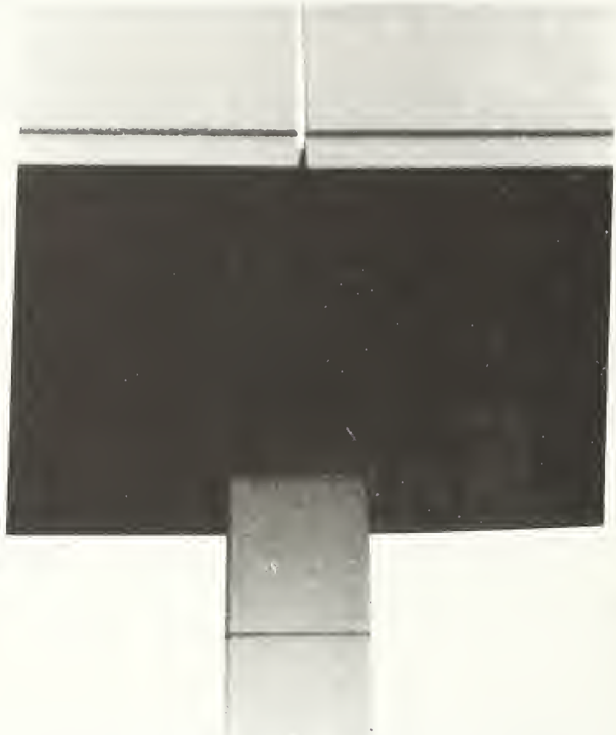

FIG. B.26. TYPICAL GAP IN NOISE BARRIER AT SUPPORT COLUMNS.

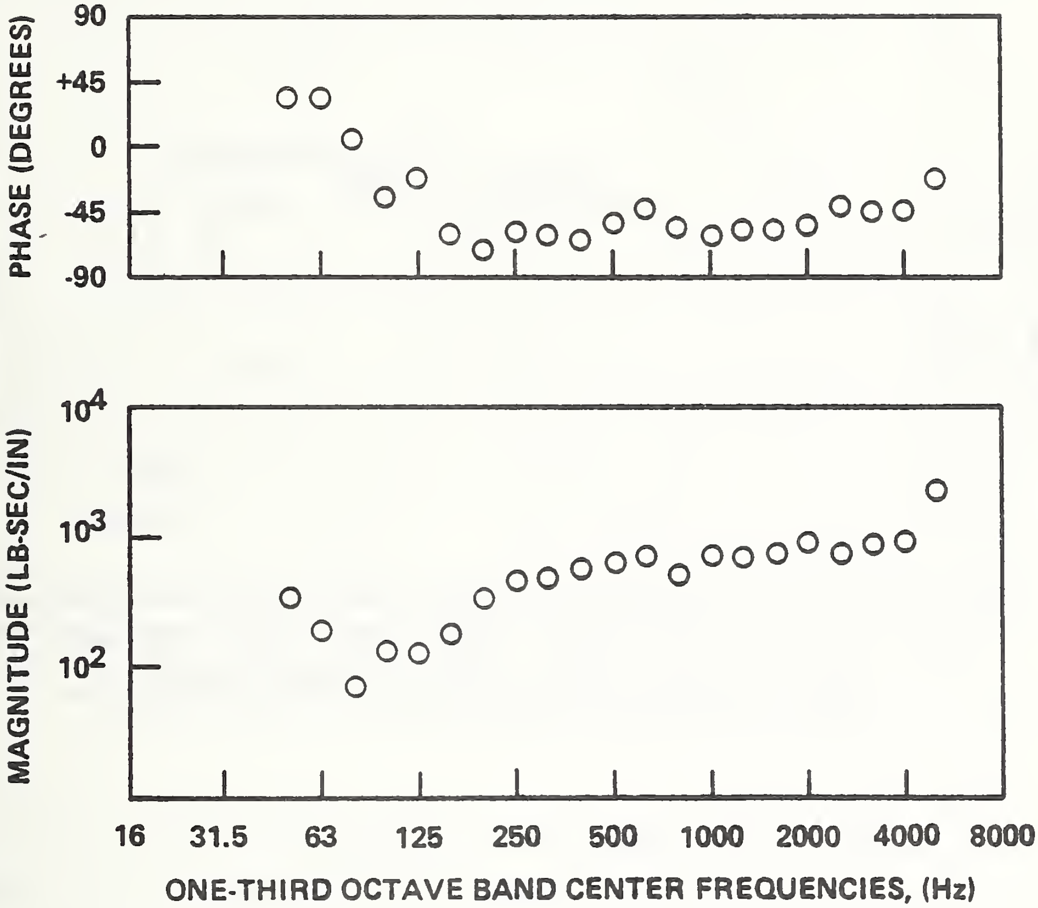

FIG. B.27. VERTICAL DRIVING-POINT IMPEDANCE OF RAIL MEASURED AT MARTA.

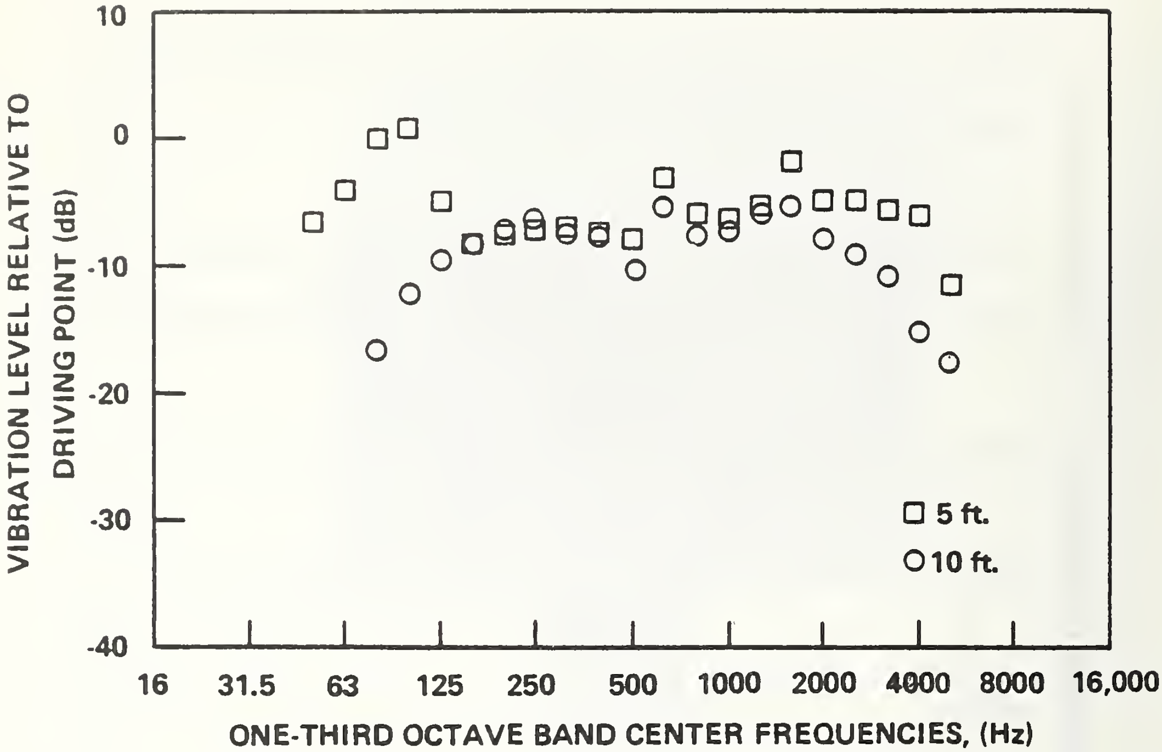

FIG. B.28. PROPAGATION OF VERTICAL VIBRATION ALONG RAIL, MEASURED AT MARTA.

APPENDIX C

MEASUREMENTS ON STRUCTURES OF THE NEW YORK CITY TRANSIT AUTHORITY (NYCTA)

Sites and Structures

Noise and vibration measurements were conducted on three separate days during the fall of 1978 to determine the noise reduction effectiveness of replacing steel tie-plate fasteners with resilient fasteners. The first set of measurements, made on 7 September, was carried out to characterize the noise and vibration levels obtained with the original fasteners. The second set of measurements was made on 24 October, after the resilient fasteners had been installed. These first two sets of measurements involved trains in regular revenue service; the third (but more limited) set of measurements, performed on 21 November, made use of a special test train with recently trued or inspected wheels.

All of these measurements were made at the same site on the IRT local line, along 10th Avenue in northern Manhattan, where it intersected with 211th Street. This site was chosen by NYCTA because of complaints coming from a grammar school located approximately 200 feet west of the transit structure. Pictures of the structure, taken from the west side, are presented in Fig. C.1. The building on the far side of the structure (the NYCTA 207th Street shop) most likely reflects sound energy back toward the school.

At this site, the structure consists of 100 lbs/yd jointed rail on an open tie deck. The wood ties (spaced 18 in. on center) are supported by steel plate girders with their webs directly under the rail axes. The girder webs are 5 ft high and 3/8 in. thick, and the flanges consist of 6 in. x 6 in. x 9/16 in. angle sections, riveted back-to-back to the top and bottom of the web. The girder spans are 50 ft long; about every 7 feet the web is reinforced by vertical stiffeners consisting of 3-1/2 in. x 3-1/2 in. x 3/8 in. angles, riveted back-to-back.

The structure carried three tracks. The center track was not used for revenue service, but was used by the special test train during the measurements conducted on 21 November. Only the southbound track (that is, the one closest to the school) was fitted with the resilient fasteners. Drawings of the steel plate fastener and of the resilient fastener are presented in an earlier report [Remington, 80], together with a discussion of their properties.

Transducer Locations and Instrumentation

Figure C.2 is a sketch of the cross-section of the structure, indicating where accelerometers were located for the first two measurements. In addition to these accelerometers, two microphones were employed; all sensors were situated in the same cross-section plane of the structure, at two-thirds the span length and one-fourth the length of the rail from a rail joint. Both microphones were at 5 ft above the ground; one was 25 ft from the centerline of the near track, and the other at 50 ft from the centerline, as measured horizontally. At the nearest rail joint, additional accelerometers were mounted on the rail foot and the girder web.

When the resilient fasteners were installed, some of the rail segments were interchanged, and the rail at the original measurement location was replaced with a new short segment of about 20 feet in length. Nevertheless, the observed vibrations do not show any significant change attributable to the presence of this short rail.

The third set of measurements, for which a test train repeatedly went south on the track fitted with resilient fasteners and then north on the unmodified center track, only made use of accelerometers on a rail foot and girder web of each track. (Noise measurements were made independently by the NYCTA environmental staff.)

The instrumentation system that was used here is the same as was employed for the MARTA measurements; a block diagram appears in Fig. B.4 of Appendix B. The 14-channel tape recorder shown in this figure was used for the 24 October measurements, even though a 7-channel Lockheed Store 7 tape recorder was used for the 7 September measurements. For these measurements, the signals were recorded in groups, with one of the vertical rail foot accelerometer signals always recorded to serve as a reference. BBN 501 accelerometers were used for all of the acceleration measurements, except near the rail joints, where B & K Type 4344 accelerometers were used to avoid overloading. Switch boxes were used to enable the operator to monitor one input and one output channel at a time on a dual-channel oscilloscope.

Test Trains and Runs

As has been mentioned, the first two measurement series were made for trains in regular transit service, and the last series was carried out with a dedicated test train that had recently trued or inspected wheels. During these measurements personnel located at the test site communicated via radio with train control personnel at the station preceding the test site, who instructed the motormen to pass through the test site either "slow", "medium", or "fast". NYCTA IRT cars do not have speedometers; during the tests, speed was measured with a radar device installed at the test site. Speeds between 10 and 30 mph were obtained.

Reduction in A-weighted Noise Level

Strip charts of the A-weighted noise levels as functions of time showed these levels to fluctuate irregularly, probably because of large variations in wheel condition from car to car. These fluctuations made the selection of peak levels difficult, if not meaningless. Therefore, instead of selecting a peak level, the A-weighted level for each record was integrated over a time period that was greater than the passage time of the train. The Single Event Noise Exposure Level (SENEL)*, obtained by dividing the integrated level by one second, was used to characterize the noise.

The results of this data analysis are plotted in Fig. C.3 for the 25-ft microphone location, and in Fig. C.4 for the 50-ft microphone location. These curves indicate that the change to the resilient fasteners resulted in noise reductions of 3 to 6

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* The SENEL description is defined as

$$\text{SENEL} = 10 \log \frac{1}{1 \text{ sec}} \int_{-\infty}^{\infty} 10^{L_A(t)/10}\, dt$$

where $L_A(t)$ is the time varying A-weighted sound level.

dBA at low speeds, and in lesser amounts at higher speeds (at which the noise from the traction motor becomes more predominant [Remington, 79]).

