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Highway Noise Criteria Study: Relations Among Frequency Rating Procedures

ERRATA:

NBS Technical Note 1113-3, Highway Noise Criteria Study: Relations Among Frequency Rating Procedures by Daniel R. Flynn and Simone L. Yaniv

1. Change line 4, last paragraph, page 16 to read:

ν_i', and ν_i that would make this expression fit the empirically-observed values

2. Change lines 11 and 12, first paragraph, page 17 to read:

change of sound intensity with distance; similarly $\sum_j (D_o/D_j)^{\nu_i'}$ goes to $(D_o/D_j)^{\nu_i'}$, where the prime indicates that ν_i' may differ from ν_i,

3. Change equation (14), page 18 to read:

$$M_o = 10 \log (\alpha_1'/\alpha_1), \tag{14}$$

4. Change equation (15), page 18 to read:

$$M_1 = 10 (\beta_1' - \beta_1), \tag{15}$$

5. Change equation (16), page 18 to read:

$$M_2 = -10 (\nu_1' - \nu_1). \tag{16}$$

NATIONAL BUREAU OF STANDARDS

Highway Noise Criteria Study: Relations Among Frequency Rating Procedures

NBS technical note

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Abstract

A series of calculations was performed to ascertain how well one frequency-weighted rating, such as weighted sound level, loudness level, or perceived noise level, may be predicted from another such rating. A total of 103 average sound level spectra, measured at several distances from different types of highways, were used in these calculations. It was found that knowing a single noise rating, such as the A-weighted sound level, enables one to predict other outdoor ratings in this set of 103 spectra with a standard deviation of the order of 1 to 2 dB. If, in addition, traffic speed and mix and the distance to the highway are taken into account, these standard deviations can be reduced to 0.5 to 1 dB, depending upon the particular noise rating of interest. Equations are given for predicting one rating from another; the associated standard deviations are presented as a measure of how well any given rating can be predicted from a single measured, or otherwise known, noise rating. It is concluded that it is not very critical which frequency-weighting procedure is used in conjunction with highway noise criteria since one descriptor can be predicted from another with a rather small statistical uncertainty. Thus, if human response criteria, or stimulus-response relationships, have been developed in terms of one frequency-weighting procedure, these may be translated into equivalent criteria expressed in terms of a metric that is easier to measure or predict.

Key words: acoustics; environmental pollution; highway noise, motor vehicle noise; noise; noise control; sound; traffic noise; transportation noise.

Table of Contents

	Page
1. INTRODUCTION	1
2. TRAFFIC NOISE SPECTRA	2
3. NOISE DESCRIPTORS	8
4. ANALYSIS	9
4.1 Additive Constant	11
4.2 Functional Relationship Between Noise Ratings	14
5. REFERENCES	29
APPENDIX A. LITERATURE ON TRAFFIC NOISE SPECTRA	31
A.1 Literature Data	31
A.2 Data from Present Study	42
A.3 References	46
APPENDIX B. EQUIVALENT LANE CONCEPT	47

List of Tables

Table 1.	Description of sites used for recordings of actual-traffic sounds.	3
Table 2.	Sites, dates, times, and traffic speeds for actual-traffic noise recordings.	4
Table 3.	Traffic flow rates and mixes for actual-traffic noise recordings.	5
Table 4.	Summary of traffic conditions for actual-traffic noise recordings.	7
Table 5.	Number of 1/3-octave band average sound pressure level spectra used for the analyses in this report.	7
Table 6.	Values of M, the average difference between a pair of ratings, and s, the standard deviation of these differences around their mean, for the outdoor LEQ free-flowing traffic noise spectra from the present investigation.	12

Page

Table 7. Values of M, the average difference between a pair of ratings, and s, the standard deviation of these differences around their mean, for the outdoor LEQ intersection-traffic noise spectra from the present investigation. 13

Table 8. Regression coefficients (for Eq. (18)), and associated standard deviations of the residuals, for predicting different noise ratings from the A-weighted sound level for free-flowing traffic. 26

Table 9. Regression coefficients (for first and third terms of Eq. (18)), and associated standard deviations of the residuals, for predicting different noise ratings from the A-weighted sound level for intersection traffic. 28