Noise and Vibration Spectra

Figure C.5 shows spectra of the wayside noise obtained at 25 ft from the track centerline with standard and with resilient fasteners, for trains passing at 22 mph, the only speed for which data for both fastener types were obtained. Although the two sets of data pertain to different trains with unknown possible differences in the conditions of their wheels, the 32-sec averaging of the data (which is roughly the passage time for a 10-car train) used here tends to obscure the corresponding small scale differences. Except for the 32-sec scaling factor, the spectra represent the total acoustical energy associated with the train passage.

Figure C.6 shows the rail vibration spectra measured in the vertical direction for the conditions pertaining to Fig. C.5. The differences in the rail vibration levels at frequencies below about 500 Hz probably are due to differences in the wheel tread condition between the trains involved in the two measurements. At these frequencies, the wheel impedance is much larger than the rail impedance, so that small changes in the combined fastener and tie stiffness would not affect the rail vibration level. The relatively large difference in the rail vibration levels above about 1600 Hz is probably due to damping of the rail provided by the resilient fasteners [Remington, 80].

Corresponding tie and girder vibration spectra are presented in Figs. C.7 and C.8, respectively. The most significant effect of installation of resilient fasteners appears to be a 3 to 6 dB reduction in the vibration levels at 500 Hz and above, together with a 0 to 3 dB reduction at frequencies below 500 Hz. The low-frequency vibration reduction is likely to be due to the reduction of the combined fasteners-and-tie stiffness, and the high-frequency vibration reduction is probably due to both this stiffness reduction and the increased rail damping.

Although a detailed analysis of these and related data are presented in a separate report [Remington, 80], it appears useful to indicate here some significant conclusions that can be derived from the spectra discussed above. The 500 and 1000 Hz octave bands are found to dominate the A-weighted noise levels. These frequencies are above the coincidence frequencies for all three structural components, so that the sound energy they radiate at these frequencies is proportional to the product of their area and their vibration velocity. One thus finds that the rails, ties, and girders all make about the same noise contribution, with perhaps a slight dominance by the ties. Because the rail vibration level does not decrease with increasing frequency as rapidly as the vibration levels of the other components, the rail probably dominates the noise in the 2000-Hz octave band.

Potential Reduction of Wheel-rail Excitation

In order to evaluate the potential for reducing the noise of NYCTA structures by reducing the wheel-rail interaction roughness, it is useful to compare the rail acceleration levels measured on the NYCTA structure with those obtained on the MARTA structure (Appendix B). Figure C.9 presents such comparison data for the bands that dominate the wayside noise levels (i.e., the 500-Hz band for NYCTA and the 1000-Hz band for MARTA), normalized by dividing the total energy for a passby by one second and by the number of cars per train. One may observe that at 30 mph the rail vibration levels measured on the NYCTA system with revenue trains are about 15 dB higher than the comparable levels measured at MARTA. For the NYCTA train with trued or inspected wheels, the rail vibration levels are seen to be about 8 dB lower than those for the revenue trains. It thus appears that the major source of the relatively high vibration levels obtained on the NYCTA structures is the roughness of the wheel treads and the rail surface, combined with the fact that the NYCTA rail is jointed; whereas the MARTA rail is welded. One may conclude that significant noise reduction can be obtained by reducing wheel tread and rail roughness, but that changing from jointed to welded rail will have little effect unless the average wheel tread condition is also improved.

FIG. C.1. NYCTA ELEVATED STRUCTURE AT 10th AVENUE AND 207th STREET.

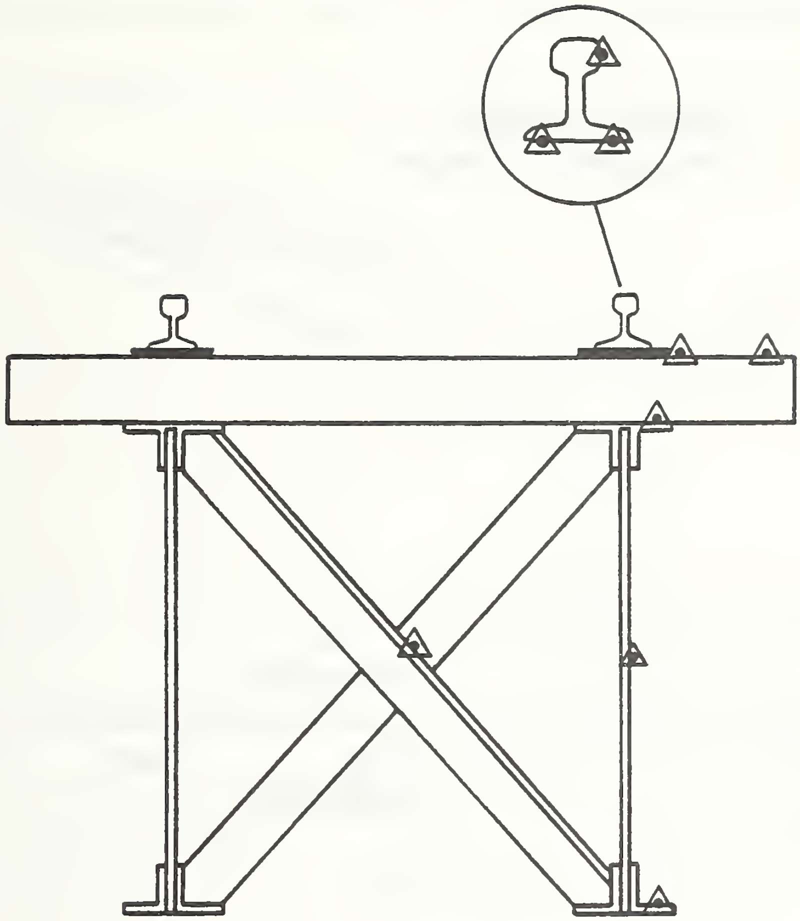

FIG. C.2. ACCELEROMETER LOCATIONS ON NYCTA STRUCTURE.

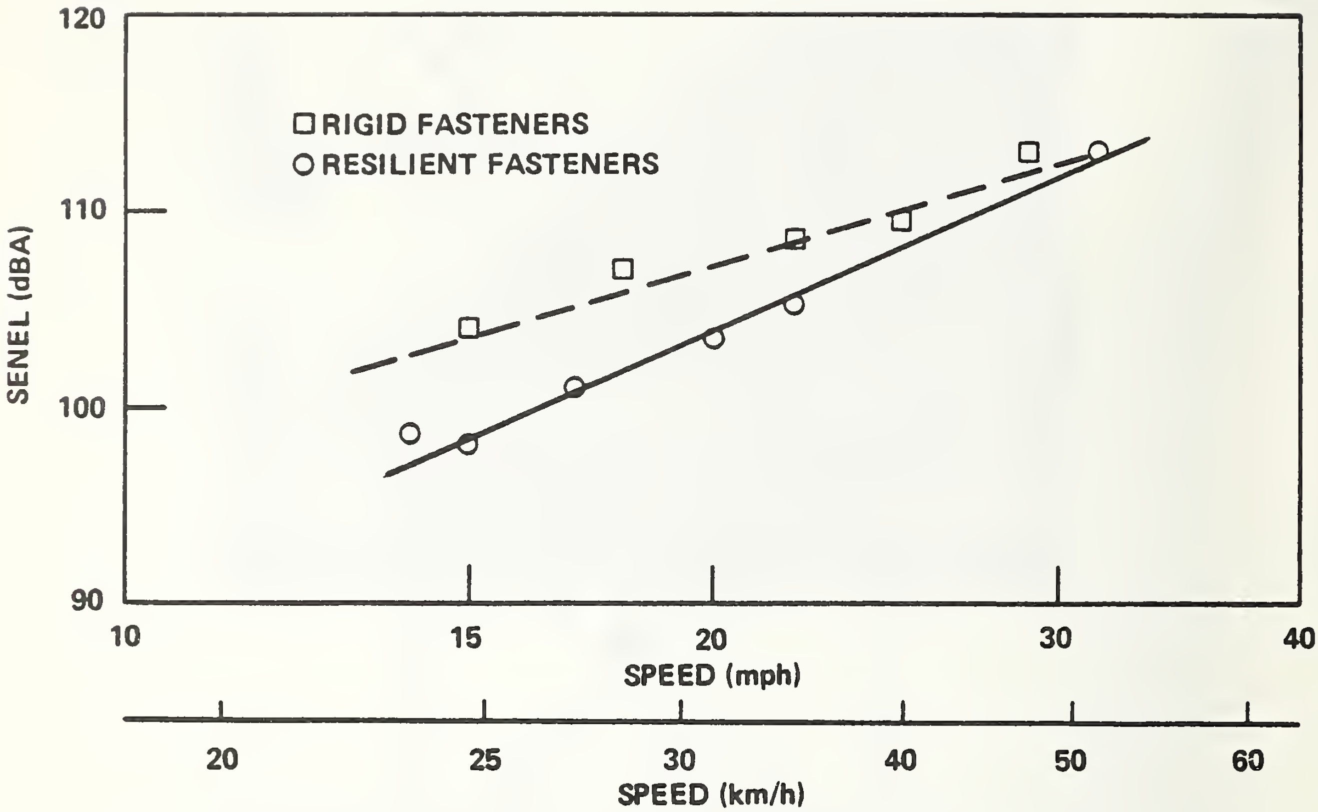

FIG. C.3. SPEED-VARIATION OF SINGLE EVENT NOISE EXPOSURE LEVEL OBTAINED AT 25 ft FROM CENTERLINE OF NYCTA ELEVATED TRACK, FOR STANDARD AND RESILIENT RAIL FASTENERS.

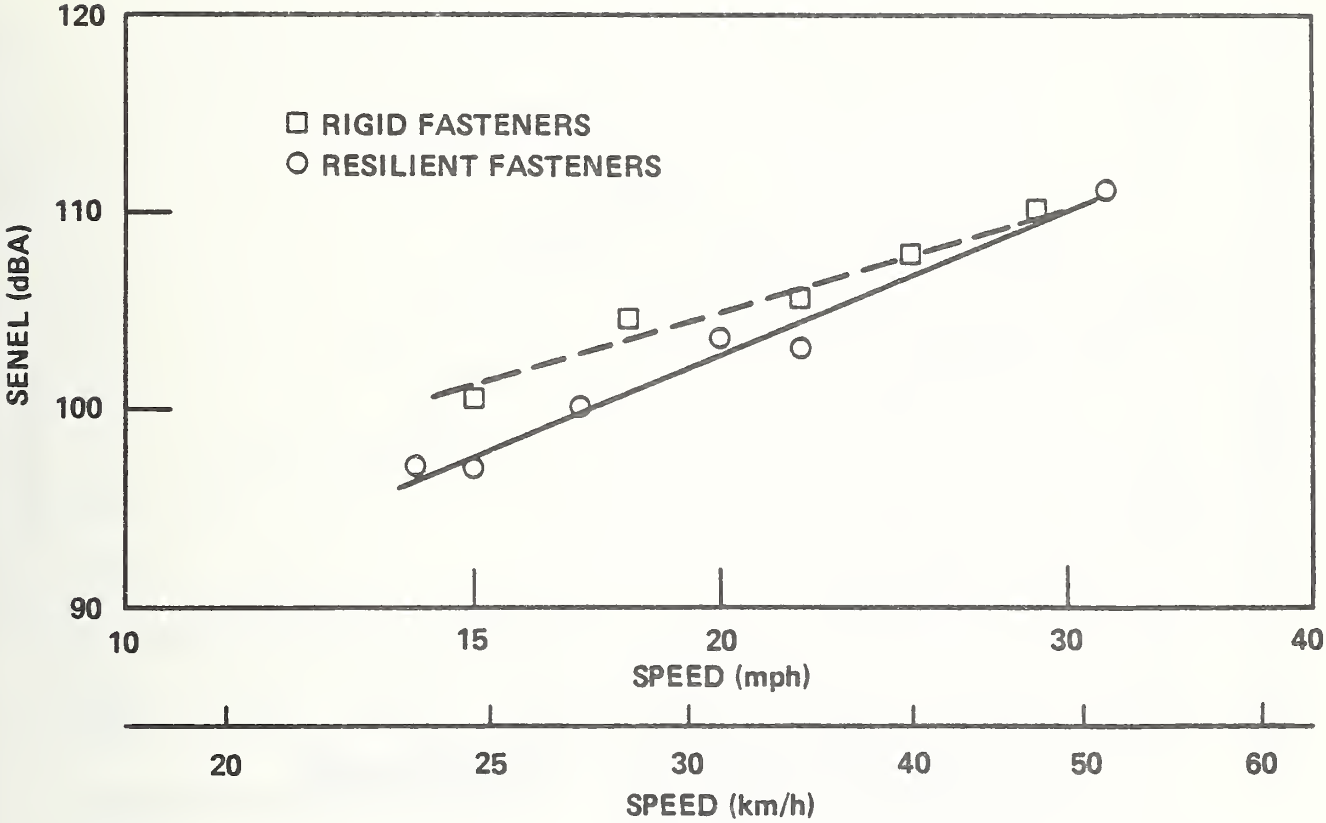

FIG. C.4. SPEED-VARIATION OF SINGLE EVENT NOISE EXPOSURE LEVEL OBTAINED AT 50 ft FROM CENTERLINE OF NYCTA ELEVATED TRACK, FOR STANDARD AND RESILIENT RAIL FASTENERS.

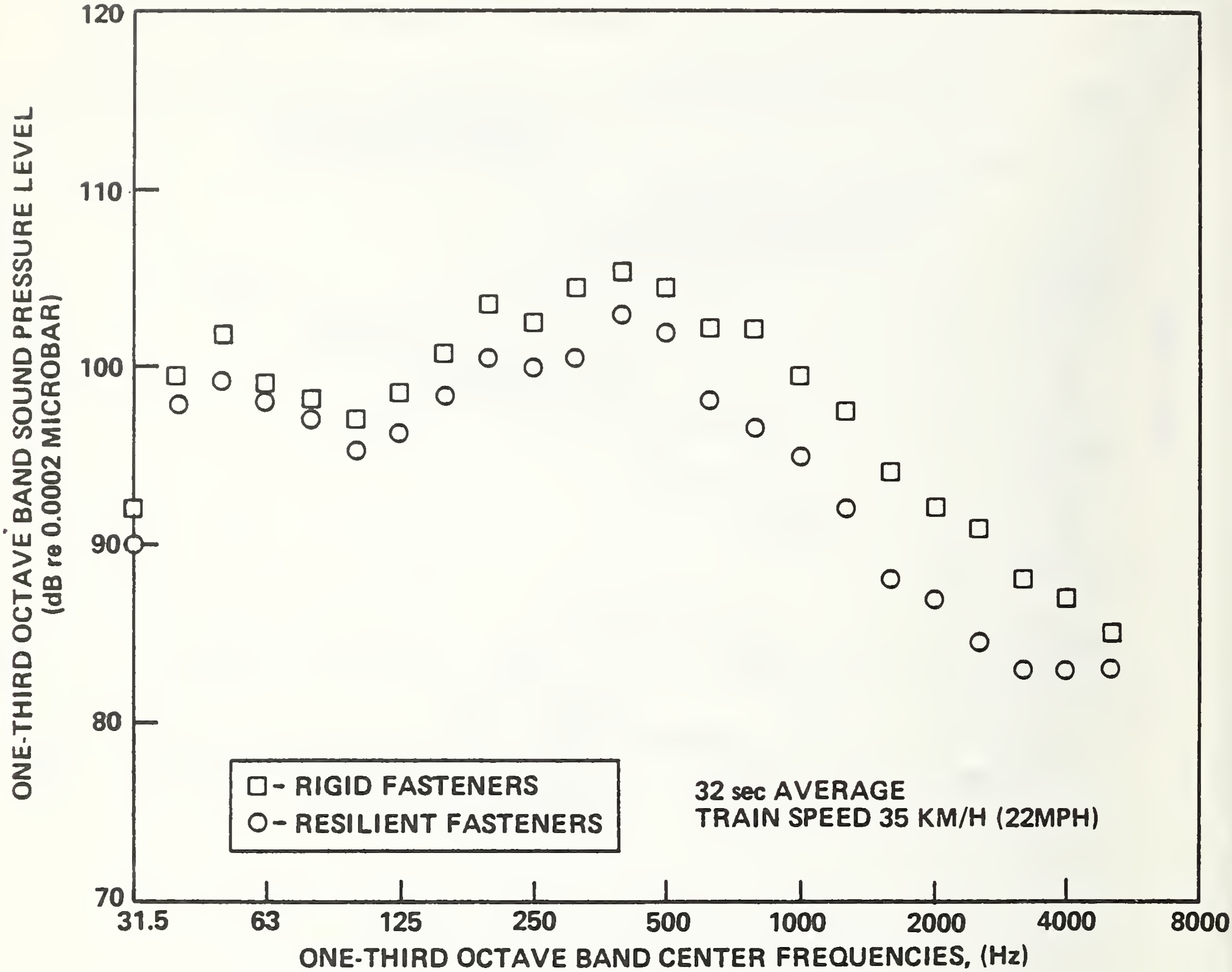

FIG. C.5. SPECTRA OF SENEL AT 25 ft FROM NYCTA ELEVATED TRACK FOR STANDARD AND FOR RESILIENT RAIL FASTENERS.

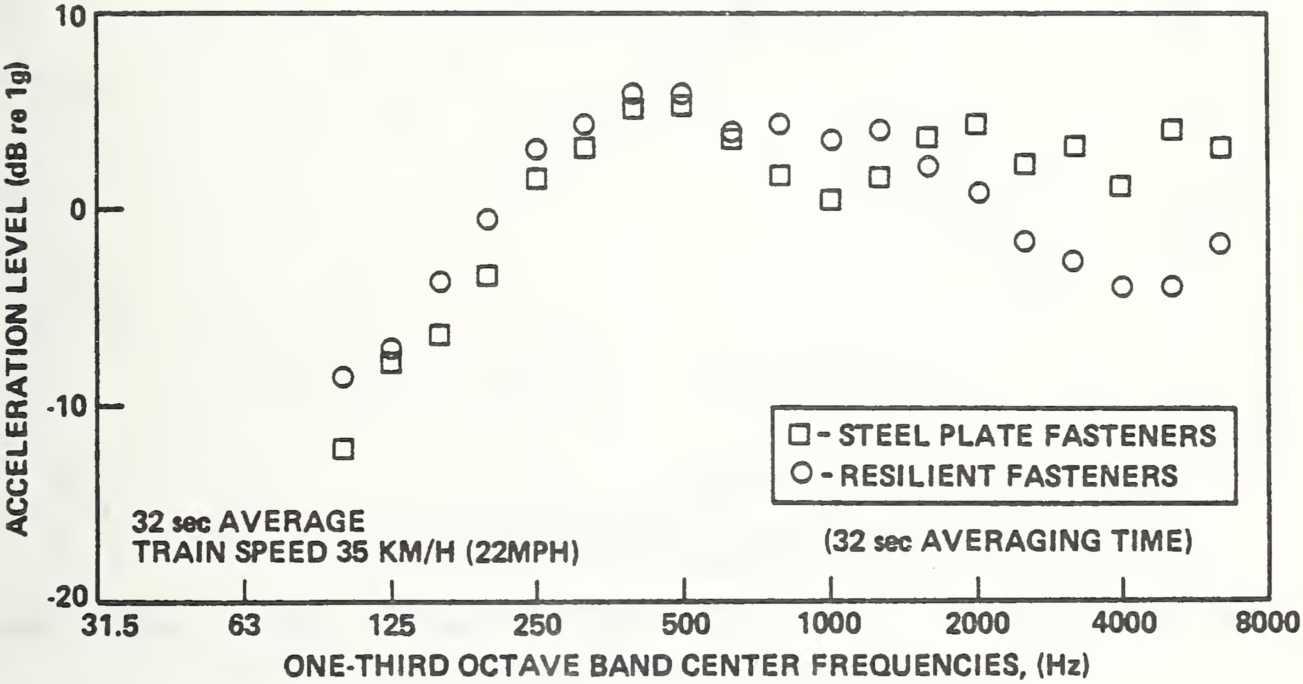

FIG. C.6. VERTICAL RAIL VIBRATION SPECTRA FOR NYCTA ELEVATED STRUCTURE WITH STANDARD AND WITH RESILIENT RAIL FASTENERS. (TRAIN SPEED: 22 mph).

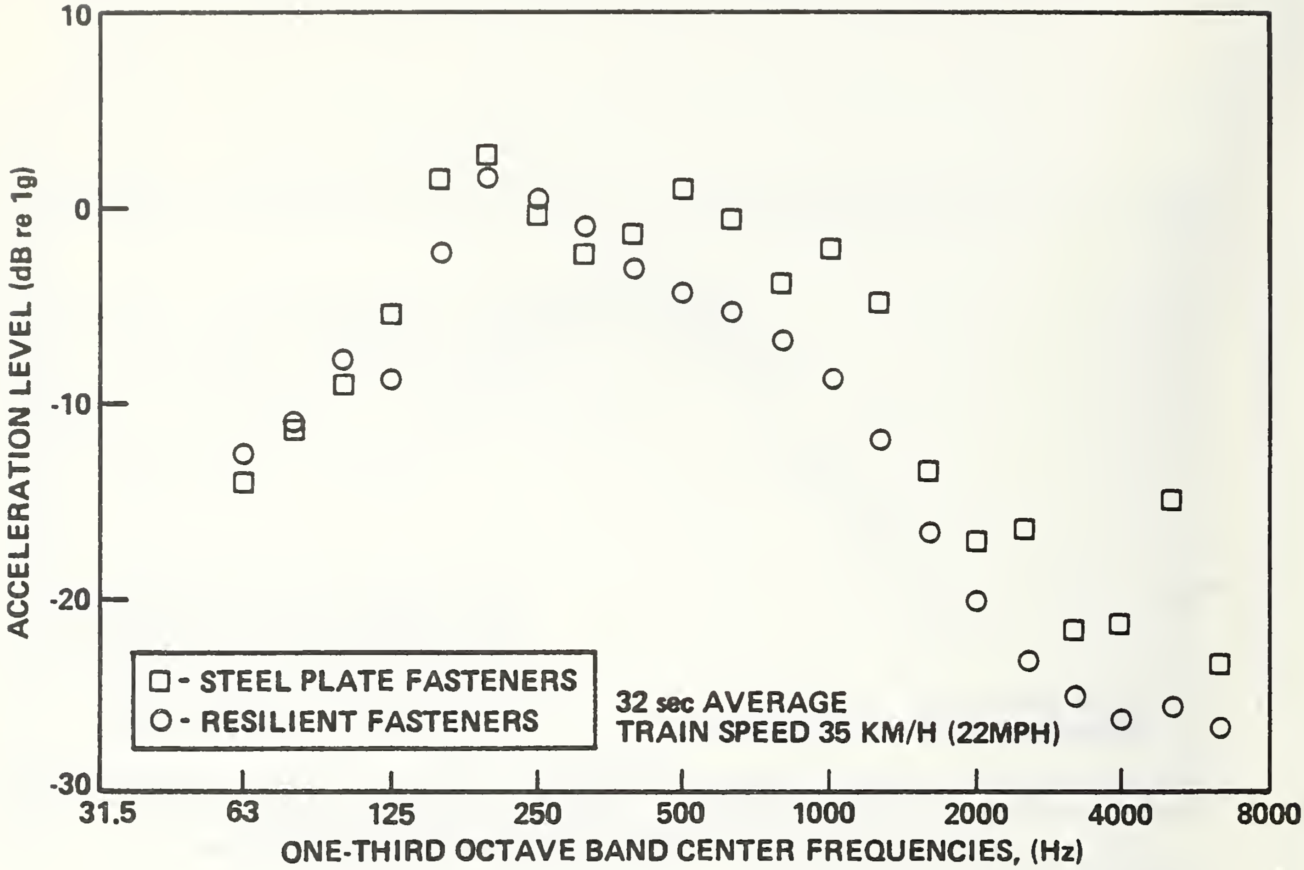

FIG. C.7. SPECTRA OF TIE VIBRATIONS ON NYCTA ELEVATED STRUCTURE WITH STANDARD AND WITH RESILIENT RAIL FASTENERS.