Table A1. Summary of conditions for the published traffic noise spectra. 36

List of Figures

Figure 1. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the three recording times at the COMSAT site. 20

Figure 2. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the I95 site. 20

Figure 3. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the five recording times at the B-W PKWY site. 21

Figure 4. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the GUDE DR. site. 21

Figure 5. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the RT. 28 site. 22

		Page
Figure 6.	Average trends of the difference between the Mark VI Loudness Level and the A-weighted sound level, as functions of effective distance, for the five sites with free-flowing traffic.	22
Figure 7.	The difference between the Mark VI Loudness Level and the A-weighted sound level, each interpolated to an effective distance of 50 m, as a function of the equivalent fraction of heavy trucks. The lower line corresponds to the twelve recording times for interstate highways. The upper line corresponds to the eight recording sessions along the side of secondary roads.	24
Figure 8.	The slopes of the curves in Figs. 1-5 (i.e., the slopes of plots of the difference between the Mark VI Loudness Level and the A-weighted sound level as functions of the logarithm, to the base ten, of the ratio of the effective distance) as a function of the equivalent fraction of heavy trucks.	25
Figure 9.	Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the 355 and S.G. intersection.	27
Figure 10.	Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the 355 and Q.O. intersection.	27
Figure 11.	Average trends of the difference between the Mark VI Loudness Level and the A-weighted sound level, as functions of effective distance, for the two intersections.	28
Figure A1.	Published "average" traffic noise spectra at 7.5 m.	32
Figure A2.	Published L10 traffic noise spectra at 4 to 25 m.	33
Figure A3.	Published "average" traffic noise spectra at 15 m.	34
Figure A4.	Published "average" traffic noise spectra at 30 m.	35
Figure A5.	Normalized "average" traffic noise spectra at 7.5 m.	37
Figure A6.	Normalized L10 traffic noise spectra at 4 to 25 m.	38
Figure A7.	Normalized "average" traffic noise spectra at 15 m.	39
Figure A8.	Normalized "average" traffic noise spectra at 30 m.	40

Page

Figure A9. Range defined by normalized traffic noise spectra. 41

Figure A10. Normalized LEQ octave band spectra for each of the seven actual traffic noise recording sites of Section 2.1 at the 15-m microphone position. 43

Figure A11. Range of normalized octave band levels for each of the seven actual traffic noise recording sites of Section 2.1 at the 15-m microphone position. 44

Figure A12. Comparison of ranges of normalized octave band levels for the published data of Fig. A9 and for the data of Fig. All from the current study. 45

1. Introduction

The analyses in this report were prepared in conjunction with a larger research program designed to assess the ability of various environmental-noise rating indices to predict accurately the adverse response associated with exposures to time-varying highway noise[1-5][1]. Since most of the noise indices developed for rating time-varying noise are based upon the A-weighted level, the psychoacoustic study conducted as part of this program focuses only upon the effects of temporal factors upon human response; the effects of frequency weighting were not addressed. This is not to say that frequency weighting is not important from a human response viewpoint, but rather that this question can be addressed, without any additional psychoacoustic studies, through analysis of available spectral data on both free-flowing and stop-and-go traffic.

Specifically, if it is shown, for highway noise spectra, that different frequency weighting procedures are highly correlated and that one can predict, with sufficient accuracy, one weighting function from another, then it may not matter much which weighting procedure is utilized in a noise-rating index.

The extent to which it is important as to which frequency weighting procedure is used can be addressed in the context of the following question:

> Let R1 designate a rating procedure that incorporates a particular temporal-weighting procedure and a particular frequency-weighting procedure. Let R2 designate a rating procedure that incorporates the same temporal-weighting procedure as is used for R1 but utilizes a different frequency-weighting procedure. If a criterion level is set at R1=X dB, what difference does it make, in terms of separating "pass" situations from "fail" situations, if one elects instead a level R2=F(R1=X), where F( ) is an empirically determined transformation from R1 to R2 for the particular spectrum shapes of concern?

For example, the A-weighted noise level is approximately 11 dB less than the perceived noise level for typical highway noise spectra. Based on this simple relationship, how accurately could one predict perceived noise levels from observed A-weighted levels? Could the prediction be improved by incorporating adjustments to account for traffic conditions or distance from the highway?

In the present report, such questions are addressed by examining the relations among different frequency ratings for the average sound pressure level spectra obtained in the course of the present investigation.

[1]Figures in square brackets indicate the literature references in Section 5 of this report.

2. Traffic Noise Spectra

As part of the present investigation, fifteen-minute recordings of actual traffic noise were made at four microphone positions (7.5, 15, 30, and 60 m from the centerline of the near lane) at several times of the day at each of seven sites, five representing nominally constant-speed traffic and two representing stop-and-go intersection traffic. The recordings that resulted were subjected to extensive analysis. In Ref. 1, the analysis procedures that were used are described and tables and graphs are included which document, for each recording, the 1/3-octave band spectra and numerous noise descriptors computed from the time-histories of the A-weighted sound level. For the present analyses, the 1/3-octave band spectra of average sound levels (LEQ) from Ref. 1 were used. These spectra are documented in Appendix B of Ref. 1, where the 1/3-octave band levels are given for band center frequencies from 50 to 10,000 Hz. The sites and the traffic speeds and mixes for these recordings are summarized below.

All recording sites were selected with the following general criteria in mind:

- o propagation over grass,
- o essentially level terrain beside highway,
- o essentially no hills or curves on highway, and
- o no barriers between highway and microphone locations.

In selecting the particular sites, these general criteria were interpreted as follows. There were no hills that would require trucks to downshift or to lose speed while going uphill. There were no curves that would result in tire squeal at normal highway speeds and, specifically, no curves of less than 300 m radius. Sites were selected where the ground elevation at the 60-m microphone location was within plus 3 m or minus 1 m of the highway elevation at the center of the nearest lane and, further, where a length of highway of at least 300 m was visible from a position 0.6 m above the ground at all four microphone locations.

The sites representing constant-speed traffic conditions were selected in order to cover a range of traffic densities (from quite light to near-capacity), a range of traffic speed limits (48-88 km/hr), a range of highway sizes (two- to eight-lane), and a range of values for the proportion of truck traffic. The sites near intersections were selected to represent a range of traffic densities and a range of values for the proportion of truck traffic. The seven sites that were used are listed in Table 1.

All recordings of actual traffic noise were started between the hours of 1300 and 1700 on weekdays during the period 13-24 June 1977. At the times of recording, the air temperature was between 21 and 29 °C, there was no precipitation, and the road surfaces were dry. Wind speeds were low, less than 4 m/s, except for occasional gusts to 6-8 m/s on 17 and 21 June.

Table 1. Description of sites used for recordings of actual-traffic sounds.

Site	Type of Highway	Truck Traffic	Speed Limit, km/hr
COMSAT	Four-Lane Interstate	Light	88
I95	Eight-Lane Interstate	Fairly Heavy	88
B-W PKWY	Four-Lane Parkway	None	88
RT. 28	Dual-Lane Road	Light	48-64 (see text)
GUDE DR.	Dual-Lane Road	Heavy	64
355 & SHADY GR.	Intersection of Four-Lane & Dual-Lane Roads	Moderate	Controlled by traffic light
355 & Q.O. RD.	Intersection of Two Four-Lane Roads	Light	Controlled by traffic light

The times at which recordings were initiated at the various sites are shown in Table 2. Also shown in this table, for the five sites where there was essentially constant-speed traffic, are the average traffic speeds, and the standard deviations and ranges of these speeds, in each direction during each recording session. No traffic speed measurements were made at the two sites where there was stop-and-go traffic.

Continuous video recordings of traffic flow were made during each recording session. Each video tape was analyzed, by visual inspection, to determine the number of automobiles, medium trucks, and heavy trucks traveling in each direction over the duration of the corresponding traffic noise recording. These data are presented in Table 3. For purpose of classification, the three vehicle categories were defined as follows:[1]

Automobiles - all 2-axle, 4-tire vehicles

Medium trucks - all 2-axle, 6-tire vehicles plus all buses and motorcycles

Heavy trucks - all vehicles with three or more axles.