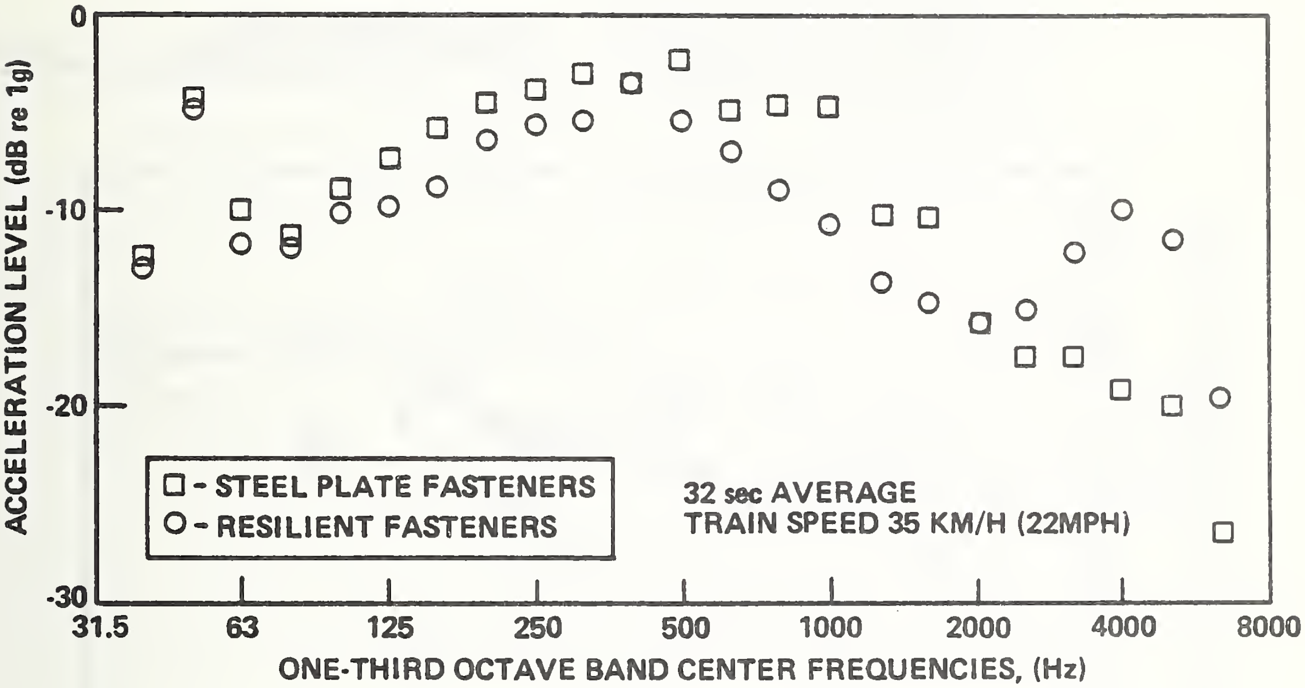

FIG. C.8. SPECTRA OF GIRDER VIBRATIONS ON NYCTA ELEVATED STRUCTURE WITH STANDARD AND WITH RESILIENT RAIL FASTENERS.

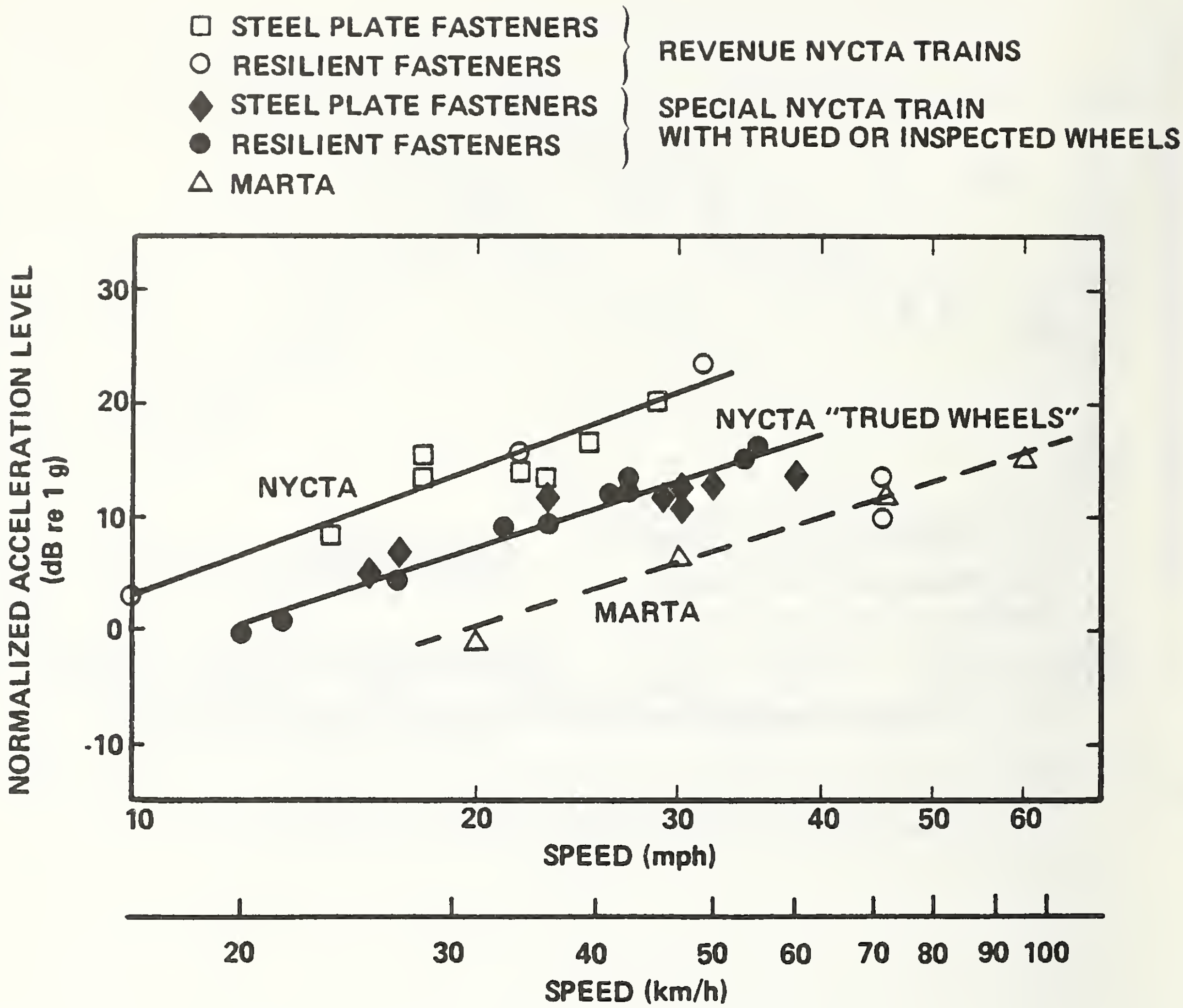

FIG. C.9. COMPARISON OF NYCTA AND MARTA RAIL VIBRATION LEVELS.

APPENDIX D

ANNOTATED BIBLIOGRAPHY

Abe, H., "Measures Associated with Iron Girders," *Permanent Way 17,* No. 63-64, pp. 26-50, 1976.

Steel bridges without ballast are 10 to 15 dBA noisier than those with ballast. Ballasted bridges may make less noise than trains on embankments.

Illustrates steel bridge treatments including: sidewalls isolated from structure, bottom plates (including of damped sandwich construction), and rubber sealing strip between vertical and horizontal shielding surfaces.

Application of at least 15 cm concrete directly to girder is required for noise reduction. Rubber asphalt on inner surfaces of box beams produced 7-8 phons reduction. Overall noise reduction requires use of bottom shields to reduce "running noise" radiation, which is equally as important as structural noise.

Vibration isolation of attached barriers is important. Ballast mats yield 4-12 dBA reduction. Absorptive materials on inside surfaces of barriers and shields are useful.

New developments include full bridge enclosures, prestressed concrete decks (some with ballast), and prefabricated barrier plates.

Abe, H., "Noise-Controlled Truss Bridges for Railways," *Permanent Way 15*(4) No. 57, pp. 1-8, 1974.

Noise occurs equally from wheel-rail interaction and from structural radiation. In general, the weight of added damping must be considered; barriers should be isolated and lined with absorbent materials.

For noise control on existing truss bridges, side barriers and bottom covers should be added. New planned truss bridges use prestressed concrete floor system, which also acts as bottom shield.

Arai, M., "Noise from Elevated Structures of High Speed Railway," *Paper DD2,* November 1978, Joint Meeting of Acoustical Societies of America and Japan.

Wheel/rail is primary noise source. Elevated steel-girder slab-track structures are 5 to 10 dBA noisier than elevated structures with ballasted track.

Structural noise radiation is less than that from wheel/rail until latter is reduced by lineside barriers. Only means for wheel/rail noise reduction consist of careful maintenance of wheel and rail; composite tread brake was found helpful.

Ballast mats reduced noise by as much as 7 dBA. Damping reduced girder vibration by up to 10 dB.

In one test section, a separately supported shielding structure was built under viaduct sidewalls supported from that structure.

Ban, Y. and T. Miyamoto, "Noise Control of High-Speed Railways," *J.Sound and Vibr.* (1975) *43*(2), 273-280.

Summarizes some information given in the "Shinkansen Noise (II) Report," as well as recommended noise countermeasures, and related environmental standards.

Ballast mat on concrete viaduct reportedly reduced noise by 7 dBA; whereas slab mat produced only 3-5 dBA reduction. Undercover for concrete viaduct gave 8-9 dBA reduction. On steel girder bridge (Morita over-road bridge), damping and undercover gave 10-13 dBA reduction.

Betzhold, C. and H. Gahlau, "Konstructive Anwendung von Geräuschdämpfenden Belägen im Maschinenbau," (Structural application of noise-reducing layers in machine design.) *VDI-Zeitschrift 11* / 1978.

Noise data (with tapping machine excitation) on box bridge with and without sandwich damping, partial and full coverage. 78 dBA reduced to 61 dBA.

Describes safety-fasteners on cover plates and effects of incomplete adhesion.

Discusses noise isolation of rail NRC traction car floor. Presents effects of damping on NRC of automobile firewall and effect of damping on noise inside a bus. It also discusses damped railroad wheels.

Blair, C., March, P., Moore, J. and Spinke, N., "Radiated Noise from Elevated Subway Systems in Boston," *Acoustics and Vibration Laboratory, MIT*, August 1974.

MIT class project carried out on the MBTA's Orange, Blue and Red Lines at both elevated structures and at grade.

Measurement position 50 ft from track centerline, 4 ft above ground.

Reported: Train speed, 1/3 octave band sound pressure spectra, overall and A-weighted levels.

Constructions included:

- Open steel girder, ties, directly fastened rail, and field welded rail. (Thompson Square, Charlestown).
- Concrete slab on 4 concrete I-beams. Rubber rail fasteners attach rail to concrete slab. Rail is continuously welded. (Neponset River Bridge)
- Riveted steel plate structure, track directly fastened to the ties, ties bolted to the support structure (Thompson Square)

Results for overall A-weighted octave and one-third octave band levels are presented in the form:

SPL = B x 20 log (V/mph + A
(SPL = Sound Pressure Level)

The intercept A and the slope constant B are tabulated together with the 90% confidence limit (±dB) deviation from this central tendency curve.

- Construction details of the structures are not given, but reasonably good quality photographs appear in the report.

Buchta, E., "Untersuchungen der Geräuschabstrahlung von Hochbahnen," (Investigations of sound radiation from Elevated Railways), *VDI-Zeitschrift* (1975) Nr.20, pp. 941-2.

Although paper refers to measurements made on two new concrete structures (Rotterdam and Nürnberg) and on two old steel structures (Berlin and Hamburg), only Rotterdam results are reported in detail. Rotterdam uses directly fastened rail and resilient wheels.

At Rotterdam, greatest sound radiation occurs at about 30° above horizontal. Up to 50 km/h, noise level increases at 3 dBA per 10 km/h; at higher speeds, increase drops to 2 dBA/10 km/h. For steel structures, greater downward directivity is observed due to radiation from structure.

Callender, A., V. Teglasi, G. Haikalis, J.E. Mahoney, "Rapid Transit Noise (EPS) and the Transportation Plan," Analysis Notes 2385, Environmental Assessment Series #3, *Tri-State Regional Planning Commission*, August 1975.

About 700,000 residents are impacted by noise from steel elevated structures. Two major commuter rail steel elevated structures: Park Ave in Manhattan, Atlantic Ave in Brooklyn; about 2 miles long each. Map of steel transit elevated structures attached. Also tabulation of numbers of trains, route miles, etc. for these structures.

Commins, D., "Évaluation du niveau de bruit de chemins de fer" (Evaluation of noise levels of railroads), *Commins-bbm*, Report No. 10, May 1977.

Discusses general environmental noise considerations and presents a simple prediction method. Mentions general noise reduction principles.

Deenik, J.F. and J.A. Eisses, "Fastening Rails to a Concrete Deck."

Reports on installation design and use experience with rubber-bonded cork pads.

Presents limited vibration and noise data indicating cork pads on concrete decks (directly fastened) are generally quieter than ballasted conventional track on such decks.

Devaux, A., "Reduction of Noise and Vibrations which affect Building Structures Caused by the Passage of Railway Rolling Stock," *Bulletin of the International Railway Congress Association*, Brussels, pp. 718-760, December 1969.

Discusses results of "Isolif" mats placed under ballast. Reduction of up to 14 dBA in spaces under track, 3-4 dBA next to track, up to 16 dBA above track were observed. Reductions in vibrations of concrete foundations between 1 and 10 dB were recorded.

Devaux, A., "Affaiblissement des vibrations transmises aux structures par le matériel ferroviaire," (Attenuation of vibrations transmitted to structures by railroad equipment.) *Le Génie Civil*, April 1968.