For the two sites at which there was stop-and-go intersection traffic, the "near-side" data in Table 3 correspond to the sum of traffic flows in the near lanes of both highways while the "far-side" data are for the far lanes of both highways.

[1]An "automobile" pulling a trailer was classified as an "automobile." A "bob-tailed" tractor (i.e., a tractor that was not pulling a trailer) was classified as a "medium truck" if it had two axles and as a "heavy truck" if it had three axles.

Table 2. Sites, dates, times, and traffic speeds for actual-traffic noise recordings.

Site	Date(a)	Time of Initiation	Vehicle Speed, km/hr: Near-Side Avg.	Near-Side Standard Deviation	Near-Side Range	Far-Side Avg.	Far-Side Standard Deviation	Far-Side Range
COMSAT	15	1510	92	5	74-103	92	8	74-117
	15	1600	92	6	77-106	93	8	74-111
	15	1700	85	6	68-101	92	8	72-109
I95	23	1400	89	6	56-105	93	8	76-108
	23	1500	92	6	72-113	92	8	74-114
	23	1600	93	6	79-114	93	8	69-113
	23	1700	92	6	69-105	93	6	72-114
B-W PKWY	20(c)	1420	90	6	79-111	85	8	71-114
	20(c)	1500	89	6	72-106	85	8	69-113
	21(b,c)	1515	90	8	71-121	87	6	71-101
	21(b,c)	1600	90	6	69-108	87	8	69-105
	21(b,c)	1700	89	6	72-111	87	6	71-106
RT. 28	17(b)	1300	69	6	60-89	69	8	55-88
	17(b)	1415	71	8	55-89	69	10	47-85
	17(b)	1500	71	10	42-84	69	8	47-85
	17(b)	1600	69	6	50-84	66	6	56-85
GUDE DR.	16	1400	64	6	40-80	63	8	39-79
	16	1500	66	6	48-80	63	6	51-80
	16	1600	66	8	48-92	61	10	40-93
	16	1700	66	6	50-85	63	8	40-92
355 & SHADY GR.	22	1400	-	-	-	-	-	-
	22	1500	-	-	-	-	-	-
	22	1600	-	-	-	-	-	-
	22	1700	-	-	-	-	-	-
355 & Q.O. RD.	24	1445	-	-	-	-	-	-
	24	1515	-	-	-	-	-	-
	24	1600	-	-	-	-	-	-
	24	1700	-	-	-	-	-	-

[a] All dates correspond to a calendar day in June 1977.

[b] On these dates, there were occasional wind gusts up to 6-8 m/s; on all other dates, wind speeds were less than 4 m/s.

[c] For these runs, no recordings were made with a microphone at 60 m since the site was heavily wooded beyond about 40 m.

Table 3. Traffic flow rates and mixes for actual-traffic noise recordings.

Site	Date[a]	Time of Initiation	Vehicle Mix							
			Near-Side				Far-Side			
			Total[b] Traffic Rate	% Auto-mobiles	% Medium Trucks	% Heavy Trucks	Total[b] Traffic Rate	% Auto-mobiles	% Medium Trucks	% Heavy Trucks
COMSAT	15	1510	1040	87.2	2.9	9.9	950	89.2	2.7	8.1
	15	1600	2010	93.2	1.2	5.6	880	92.8	1.1	6.1
	15	1700	3340	96.0	1.7	2.3	820	91.2	3.4	5.4
I95	23	1400	1280	77.1	6.6	16.3	1580	77.5	7.6	14.9
	23	1500	1420	85.8	4.8	9.3	1700	78.9	7.6	13.5
	23	1600	1490	88.3	4.5	7.3	2110	86.4	4.0	9.7
	23	1700	1710	88.4	3.1	8.5	2620	88.6	4.0	7.4
B-W PKWY	20	1420	970	98.2	1.4	0.5	1220	98.2	1.1	0.7
	20	1500	1140	98.6	1.1	0.4	1400	97.7	1.7	0.6
	21	1515	1340	97.0	3.0	0.0	1490	99.1	0.9	0.0
	21	1600	1860	98.0	1.5	0.4	1880	98.1	1.5	0.4
	21	1700	2200	98.9	0.7	0.4	1730	98.1	1.4	0.5
RT. 28	17	1300	350	96.0	1.3	2.7	310	88.2	10.3	1.5
	17	1415	390	90.7	7.2	2.1	370	93.3	5.6	1.1
	17	1500	350	95.6	2.2	2.2	360	93.6	4.3	2.1
	17	1600	620	96.2	1.9	1.9	510	89.1	8.5	2.3
GUDE DR.	16	1400	550	86.0	5.0	9.1	480	89.6	3.8	6.6
	16	1500	510	84.0	9.6	6.4	570	84.4	2.8	12.8
	16	1600	600	89.2	2.7	8.1	710	88.1	8.5	3.4
	16	1700	590	92.4	1.4	6.2	840	94.6	4.4	1.0
355 &	22	1400	1180	87.6	7.8	4.5	1580	88.5	5.6	5.8
SHADY GR.[c]	22	1500	1070	88.5	4.9	6.7	1750	89.3	6.4	4.3
	22	1600	1320	92.1	4.3	3.6	2360	91.6	5.6	2.7
	22	1700	1270	94.7	3.8	1.6	2990	97.6	1.5	0.9
355 &	24	1445	1900	93.7	4.6	1.6	1190	94.1	4.0	1.8
Q.O. RD.[c]	24	1515	1950	93.4	4.9	1.7	1370	90.6	6.1	3.3
	24	1600	2510	95.8	3.1	1.1	1580	94.6	3.3	2.0
	24	1700	3650	98.8	1.2	0.0	1730	96.7	2.8	0.5

[a] All dates correspond to a calendar day in June 1977.

[b] Total vehicles per hour, computed from the observed traffic rates over the duration of each noise recording.

[c] See Appendix A of Ref. 1 for more detail on traffic counts at these intersections.

The data of Tables 2 and 3 are summarized in Table 4.

Recordings were made at distances of 7.5, 15, 30, and 60 m (from the centerline of the near lane) for each of the 28 recording times listed in Tables 2 and 3 except at the B-W PKWY site where no recordings were made with a microphone at 60 m since the site was heavily wooded beyond about 40 m. Thus a total of 107 recordings were made, each nominally 15 min in duration. Examination of the 1/3-octave band average sound pressure level spectra, as well as audition, revealed excessive background noise (probably due to air conditioning equipment at a nearby building) at the 60-m microphone location at the RT. 28 site; accordingly, spectra from these four recordings were not used for the study described in the present report. Thus a total of 103 spectra were used, as summarized in Table 5. There were 43 spectra corresponding to recordings made along interstate highways and 28 spectra for noise from secondary roads, making a total of 71 spectra for free-flowing traffic. The number of spectra for noise from intersection traffic was 32.

A comparison of traffic noise spectra from the literature with spectra from the present investigation is given in Appendix A. It is concluded there that the shapes of traffic noise spectra from the literature are consistent with the spectra described above and used for the analyses in the present report.

Table 4. Summary of traffic conditions for actual-traffic noise recordings.

Type of Highway	Interstate			Secondary			Intersection		
Sites (No. Lanes)	COMSAT(4) I95(8) B-W PKWY(4)			RT. 28(2) GUDE Dr.(2)			355 & SHADY GR.(-) 355 & Q. O. RD.(-)		
Traffic Parameter	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Average Traffic Speed, km/hr	85	90	93	61	67	71	-	-	-
Total Traffic Volume, veh./hr	1990	3020	4330	660	1010	1430	2760	3680	5380
Percent Automobiles	77.4	91.9	98.6	84.2	90.8	94.6	88.3	93.2	98.1
Percent Medium Trucks	1.0	2.8	7.1	3.2	4.9	6.4	1.7	4.3	6.5
Percent Heavy Trucks	0.0	5.3	15.5	1.6	4.3	9.8	0.2	2.5	5.2

Table 5. Number of 1/3-octave band average sound pressure level spectra used for the analyses in this report.