Presents analysis of action of "Isolif" mats under ballast and reports related noise/vibration measurement data.

Eisenmann, J., "Eisenbahnoberbau für hohe Geschwindigkeiten" (Railraod track structures for high speeds), *ETR - Eisenbahntechnische Rundschau*, Heft 6, 1972.

Discusses requirements for concrete and asphalt support panels, ballast, and elastic track fasteners. Construction information, but nothing related to vibration/noise.

Gabrielsen, B.L., "MARTA Qualification Test Results for the Hixson Direct Fixation Rail Fastener," *Scientific Services, Inc.*, Report 7639-1, March 1977.

Gives data from load, restraint and voltage tests, including comparison of static to dynamic stiffness (the latter measured at 20 Hz). Ratio of dynamic stiffness at 20 Hz to static stiffness typically is 1.05.

Grünewald, E., "Auswertung von Schallmessungen an Eisenbahnbrücken der Deutschen Bundesbahn," (Evaluation of noise measurements made on railroad bridges of the German National Railway), *Vereinigte Flugtechnische Werke - Fokker GmbH*, Rept. No. Ef-B 769, 16 October 1978.

Results of 40 data reports for 38 railway bridges are summarized in uniform format, including corrections for measurement locations, train length & speed, environment. Presents data summary charts.

Points out that embankment and bridge noise comparisons are valid only if train length is equal to bridge length. Massive bridges with ballast mats are quietest. Steel trough bridges without ballast are noisiest.

Rank-ordering of Bridges

$L_{Bridge} - L_{Grade}$ (dBA)	Bridge Type
-1.5	Concrete with box-beam, ballast with ballast mat
-0.5	Steel truss with track slab
1	Solid web steel beams, deck slab, ballast with ballast mat
2	Steel truss, ballast
2	Solid web steel beams, rail carrier truss, ballast with mat
4	Solid web steel beam trough, ballast
7	Steel truss, wood ties
7	Solid web steel beams, rail carrier truss
8	Steel truss, orthotropic rail support plate, direct fixation
8	Steel truss, no ballast
9.5	Solid web steel beams, rail carrier truss, no ballast
10.5	Solid web steel beams, rail carrier truss, steel deck, no ballast
20	Solid web steel beam trough, no ballast.

Halpenny, J., "Reduction of Railway Noise with Composite Concrete Rails," *High Speed Ground Transp. Jour. 11 (2)*, 173-5 (1977).

Suggests imbedding steel rail in concrete to obtain stiffer structure to distribute the load and help keep rail from vibrating.

Hanel, J.J. and T. Seeger, "Vorläufiger Abschlussbericht zum Forschungsvorhaben 'Schallgedämpfte Stahlkonstruktionen'," (Interim final report for research project "Damped Steel Structures"), *Institut für Statik und Stahlbau, Technische Hochschule Darmstadt,* January 1977.

Measurements on two box-type steel bridges (over Hammerbrook Street) of Hamburg S-Bahn demonstrated 13 dBA reduction as result of application of constrained-layer damping treatments. Detailed noise and vibration data on treated and untreated bridges are included.

Extensive preliminary studies are summarized dealing with (1) the effects of loading, fatigue, and temperature on the viscoelastic material and its adhesion, (2) corrosion protection, (3) fastening systems. A summary table of earlier noise control studies is included.

Hanel, J.J. and T. Seeger, "Schallgedämpfte Stahlkonstruktion im Brückenbau - Grundlagen und erste Anwendung," (Noise Control on Railway Steel bridges - Fundamentals and First Application), *Publication of the Institut für Statik und Stahlbau der Technischen Hochschule Darmstadt,* Report No.32, 1978, 166 pages.

Same data as January 1977 Interim Report, but includes results of measurements after one year of use.

Hanel, J.J. and T. Seeger, "Luftschallpegelsenkung bei Stählernen Eisenbahnbrücken durch Applikation Körperschalldämpfender Verbundsysteme am Tragwerk," (Reduction of airborne sound levels of steel bridges by application of structureborne-damping systems attached to the structures), *VDI-Berichte*, Nr. 278, 1977.

Tests on two box-type bridges (with two different constrained layer configurations) gave up to 19 dBA reduction - approaching "at grade" noise. Noise reduction occurred over entire audio spectrum.

Hanel, J.J. and T. Seeger, "Experimentelle Untersuchungen an Körperschalldämpfenden Verbundsystemen in Hinblick auf Schalldämpfungsmassnahmen an Stählernen Eisenbahnbrücken," (Experimental investigations of vibration-reducing adhered systems in relation to noise reduction of steel railway bridges), *Der Stahlbau 47*, Jan 78(No.1) pp. 1-6 and Feb.78(No.2) pp. 57-62.

Reviews relation between loss factor and noise reduction. Discusses practical support, adhesion, corrosion problems and presents related laboratory test results. Estimates that damping can reduce noise of steel box bridges by up to 15 dB.

Hanel, J.J. and T. Seeger, "Schalldämpfungsgrossversuch an zwei stählernen Eisenbahn-Hohlkastenbrücken," (Full-scale noise reduction experiment on two steel box-beam railroad bridges), *Der Stahlbau 47*,(12), December 1978, pp. 353-361.

Noise and vibration measurements were made on two bridges (of S-Bahn, Hamburg) before treatment, after application of partial treatment, and after application of full treatment. The latter measurements were also repeated after one year. Treatments are of three-layer visco-elastic type.

Reported noise reductions are 13 to 18 dBA (with excitation by train or tapping machine); vibration reductions are 2-3 dB greater.

Heckl, M., "Lärmminderung an Brückenbauwerken," (Noise reduction on bridge structures), *VDI-Berichte*, No. 170 (1971), pp. 43-45.

Added mass should be placed as near as possible to the excitation. In floated systems, the floating mass per unit length should be at least ten times the mass of a truck, divided by the axle distance. 30-50 cm concrete has proven useful in subways. On elevated structures, floated slabs will also radiate sound. Weight increase is at least 50%.

Resilient elements must have lower impedance than both vehicle structure and bridge structure. Static deflections of 2mm under train weight have proven useful on heavy concrete bridges, but not on steel bridges; the latter deflect more than the resilient elements.

Added damping is useful only if it provides at least a 300% damping increase. Steel bridges have loss factors of 0.005, or more, concrete bridges have about 0.02.

Reduced radiation can be achieved by including structural breaks in radiating surfaces, replacing beams by trusses, using perforated or expanded metal walkways.

Heckl, M., "Theoretische Untersuchungen über die Körperschalldämmung von elastischen Schienenelementen," (Theoretical investigations concerning vibration attenuation by elastic rail supports), *Müller-BBM GmbH*, Report No. 2402, 9 April 1969.

Presents simple model showing reduction of vibratory force acting on tunnel floor obeys

$$20 \log \left[F_o/F_1 \right] = 20 \log \left[1 + i\omega Z_1/s \right]$$

Z_1 = impedance of rail plus wheelset above elastic supports

s = spring stiffness

Improvement occurs only where $[\omega Z/s] >> 1$. Also derives relation for beams joined by elastic elements.

Japanese National Railways, "Shinkansen Noise," August 1973.

Contains some of the information summarized in August 1975 report. (Only additional significant information is noted in this abstract.)

Rail corrugations of 0.05 to 0.1 mm increased noise levels by 2-3 dBA; corrugations of 0.15 mm yielded 5-7 dBA increases. Barriers on elevated structures were found to yield 5-8 dBA reductions.

Data on variation of ground vibration with distance are also reported.

Japanese National Railways, "Shinkansen Noise," August 1975.

Noise contours in a plane perpendicular to the rail show that the noise levels from a typical (concrete) elevated structure are highest at the wheel/rail contact area.

Average noise levels measured to side of embankment differ little from those to side of elevated structure. However, ballastless steel girder structure is 10 to 15 dBA noisier than ballasted structures of either steel or concrete.

Japanese National Railways, "Shinkansen Noise (II)."

Report summarizes quantifications of noise sources and results of noise control treatment installations.

Axle box, truck frame and car body do not contribute significantly to rolling noise. Wheel/rail interaction effects are under study. Slab track generally vibrates more than ballasted track, on viaducts. Power collector noise becomes significant if wheel/rail are fully screened.

Noise level under floor and inside car typically is 7 dBA less on ballasted track than on slab track.

No correlation was found between girder depth and noise measured under girders of elevated structures.

Resilient wheels gave 1-2 dBA reduction of noise.

Tests of dampers attached to rail base and on steel girders of unballasted tracks are planned. Sound barrier walls with overhangs are being studied extensively, as well as ballast mats and undercovers for viaducts. Much noise/vibration data is reported, but construction and noise-control parameter values are not.

Damping of steel box-beam of composite girder system reduced vibration by 15 dBA, but reduced noise by only 5 dBA nearby and by less, further away. Added barriers reduced noise by about 10 dBA at all distances. Ballast mats reduced both noise and vibrations by 10 dBA. Elastomer pads between ties and ballastless steel girders were ineffective. Isolated, damped undercovers and side covers proved very effective.

On a ballastless steel girder bridge, sidewalls reduced noise by 5 dBA, indicating that running noise is more significant than that from structure.

Effects of ballast mats on ballasted bridge and of hood installation on another bridge are also reported.

Jovicic, S., "Schalltechnische Untersuchungen an Hochbahnen verschiedener Bauweisen," (Acoustical investigations on elevated railroads of various configurations), *Müller-BBM GmbH,* Report No. 3577, December 1974.

Discusses train as point source, referred to sound power from single axle(truck). Compares theoretical drop-off with distance to data in open flat terrain on embankments, in cuts, and on concrete and on steel bridges. Concrete bridges are found to make no significant noise contributions in contrast to steel bridges (where increases of up to about 15 dB are observed).

Effects of buildings on one or both sides of a noise source are discussed on the basis of image theory.

Data are given in terms of dBA; no spectra.

Keevil, W.R., "Noise and Vibration in Rapid Transit Trucks," *APTA Rapid Transit Conference,* Chicago, June 1978.

Reports the CTA had good results with ring-dampers on wheels; 8 dBA screech reduction.

New trucks, built by Wegemann Company of West Germany, have unique flexible frame and allow for inclusion of adequate primary springs. Cars with new trucks are reported to produce less wayside vibration and noise.

King, W.F.III, "On the Prediction of Wayside Noise Levels for High-Speed Railway Vehicles," *DFVLR-Institut für Turbulenzforschung,* Berlin, IB 257-77/6, N77-32846.

Deals primarily with aerodynamic noise, which is estimated to predominate potentially at speeds above 25 km/h ≈ 155 mph.

Kirschner, F., V. Salmon and S.K. Oleson, "Viscoelastic Damping for Rapid Transit Structures," *5th International Congress on Acoustics,* September 1965, Paper F31.

Scale model study on structures in anechoic chambers and excited by hammer system showed damping by added visoelastic layers to be effective for noise control. Models studied included: prestressed concrete, concrete deck on steel girder, all-steel girder.

Measurements on 79 ft. long section of full-scale concrete deck-steel box structure, excited by hammer system, showed noise reductions of 5 to 18 dB due to damping.

Koch, H.W., "Propagation of airborne sound caused by trains running at a maximum speed of 260 km/h without and with a sound protection screen," *J/Sound & Vibr. 51 (3),* pp. 389-392, 1977.

Measurements with test cars on test track at 7.5, 25, 50, 100 m from track.

2 m high barrier and 3.8 m from track centerline gave 9 dBA to 12 dBA reductions observed at 25 m.

Kurek, E-G., "Massnahmen zur Schalldämpfung an Schienenfahrzeugrädern und Schienen," (Means for reduction of noise of rail vehicle wheels and rails), *Dr.A.Stankiewicz GmbH reprint from ETR-Eisenbahntechnische Rundschau,* 1972.

Development of wheels and rails with constrained viscoelastic layer treatments. Field data (limited) show good screech reduction effectiveness.

Kurze, J.J., "Schallgedämpfte Stahlbrücken für Schienenverkehr," (Noise-controlled steel bridges for rail traffic), *Report prepared for Studiengesellschaft für Anwendungstechnik von Eisen und Stahl e.V. (Research Association for Application Technology for Iron and Steel)*, Düsseldorf, January 1973.

Summarizes and evaluates investigations sponsored by SAES for reducing noise of steel bridges. Discusses utility of elastic rail fasteners, of floated slabs, and of structural damping. Indicates importance of isolation and damping of nonloadbearing elements to reduce radiation.

SAES has sponsored work on (1) damping materials and applications, (2) special elastic rail fasteners, (3) floated concrete slabs.

Damping of a bridge part was found to yield 7-15 dB noise reduction. Elastic rail fasteners gave 12 dB less airborne noise above 500 Hz. Damped rail gave no appreciable noise reduction.