Type of Highway	Site	Number of Spectra			
		7.5 m	15 m	30 m	60 m
Interstate	COMSAT	3	3	3	3
	I-95	4	4	4	4
	B-W PKWY	5	5	5	-
Secondary	RT. 28	4	4	4	-
	GUDE DR.	4	4	4	4
Intersection	355 & SHADY GR.	4	4	4	4
	355 & Q. O. ROAD	4	4	4	4

3. Noise Descriptors

Using the 1/3-octave band spectra of average sound levels for the 103 15-minute recordings of traffic noise, as described above, computations were made of the following noise ratings (the abbreviation given in parentheses after each rating is used in this report):

Weighted Sound Levels

- A-weighted sound level, (A) [6]
- B-weighted sound level, (B) [6]
- C-weighted sound level, (C) [6]
- D-weighted sound level, (D) [7]
- E-weighted sound level, (E) [8,9]

Loudness Levels

- Stevens Mark VI loudness level, (MK6) [10, 11]
- Stevens Mark VII loudness level, (MK7) [8]
- Zwicker loudness level (free-field), (ZWK) [11]

Noisiness Levels

- Perceived Noise Level, (PNL) [12]
- Tone-Corrected Perceived Noise Level, (PNT) [13]

Speech Interference Level

- Preferred Speech Interference Level, (PSIL) [14]

These ratings (rounded to the nearest 0.1 dB), along with data on highway configurations, microphone locations, and traffic speed and mix, were used for the analyses described below.

4. Analysis

The analyses given in the remainder of this report are linear regression analyses in which a functional relationship between two variables (in this case, two different noise ratings) is assumed and the regression coefficients are obtained by least-square fitting. It is important to stress that the problem that is being addressed in this report is quite different in one respect from regression problems such as are usually encountered in physics, engineering, or experimental psychology. We are not dealing with random variations in the variables of concern. We start with a precisely-defined one-third octave band spectrum, say, L_1, L_2, L_3, ... L_{24}. We then utilize precisely-defined algorithms to compute, for example, the A-weighted sound level, $A(L_1, L_2, L_3, \ldots L_{24})$, and the D-weighted sound level, $D(L_1, L_2, L_3, \ldots L_{24})$. The quantities which are calculated are known exactly for the given spectrum. The type of question that is asked in the present report can be phrased as follows: If we throw away our knowledge of the individual one-third octave band levels, how well can we predict, for example, the D-weighted sound level from the A-weighted sound level, provided that we take advantage of the fact that the shape of traffic noise spectra is reasonably fixed and, in the analyses in Section 4.2, we use traffic parameters and microphone locations as surrogate independent variables?

Let us first consider the very simple analysis in Section 4.1, where it is assumed that one descriptor can be predicted from another simply by adding a fixed constant to the known descriptor. In this extremely simple model, it is assumed that we know nothing about traffic parameters or microphone location. To gain insight into the functional form that is consistent with this assumption, consider a single highway with one microphone at a fixed location beside the highway. For a given traffic speed and mix (i.e., percentage of automobiles, medium trucks, and heavy trucks), the spectrum shape will not change significantly as the total volume of traffic changes. Rather, if the traffic volume increases by a factor N, each one-third octave band level will increase by an additive increment, ΔL, that is proportional to log N. The algorithms for computing the weighted levels and the Preferred Speech Interference Levels are such that if the spectrum is shifted by a fixed amount, say ΔL, with no relative changes in individual one-third octave band levels, then each of these descriptors also will change by exactly ΔL. Thus, for these descriptors, the difference between, say, the D-weighted level and the A-weighted level is not changed by an increase in traffic flow.

The value of any given descriptor is generally controlled by the one-third octave band levels covering a narrow range of frequencies. If traffic mix, traffic speed, pavement surface, or microphone location is changed, the first order effect will be a uniform shift in the important part of the spectrum, leading to an equivalent uniform shift in each of the weighted levels and in the Preferred Speech Interference Levels; there will be some changes in the spectrum shape but these will be second order effects.