Suggests that wheel truing, damping of wheels and rails, rail grinding and acoustical barriers with absorption should also be useful. Also suggests further studies.

Kurzweil, L.G., "Prediction and Control of Noise from Railway Bridges and Tracked Transit Elevated Structures," *J.Sound and Vibr. 51(3)*, pp. 419-439, 1977.

Classifies elevated structures and ranks then in terms of sideline noise level. Summarizes noise reduction approaches and their noise reductions as reported in the literature. Also discusses analytical noise model.

Kurzweil, L.G., R. Lotz, "Prediction and Control of Noise and Vibration in Rail Transit Systems," Report No. UMTA-MA-06-0025-78-8, September 1978.

Compilation of means for assessment and control of noise and vibration in community, noise in cars and locomotive cabs, noise in stations and tunnels. Also data summary.

Lindholm, G., "Bullerdämpening av Sofielundsviadukten," (Noise reduction on Sefielund viaduct), *AB Storstockholms Lokaltrafik,* Test Report KV nr.7207, July 1972.

Measurements were made at 30 m to side of centerline of steel bridge, at 1.2 m height, for 10-car train at 50 km/h, before and after installation of rubber under wood ties. Noise reduction was about 5 dBA, with primary effect in bands above 500 Hz.

October 1973 letter by L. Bäckström to L. Wittig indicates that later installations used rubber between rail and ties with similar or better results.

Manning, J.E., D.C. Hyland, J.J. Fredberg, N. Senapati, "Noise Prediction Models for Elevated Rail Transit Structures," Report No. UMTA-MA-06-0025-75-12, August 1975.

Discusses wheel/rail interaction and radiation from rails. Presents classifications of elevated structures, then sets up Statistical Energy Analysis model for vibration prediction. Presents data measured on 3 MBTA elevated structures, compares results to predictions, and suggests noise control approaches.

Messerschmitt-Böklow-Blohm GmbH, "Abschätzung des Geräuschpegels für die Schnellbahn-Versuchsanlage in Donauried by NT-Fahrzengen," (Estimation of the noise level for the high-speed train experimental facility at Donauried, for NT vehicles), Report GBJ-Dok.Nr.: MBB-73/36., August 1973.

Estimates flow noise, including flow changes along the magnetic suspension.

Miura, S., "Theoretical Study of Mechanical Properties of Elevated Open-Floored Direct Fastened Tracks," *Quarterly Reports 17(1),* pp. 36-37, 1976.

Effect of elastic rail supports on rail natural frequency, rail ends is calculated for various axle loads and vehicle speeds. It is concluded that rubber rail supports can work even for 260 km/h speeds of the Shinkansen.

Miyaji, K., "Noise Control on Shinkansen," *Railway Gazette International*, pp.249-251, July 1973.

General discussion of noise levels and noise reduction approaches.

Nimura, T. and M. Ebata, "Analysis and Estimation of the High-Speed Railway (Shinkansen) Noise and Its Control by Barrier," Joint Meeting of the Acoustical Societies of America and Japan, Paper DDD3, November 1978

Shows noise spectra for contributions from various car components, track, and underside of viaduct slab.

Indicates effects of various barriers and describes two-dimensional model used to study effectivenesses of barrier designs.

Nimura, T., M. Ebata, T. Sone, S. Kono, and T. Takahashi, "Estimation and Consideration of the Shinkansen Noise for a Newly Established Line," (No publication information indicated, but contents are similar to Inter-Noise 76 paper by Nimura, Ebata and Takahashi).

Presents estimates for contributions of various noise sources. Indicates that "under-car" noise predominates if no barriers are used, but noise radiated from (concrete slab) viaduct becomes predominant in presence of barriers.

Shows vibration distribution across viaduct. Suggests preferability of ballasted over slab track and indicates improvements available from use of ballast mat.

Nimura, T, M. Ebata and T. Takahashi, "Estimation and Consideration of the Shinkansen Noise for a Newly-Established Line (Near Tokoku Line)," *Inter-Noise 76*, pp. 197-202, April 1976.

Same data as in paper by Nimura, Ebata, Sone, Kono and Takahashi.

Oleson, S.K., "Aerial Structure Noise Measurements," *Stanford Research Institute*, Technical Report, Contract Z823 (SRI Project PH-4579) August 1965.

Noise measurements were made near the Walnut Creek structure (steel box girder with single concrete deck supporting two tracks) and Bancroft structure (steel box girders supporting separate single-track decks.) Test car provided excitation, avg 48 mph at Walnut Creek, 51 mph at Bancroft.

At 10 ft from structures, Walnut Creek was 4 to 10 dBA noisier; at 70 ft, Walnut Creek was 2-3 dBA (at most) noisier. Spectra indicate that Walnut Creek exceeds Bancroft noise primarily in region below 500 Hz.

Report also provides an estimate of the required damping of the steel structure.

ORE, C137/RP5/E, "Question C 137; Railway Noise," Report No. 5, October 1977.

Survey of information on generation and propagation of railway noise at free-field, cuttings, embankment sites, for different types of traffic and track structures.

Standard measurement distance is 25 m. dBA levels reported by various sources vary as n log (speed), with n between 20 and 40. Variation may be greater for rapid transit systems. Rail corrugations can produce increases up to 15 dBA. Noise contours and levels are summarized.

ORE, D87/RP6/E, "Question D 87 - Unconventional Tracks. Noise and Vibration from Unconventional Tracks: Experiments at Radcliffe-on-Trent 1969 and 1970," Report No. 6. April 1973.

Measurements were made on 6 types of ballastless track, one section of ballasted track on concrete slab, one section of BR track on concrete ties and ballast. Noise was measured (at grade) at 4m and 7.5m from track; also under vehicles. Vibrations were measured on track structure and on pile in the ground. Noise reductions were found to be negligible, ground vibrations in 25 to 315 Hz range were reduced by 10 to 30 dB. No pad stiffness data are given, but a stiffness effect is indicated.

ORE D87/RP7/E, "Question D87 – Unconventional tracks. Test track at Radcliffe-on-Trent: Construction and Running Experience," Report No. 7, April 1974.

No noise/vibration information. Test lengths showed no significant deterioration in four years of normal service.

ORE D87/RP8/E, "Question D87 – Unconventional tracks. Laboratory and site measurements of stiffness and damping of selective types of direct fixing for tracks without ballast," Report No. 8, April 1973.

Field measurements were made by observing strains in rail and deflections under axle of test locomotive (at various speeds). Also, accelerometer records were made for impulsive loading due to single wheel dropping onto rail from 12 to 24 mm wedge. Laboratory measurements on fastener assemblies were made with electrodynamic shaker driving large concrete mass; fastener preloaded realistically by large spring - data up to 1 K hz.

Most data is for frequencies below 30 Hz. Higher-frequency measurements not well exploited.

ORE D105/RP 1/E, "Question D105; Noise Abatement on Bridges," Report No. 1, October 1966.

The report presents one-third octave band noise spectra for 16 European bridges, gives descriptions and photos of the bridges, and rail fastening details.

Excitation: Single locomotive, 16 to 17 ton axle load, coasting at 60 km/h (some measurements also at 80, 40, and 20 km/h).

Microphone Locations:

1. On bridge - 2m from center of track, 2m above rail
2. 25m lateral - 1.6m above ground
3. Below bridge - 1.6m above ground
4. Open section - 2m from track center, 2m above rail
5. Open section - 25m lateral, 1.6m above ground

Data is presented with no analysis.

Reference is made to simultaneous vibration measurements which are not reported here.

Extracted results are tabulated below:

BRIDGE LOCATION	ADMINI-STRATION	DESCRIPTION	dBA at 25m Bridge	At Grade	Difference
Valserstrasse	DB	Steel box beam, steel floor plate, direct fixation	92	-	-
Emmerfluss	DB	" " " "	87.5	-	-
Giesingerbergstrasse	DB	Steel box beam, steel floor plate, tie & ballast	77	77	0
Amalienburgstrasse	DB	(a) Solid web beam trough, steel floor, direct fix'n	92	75	17
		(b) Same, but tie & ballast	79.5	73	6.5
Verdistrasse	DB	Solid web beam trough, steel floor, tie&ballast	78	75.5	0.5
Pilgersheimerstrasse	DB	Trusswork, wood tie deck	81	77	4
Lammenschansweg	NS	Solid web beams, steel floor, direct fixation	84	74	10
Stamweg	NS	" " " "	87	79	8
Amsterdam-Rijnkanaal	NS	Truss, carrier beams, ties	85	75	10
Zwolle-Ijselkanaal	NS	Solid web, carrier beams, direct fixation	82	79	3
Emmefluss I	CFF	Solid web, carrier beams, wood ties	86	75	11
Emmefluss II	CFF	Steel beam trough, concrete deck, ties & ballast	74	75	-1
Anizan Cavillon	SCNF	Plate beams, I-beam carriers, wood ties	88	71.5	16.5
Réservoir Seine	SCNF	Steel beam trough, concrete floor, tie & ballast	73.5	77	-3.5
Sambrefluss	SCNF	Steel beam trough, carriers, wood ties	85	-	-

ORE D105/RP 2/E, "Question D105; Noise Abatement on Bridges, Noise Measurements on the Rosenheim Bridge," Report No. 2, April 1969.

Reports vibration (5 positions) and sound measurements (6 positions) for the passage of a diesel locomotive (16 Mp axle load) coasting over an experimental bridge especially built for these experiments. Train speeds: 20, 40, and 60 km/hr.

3 different track conditions were investigated:

a) direct rail laying, with a 15 mm rubber pad inserted. (Rubber pads are short-circuited.)

b) Same as a) but continuous rubber pad

c) "Elastomer-Tie," complete structural separation of rail and steel deck by rubber mounts (no short circuit) that give 1.5 mm static deflection under axle load.

The same rail fastening changes were implemented also on level ballast track, and rail vibration and sideway noise level changes recorded.

Observed speed dependence:

$$\Delta L_A = 30 \log \left[V_2 / V_1 \right]$$

In spite of the spectacularly unsuccessful results of all the noise control measures attempted (which would have been obvious if some time would have been spent to design the experiment on theoretical foundations), this report describes one of the best documented airborne and structureborne noise measurements conducted on an elevated structure. However, there is a lack of geometry information and dynamic properties data on the elastic materials used.

ORE D105/RP3/E, "Question D105. Noise Abatement on Bridges," Report No. 3 - Final Report, April 1971.

Summarizes noise measurements on 20 bridges and characterizes these by type and noise level at 25m. Draws some conclusions concerning mechanisms. Reports noise and vibration data on 2 similar bridges with different track supports and on another bridge before and after rebuilding. Includes extensive appendix by M.Heckl on theoretical estimation of noise reduction due to elastic rail fasteners on steel bridges.

ORE E82/RP 4/E, "Question E82 - Noise Abatement - (Final Report) Measuring principles for noise abatement in the field of railway transportation." October 1969, Report No. 4.

Indicates preferred units, instrumentation, measurement positions.

Microphone positions for bridges:

1) At middle of bridge, 1.2m above rails, 7.5 to side of track centerline
2) In free field, 25m from track C.L., 1.2m above ground level, as near as possible to bridge
3) Under bridge, at track C.L., 2m below undersurface of deck
4) In free field on open track (away from bridge) at 7.5m and 25m from track C.L., at two heights: 1.2 and 3.5m above rail level

Accelerometers for bridges (vertical only):

1) At middle of bridge, on web of rail, at a tie (or possibly on rail foot)
2) Same, on rail foot between two ties
3) As above (both), but away from bridge
4) On bridge deck, in C.L. of track
5) At middle of metal surface of parapet or on the deck, in case of large vibration-transmitting surfaces.

Excitation (bridges): diesel or electric locomotive, with 18 ton axle-load, coasting at 60 km/h.

Paolillo, A., "Preliminary Report of Noise Measurements at Public School 98; 212th Street, Manhattan," *New York City Transit Authority,* October 27, 1978.

Reports 3 to 5 dB noise reduction achieved from installation of 1-inch thick butyl rubber pads under rails of elevated structure.

Noise measurements were made at four outdoor locations and inside a school room. Accelerometers were mounted on the rail (at a joint), on the girder (below the joint) and on the girder web.

Paulson, J.N., M.L. Silver, T.B. Belytschko, "Dynamic Three-Dimensional Finite Element Analysis of Steel Transportation Structures," *DOT-TST-76-46,* December 1975.

Beam-element finite element model was developed and applied to typical 50 ft span section of CTA Douglas Park elevated line, for which field measurement data were available. Calculations up to 800 Hz for steady sinusoidal point loading showed major resonance peaks similar to measured data.

Remington, P.J., L.E. Wittig, R.L. Bronsdon, "A Prediction of Noise Reduction in Urban Rail Elevated Structures," *Bolt Beranek and Newman Report No. 4347,* March 1980.

Remington, P.J., L.E. Wittig, M.M. Myles, K.M. Eldred, C.E. Hanson "Reduction of Noise Generated by Rapid Transit Cars," *Bolt Beranek and Newman Report No. 4059,* March 1979.

SNCF "Mesures de Buit sur les Ponts. Ponts de La Varenne sur la Marne," (Measurement of Noise on Bridges. The Bridges of La Varenne on the Marne), Essai 466, ORE D105, 1979.

Comparison of two bridges of same span, located near each other and on the same supports; one of metal deck, the other of concrete/metal deck configuration. Compared to wood-tie on ballast at-grade noise, metal bridge made 8-10 dBA more noise and concrete bridge made 5-7 dBA more noise (for locomotive coast-by at 60 km/h).

1/3 OB spectra of noise and accelerations are given. Metal deck has rail on wood ties; concrete deck has rail directly fastened atop rubber plates.

SNCF Report (Preliminary) 925, "Bruit sur les Ponts. ORE C137, UIC Ponts," (Noise on Bridges), October 1978.

No text. Figures, photos, charts, sketches, show measurement locations, bridge structures, pass-by noise histories and spectra for bridges of various structural types and nearby at-grade areas. No noise reduction data indicated.

Results summary is given in table below:

BRIDGE LOCATION	DESCRIPTION	dBA at 25m (80 to 90 Km/h)		
		BRIDGE	AT GRADE	DIFFERENCE
Conflans	Steel beam trough, concrete floor, ties on ballast	82.5-83.5	77-78.5	-5 to -5.5
Cambo	" " "	86.5	85.5	-1
LeLuy - old	Lattice girder, steel I-beam carrier, open tie deck	98.5	87.5	11
new	Steel beams, concrete slab, ties on ballast	89.5	85.5	4
Empalot	Steel beams, concrete deck, ties on ballast	86-88	88.5-89	1-2.5
Ville-pinte	Concrete trough, ties on ballast	77.5-81	80-81.5	0.5-2.5

SCNF, "Code de Points de Mesure," (Standard Measurement Points), *Direction du Materiel, Departement Essais, Section Acoustique,* April 1974, October 1977.

Lists standard microphone positions in car interiors, microphone and accelerometer positions on car exteriors, microphone positions at wayside in free field, microphone and accelerometer positions in and near propulsion cars. Also lists microphone positions for evaluation of noise transmission into cars and microphone positions to be used on and near bridges.

Sato, Y. and T. Usami, "Development of Track Ballast Mat," *Permanent Way 15 (3),* No. 56, pp.1-10, March 1974.

Discusses development of ballast mat, installation, and field tests on Shinkansen elevated structures. Reports structure vibration reduction by 45% and wayside noise reduction of 4 phons. Also studies aging of mat and breakage of ballast.

Same data as paper by Sato, Usami, Satoh in Quarterly Reports 15 (3) 1974, pp.125-130.

Sato, Y., T. Usami, Y. Satoh, "Development of "Ballast-Mat"," *Quarterly Reports 15 (3),* pp. 125-130, 1974.

Tests with 2mm mats of ground-up used automobile tires (stiffness about 45 Kg/cm^3) placed under gravel ballast on Shinkansen elevated structures showed that ballast mats resulted in 6 dB reduction of vibrations of elevated structures and of about 8 dB of noise at the wayside.

Ballast mats were found to be practical and durable.

Satoh, Y., S. Umekubo, G. Hirata, M. Arai, T. Chino, K. Tsukamoto, T. Sawada, "Resilient Rail," *Quarterly Reports 13,* No. 2, pp. 76-84, 1972.

Development of rail supported between continuous rubber strips. Stress and deflection calculations (beams joined by elastic spring).

Comparison measurements between resilient and conventional rail on steel girder bridge show 5-10 dB noise reduction in 1 to 8 Khz octave bands, but no noise reduction below 500 Hz and no more than 5 dBA overall reduction.

Girder vibration reductions were 5-15 dB over entire frequency range - indicating that wheel/rail noise is a dominant part of total noise.

Rubber durability results are also provided.

Schieb, A., "Darstellung und Definition der verschiedenen Oberbauarten," (Presentation and Definition of the Various Track Constructions), *VDI Berichte* Nr. 217, 1974.

This paper gives an excellent overview of 35 different track structures. It points out that the traditional ballast tie system requires too much maintenance and the new experimental track systems (which acousticians think were developed solely to provide lower noise and vibration levels) were mostly conceived to yield a "permanent way" instead of "fine clockwork" which must be continuously regulated and adjusted. It provides details and pictures of a large number of slab tracks and lists relevant reference sources.

Schommer, A. and G. Volberg, "Untersuchung des Geräuschverhaltens von Stahlbrücken," (Investigation of the Noise Properties of Steel Bridges), *Müller-BBM*, Report No. 5121/2, 16 February 1977.

Summarizes noise level data on 26 different steel bridges of various types, largely taken from the literature. Cites data on noise reduction methods: added sand, mass/damping layers, added wood ties on ballast, stiffening of thin sheets, added barriers/covers, elastic rail supports, damping layers.

Suggests further work on girder type bridges: extensive vibration measurements to identify primary radiating surfaces; then full-scale studies of a) reduced radiating areas, b) covers, c) perforated structural components, d) elastic rail supports. Also suggest studying effect of concrete deck addition.

Shipley, R.L. and H.J. Saurenman, "In-Service Performance and Costs of Methods to Control Urban Rail System Noise - Initial Test Series Report," *U.S. Department of Transportation*, Report No. UMTA-MA-06-0025-78-7, August 1978.

Not fully completed test program carried out on SEPTA showed that propulsion equipment noise is only 5 dBA below wheel-rail noise, so that wheel/rail changes can result only in small amounts of noise reduction.

Rail grinding reduced roar noise by 2 to 4 dBA, wheel truing by 1 to 2 dBA, resilient wheels by 0 to 4 dBA - but effects are not cumulative. Rail grinding increased screech, resilient wheels reduced its incidence. In-service use increased noise towards levels present before grinding and truing.

Damped wheels were not studied.

Costs associated with grinding, truing, and resilient wheels are reported.

Saurenman, H.J., "Vibration and Noise Control Recommendations for Aerial Structures for the Metropolitan Atlanta Rapid Transit Authority," *Wilson, Ihrig & Associates,Inc.*, September 1975.

Reviews BART data results and makes noise projections for MARTA. Discusses damping of steel box beams of composite structure and use of sound barrier walls.

Saurenman, H.J., "In-Service Performance and Costs of Methods to Control Urban Rail System Noise - Second Test Series Report," *Report No. UMTA-MA-06-0099-79-4*, October 1979.

Measurements were made on SEPTA's Maket-Frankford Line to evaluate noise reductions obtained from resilient wheels, damped wheels, wheel truing, rail grinding. Propulsion equipment noise was also evaluated. Test tracks include tangent welded and jointed rail on ballasted elevated structure, curve at grade, and tangent welded and jointed rail in subway. Measurements include noise in cars and at wayside, ground vibrations.

Resilient wheels reduced ground vibrations by 5 to 10 dB above 16 Hz. Worn standard wheel gave 3 to 10 dB higher vibration levels than trued wheel over most of frequency range. Rail grinding reduced vibrations by 3-8 dB.

Analysis of results re speed-dependence of noise.

Saurenman, H.J, R.L. Shipley, and G.P. Wilson, "In-Service Performance and Costs of Methods to Control Urban Rail System Noise - Final Report," *Report No. UMTA-MA-06-0099-80-1*, December 1979.

Summarizes results given in previous reports and compares them to data from other systems. Presents economic analysis.

Schultz, T.J., "Noise Rating Criteria for Elevated Rapid Transit Structures," *Report No. UMTA-MA-06-0099-79-3*, May 1979.

Shoff, D.A., *et al*, "Design Requirements of Direct Fixation Fasteners," *APTA Rapid Transit Conference, Chicago*, 8 June 1978.

Ballast track for subways and elevated structures is undesirable, because it requires maintenance to avoid debris, dirt, mud clogging, which is difficult because of the restricted working room and the frequency of train passages. Ballast also requires larger and therefore heavier tunnel structures which are more costly.

Design requirements for direct fixation devices for rail are typically:

- Lateral Rail and Fastener Stability (to resist gauge widening, especially on curves) 4000 lb.

- Lateral Adjustment (to compensate for construction tolerances line and gauge) ± 2 in. should be provided

- Vertical Stability - Live load, pull-out (or uplift) provided by wave propagation in the rail

  - 1/8 in. downward deflection for axle load should not be exceeded

  - Vertical stiffness should be between 140,000 lb/in. and 160,000 lb/in.

- Longitudinal Rail Restraint - Conflict between track designer (infinite restraint) and structural engineer (no restraint to avoid stress concentrations); strong restraint requires substantial supporting structure.

  Rail brake and cold temperatures require large gap. Train can negotiate *2 in. to 3 in. gap* safely.

- Simplicity, uniformity and interchangeability are "musts".

- General fastener size 10 in. x 20 in. by 1-1/2 in. thick; spacing 30 in. to 36 in.

Stankiewicz, A., "Geräuschdämpfende Beläge und Elemente für Fahrzeuge und Maschinen," (Noise-reducing layers and elements for vehicles and machines), *VDI-Zeitschrift Nrs 15-16*, 1977.

Brief discussion of vibration isolation. General discussion of viscoelastic damping layers, materials, damping measurements.

Stüber, C., *et al*, "Geräuschmessungen an der Überführung Amalienburg-Strasse in München - Obermenzing," (Noise measurements on the Amalienburg Street Viaduct in Munich-Obermenzing), *Deutsche Bundesbahn Versuchsanstalt München*, Reports 155G/1965, 1566/1965, 157G/1965, January 1966.

Measurements of noise at 2m and 25m to side of the bridge and at similar locations at nearby embankment. Also vibration measurements at rail foot on bridge and on embankment and on main girder and cover plate of bridge. Data taken with rails directly fastened to top steel plate (initial configuration) and later when rail on wood ties atop ballast was introduced.

Gives spectra for each measurement location, for 4 speeds (20, 40, 60, 80 km/h) of test locomotive.

At 60 km/h, tie-on-ballast resulted in noise reductions of 6 to 13.5 dBA at various measurement locations, as well as appreciable (but different) reductions in structural vibrations - however, the rail vibrations increased.

Stüber, C., "Geräuschentwicklung bei Befahren stählernen Eisenbahnbrücken und Abwehrmassnahmen," (Noise Generation by Train Passages over Steel Railroad Bridges and Noise Control Measures), *VDI, Berichte*, Nr 68, 97-101, 1963.

The paper reports on various noise control measures that were tried, including:

- layer of sand over the deck plate (6.2 cm);
- tar layer, 2.6 kg/m^2, 0.6 cm thick;
- resilient skin, 2mm steel plate, 20mm cork, 30mm glass fiber;
- ballast & wooden ties;

Data is given on speed dependence of radiated level; shows no dependence below 250 Hz; 10 dB/speed doubling at higher frequencies.

Stüber, C., "Schienenverkehrslärm und Lärm gewerblicher DB-Anlagen," (Rail traffic noise and noise of industrial facilities of the DB), *Die Bundesbahn*, 13/14, pp.821-826, 1972.

Includes bridge noise spectra with and without ties and ballast, compared to at-grade spectra.

Also shows tunnel vibration spectra for floor, rail footing, wall, and wall of nearby building basement.

Also discusses interior noise, effects of muffler and enclosure.

Stüber, C., "Schienenverkehrslärm," (Rail Traffic Noise), *Kampf dem Lärm* 21, Heft 3, pp. 71-75, 1974.

General summary of exterior and interior noise.

Exterior noise variation in dBA with speed at 25, 50, 100 meters. Concrete ties about 2 dBA quieter than wood ties. Also, wet rails are 2 dBA quieter than dry. Removal of gravel ballast and use of concrete floor plate adds 4 dBA.

Concrete bridge with ballast makes same noise as at-grade track. Steel bridge with directly fastened rail, without ballast, is 17 dBA louder. Addition of ballast reduced noise by 12 dBA.
21 bridges fall within a 21 dBA interval. Truss bridge with wood ties is up to 10 dBA noisier than at-grade track.

Stüber, C., "Versuche zur körperschalldämmenden Lagerung von Eisenbahnschienen," (Experiments with Structureborne Noise Attenuating Track Support Structures), *VDI-Berichte*, Nr. 113, pp. 143-50.

Noise measurements (airborne) made near bridge with directly fastened rail and with rail on wood ties and ballast. The latter was found to be 8 to 13 dBA quieter and to result in correspondingly reduced vibrations of the steel deck.

Stüber, C., "Beispiele zur Lärmabwehr bei der Deutschen Bundesbahn," (Examples of Noise Control in the German Railway), *Lärmbekämpfung 9* (1/1965) and (2/3), 1965.

Exterior noise: Examples of noise spectra. Dependence of L_A on speed. Rail corrugations. Wheel radiation.

Comparison of noise on box-bridge with at-grade noise. 6.2 cm of sand on bridge deck gave 7 dB(B) reduction.

Interior noise: double walls. L_A variation with speed.

Stüber, C., "Schienenverkehrslärm" (Rail Traffic Noise), *Der Ärtzliche Dienst DB*, Heft 9/10, pp. 143-150, September/October 1976.

General summary of exterior and interior noise.

Includes dBA data on pass-by noise of various vehicles on bridges and at grade.

Stüber, C., G. Hauck, L. Willenbrink, "Innen- und Aussengeräusch von Schienenfahrzeugen der Deutschen Bundesbahn" (Interior and exterior noise of rail vehicles of the German railway), *Lärmbekämpfung 15* Heft 2/3, pp. 43-47, June 1971.

Some spectra of bridge noise with and without ballast, compared to at-grade.

Vibration spectra of subway and train tunnels, nearby housewalls.

Swanson, R.C., D.B. Thrasher, H.F. Neff, "Rapid Transit Train Noise and Vibration on Aerial Structures: The Influence of Rail Fasteners," *The B.F. Goodrich Company Research Center,* Technical Note, November 15, 1966.

Measurements made at BART test track on rail fasteners supplied by (1) Goodrich, (2) General Tire & Rubber Company, (3) The Lockspike Co., Ltd.: "Pandrol" type and (4) the existing standard one. Also studied effect of acoustical barrier.

No great differences were found in performances of various fasteners relative to noise. Barrier gave up to 10 dB reduction above 300 Hz, but only affects train noise; total reduction ranged from 0 to 4 dB because of significant structural noise contribution.

Tatematsu, T., "Technological Development Relating to Measures Against Sources of Noise," *Permanent Way 17,* No. 63-64, pp. 11-25, 1976.

Noise of Shinkansen on concrete elevated structures appear to be strongest in the plane of the rails. Barriers help here.

Attenuation with distance is about 3 phons per distance doubling up to 100m, 4 to 5 between 100 and 400m, 6 phons/dd beyond 400m.

Indicates ranges of noise levels at wayside obtained before and after installation of various treatments. Reviews all conceivable noise control treatments and summarizes JNR's test plans.

Tocci, G., J. Fredberg, N. Senapati, "Measurement and analysis of noise radiation from a slab on steel beam rapid transit structure," *Internoise '74,* 253-56, October 1974.

Noise measured near the train and near the structure is used to determine car and bridge contributions to wayside levels. Essentially takes wheels as point sources with $\cos^2$ directivity and bridge web as line source.

Towers, D.A., "Noise Impact Inventory of Elevated Structures in U.S. Urban Rail Rapid Transit Systems," *Bolt Beranek and Newman Report No. 4239,* January 1980.

Towers, D.A. and C.E. Hanson, "Assessment or Vibrations in Buildings Near the Metropolitan Dade County Rapid Transit System: Coulter Electronics *Bolt Beranek and Newman Report No. 4130,* June 1979.

Ground vibration data obtained from measurements near PATCO elevated structures is applied to estimate vibrations near new Miami system. Criteria for sensitive equipment at Coulter Electronics are suggested on basis of measurements of current environments there. Estimates are compared with criteria; no serious problems are anticipated.

Ulrich, A. and T. Van den Brulle, "Geräuschmessungen am Transrapid TR04," (Sound measurements on the Transrapid TR04), *Messerschmitt-Bölkow-Blohm,* Report No. TN-BT22-16/75, 8 August 1975.

The TR04 is a magnetically levitated, LIM-driven vehicle. Time-histories of pass-by noise (in dBA) are reported at various speeds, with and without LIM operation. About 80 dBA are measured at 100 km/hr at 15m. At high speeds, data approach V^6 dependence. Radiation from support structure is responsible for noise due to LIM.

van Os, G.J., "Lawaaibestrijding bij Rotterdamse Metro VI. - Onderzoek viaducten," (Noise control the the Rotterdam Metro - Elevated structures investigation), *Technisch Physische Dienst T.N.O en T.H.,* Report No. 62. 322 VI, 15 March 1965.

Measurements at Rijswijk: Excitation: 17.5 ton streetcar at 40 km/h. Bridge is 70cm thick concrete; rails fastened directly to steel or wood ties. On earth berm, rails rest on sand ballast. Bridge is up to 14 dB noisier in 250 to 1000 Hz range.

Measurements at Franselaan. Excitation: Rail vehicle and freight car. Earth berm with gravel ballast, wood ties, compared to bridge with rail on cork-rubber plates. Resiliently supported rail and resilient wheels give some increase in rail vibrations.

Measurements at Delft. Excitation: freight car at 8 km/h; steel wheels. Rails on cork-rubber plates in one case, on rubber isolators in the other. Rubber isolators reduce structure vibrations by 20 dB, increase rail vibration slightly; noise reduction 2 to 4 dBA.

Measurements at Spaanse Bocht. Excitation: Electric streetcar with wheels that have rubber inside the rim. First bridge has usual cork-rubber plates and also a softer type. Second bridge has gravel ballast. Softer cork-rubber plates turn out to be better by 2-3 dBA. Ballast is useful only for higher frequencies.

Recommendation: Use elastic rail fasteners.

van Os, G.J., "Lawaaibestrijding bij de Rotterdamse Metro (I)," (Noise control in the Rotterdam Metro - I), *Technische Physische Dienst T.N.O. en T.H.*, rapport no. 62.322 - I, June 1963.

General lines of investigation:

A. Establishment of existing conditions

B. How much noise does conventional public transport make?

C. Metro on elevated structure as noise source - mentions importance of understanding noise mechanisms, which depend on structural features.

D. Conceptual noise reduction means

E. Experiments concerning means

Mentions experiments on shielding of wheel and rail, viscoelastic damping of rail.

Measurements were made on several viaducts:

With wheels having rubber-isolated rims, up to 12 dB more noise was observed. Unisolated wheels on cork-rubber plates increased noise 10 dB. Concl: certain changes may cause noise problems. Soft rail mounts (as soft as possible) reduce noise by 20 dB. Wheel flats gave increase of 10 dB or more.

Isolated wheels on viaduct increase mid-frequency noise (vs. at grade); rigid wheels result in increase at low frequencies (≈125 Hz).

Replacement of stiff cork-rubber plates by soft rubber plates on viaduct reduces vibrations by 20 dB, but noise *under* viaduct by less – due to direct radiation from car.

Venema, T. and M.L. Silver, "Field Measurements of the Vibration Properties of Elevated Rapid Transit Structures," *Report No. DOT-TST-75-43*, December 1974.

Measurements on several Chicago elevated structures. Peak accelerations on various structural components are reported, together with "relative amplitude spectra" (power spectral densities).

Volberg, G., "Luft - und Körperschallmessungan an schallgedämpften Stahlbrücken." (Measurements of airborne and structureborne sound on steel bridges with noise reduction means), *Müller-BBM GMBH Paper*, 30 June 1977.

Two steel-box bridges in Hamburg were provided with constrained-layer damping; initially only some surfaces were covered with treatment, later all of them. Measurements were made with excitation provided by a train and also with excitation by a hammer system.

Measured results agree reasonably with predictions made on basis of earlier model study.

After one year, noise did not change.

Volberg, G., "Untersuchungen des Geräuschverhaltens von Schnellbahnen in Hochprofil-Konstruktion," (Investigations of the noise properties of high-speed trains on elevated structures), *Müller-BBM, GmbH,* Report 4737, May 1976.

This report deals with evaluation of data from the literature and from measurements made on a model for the purpose of predicting the noise from a magnetically suspended train. Field data obtained for such a test train are also reported.

von Meier, A., "Beperking van geluidhinder veroorzaakt door de Zoetermeerlijn, bouwfase 1-B," (Avoidance of noise annoyance caused by the Zoetermeer Line, building phase 1-B), *Melzer & Partners, Report No. M.ZOE. 72.1.6,* 21 January 1975.

Discusses means for environmental noise prediction, beginning with subjective effects (use of dBA), energy-equivalent levels (L_{eq}). Criteria: 2 car train at 60 km/h may produce no more than 80 dBA at 25m (measured according to VDI 2562 and DIN 45637). At 25m, vibration velocity level must not exceed 65 dB in each octave band from 31.5 to 500 Hz. Discusses noise control possibilities: wheels, skirts, rail maintenance, elastic rail fasteners, barriers under viaducts and at the side. Suggests criteria for various type of building usages.

Willenbrink, L., "Ergebnisse schalltechnischer Messungen der Deutschen Bundesbahn an verschiedenen Oberbauten," (The results of noise measurements of the German Federal Railways on various tracks), *VDI-Berichte,* Nr 217, 25-29, 1974.

The author shows that the scatter in vibration measurements, even if performed under very favorable conditions is very large.

Vibration measurements at 7 points 20m apart and spaced the same distance from the track showed a scatter of 10 dB. This was in spite of simultaneous recording with a 7 track tape recorder of the same passage of a locomotive. Similar scatter was observed in measuring vibration in subway tunnels.

From the data presented, one can conclude that:

No valid comparison of track constructions can be made if vibration is measured only at one section; an average measurement at a large number of similar locations is necessary to make any valid comparison.

This unfortunate fact substantially increases the cost of field measurements. However, if one cannot afford to develop a statistical data base, one cannot claim to make valid comparisons.

Wilson, G.P., "Aerial Structure Noise and Vibration Measurements," Wilson, Ihrig & Associates, Inc., *Technical Report for Parsons Brinckerhoff-Tudor-Bechtel, Contract 3Z 4966,* October 1966.

Results of measurements at aerial structure section of test track of BART, to compare effects of different rail fasteners on wayside noise and to evaluate acoustic parapet. Three microphone positions and two accelerometers (one on rail, one on track bed at center of beam span).

Noise measurements revealed up to 5 dBA difference between fasteners; corresponding beam vibration levels were somewhat greater; rail vibrated less for quieter fasteners. Parapet gave 11 dBA reduction at 50 ft.

Wilson, G.P., "Aerial Structure Noise for the Washington Metropolitan Area Transit Authority Metro System," *Wilson, Ihrig & Associates, Inc.,* June 1972.

Presents predictions for WMATA structures, largely on basis of (unreported - at least here) data obtained on BART: resilient fasteners on concrete deck give 10 dB reduction, damping applied to girders reduces vibrations by 4-12 dB and noise by 5 to 10 dB; rail grinding can make 8 dBA difference.

Yorino, T., "Effect and Standard Measures of Railway Noise," *Permanent Way 17*, No. 63-64, pp. 1-10, 1976.

Discusses Japanese legislation relative to noise of Shinkansen trains. Cites expected effects of noise control measures:

Barriers on embankment - 8 dBA reduction
Barriers on viaduct with ballast - 8 dBA
Barriers and bottom covers on steel elevated structures - 12 dBA
(all measured at 1.2m above ground, 25m from tracks)

Zboralski, D., "Die Lärmabwehr bei den europäischen Eisenbahnen," (Noise control in the European Railroads), *Die Bundesbahn, Nr.6*, 1979.

Summarizes how ORE operates and discusses how ORE has addressed Question C-137 "Noise Control in Railroads" - including: (1) noise propagation, including from bridges, (2) noise reduction in older systems, noise of trackwork machinery, (3) noise at curves and from braking, (4) noise generation by wheel/rail interaction, (5) measures for reduction of rolling noise. The following will also be considered until 1981: (1) criteria for noise and vibration exposure of railroad personnel, (2) effectiveness of skirts, (3) comparison of various types of bridges, (4) environmental noise from trackwork machines, (5) wheel/rail interaction noise, (6) phenomena causing rail corrugations with various brake shoe types, (7) effectiveness of noise-controlled wheel sets.

Indicates that rail noise is less bothersome than other traffic noise, as found from many surveys. Summarizes (lists) noise control laws/regulations of about a dozen countries.

Discusses noise propagation, effects of corrugations, of speed. Summarizes effects of noise barrier walls, skirts around propulsion gear, wheel and rail damping. Indicates guidelines for noise control on older equipment.

APPENDIX E

REPORT OF NEW TECHNOLOGY

This report is a discussion of the mechanisms responsible for the generation of wayside noise from elevated structures, noise-control concepts, and the effectiveness of noise-control means reported in technical literature.

For the first time elevated urban rail transit structures have been classified in terms of their noise-radiating components. The noise control means that are most suitable for the various major classes of structures are indicated. In particular, noise reduction results achieved on a MARTA structure as a result of damping and adding a barrier, and reductions on an NYCTA structure resulting from installation of resilient rail fasteners, are presented.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1981--700-663--310