Thus, for a given and fixed spectrum shape, any two weighted sound levels (e.g., the A-weighted and D-weighted levels) will differ from one another by a constant that is independent of the magnitude of the sound pressure level. In the range of sound levels of interest in the present study, the equal-loudness (or equal-noisiness) contours used in a given rating scheme are very nearly parallel with one another (e.g., the 1 sone contour and the 2 sone contour differ only slightly in shape). If the contours were exactly parallel, the additive constant relating one rating to another, for a fixed spectrum shape, would be independent of the sound level. Since the loudness, or noisiness, contours are not exactly parallel and since the traffic noise spectrum shapes vary somewhat, the differences between any two ratings will vary around some average value. The analysis of Section 4.2 attempts to "correct" for slight variations in spectrum shape by including terms involving distance from the highway as well as traffic speed and mix.

It is also important to stress that the present analysis does not utilize inferential statistics to attempt to predict the confidence with which one could predict one noise rating from another for a spectrum selected at random. Such a use of inferential statistics would be meaningful only if the entire universe of traffic noise spectra of interest had been defined and if a random sample from that universe were available for analysis. The sample population used in the present report clearly was not drawn randomly from any such well-defined universe.

The fitting, in a least-squares sense, of a regression curve is a well-defined operation that can be carried out for any arbitrary sample population of data. However, if one is to attempt to draw the usual statistical inferences about some universe from which the sample population was taken, then a number of assumptions must be met. These include, in addition to the requirements that the independent variables be known without significant error and that the functional relationship, or model, chosen be appropriate, the following:

a) the sample population must bear a known relation to the universe about which it is desired to make inferences (preferably, the sample population should have been randomly selected from the target population),

b) the errors (observed minus predicted values) of the dependent variable are random,

c) the errors are mutually independent,

d) the errors are homoscedastic (i.e., have a common variance),

e) the errors have zero mean, and

f) the errors are normally distributed

Briefly stated, none of these conditions is met. Probably the most serious problem, which was mentioned before, is that the sample population was not randomly selected from any well-defined target population. As a result of this, it is believed that assumptions b), c), and d) also are violated.

Any two descriptors which are to be related were computed, using different algorithms, from the same one-third octave band spectra; the nature of the algorithms involved is such that assumptions e) and f) are probably violated as well.

For these reasons, all statistical descriptors presented below should be thought of as descriptive of the population of traffic noise spectra that was used in these analyses and should not be used to infer the uncertainty with which one noise rating can be predicted from another for an arbitrary spectrum. Nonetheless, in a qualitative sense it seems probable that the functional relationships given below should yield good predictions for site configurations and traffic conditions similar to those used in the present analyses.

Consistent with the use of regression analyses based on functional models that are in keeping with physical reality (see Refs. 15-16), the goodness of fit between the data and a given model is described in terms of the standard deviation of the residuals and not in terms of correlation coefficients (see Refs. 15, 17-19).

4.1 Additive Constant

As pointed out above, if all traffic noise spectra had the same shape, the difference between two weighted levels, say the A-weighted sound level and the D-weighted sound level, would be a constant. Similarly, the difference between the Preferred Speech Interference Level and a weighted level would be constant for a fixed spectrum shape. For a family of spectra of slightly differing shapes, the differences between two noise ratings would be expected to vary somewhat around an average value. Thus the simplest regression equation that is reasonable to try is

$$Y = X + M, \qquad (1)$$

where X is a known noise rating, M is an additive constant (for the given pair of rating procedures), and Y is the noise rating to be predicted. Given a set of N spectra, the additive constant is given by

$$M = \frac{1}{N}\sum_{i=1}^{N} (Y_i - X_i) = \overline{Y} - \overline{X}, \qquad (2)$$

where X_i and Y_i are the noise ratings corresponding to the i-th spectrum. A measure of how well Eq. (1) can be used to predict Y from X is the standard deviation of the $(Y_i - X_i)$ values around their mean value:

$$s(X,Y) = \left\{\frac{1}{N-1}\sum_{i=1}^{N} [Y_i - X_i - M]^2\right\}^{1/2} . \qquad (3)$$

Table 6 shows the values of M and s, computed from Eqs. (2) and (3) for the 71 spectra corresponding to free-flowing traffic (the first five sites in Tables 1-3), for all possible pairs of the noise descriptors listed in Sec. 3. For each descriptor listed in the first column, the first row gives the values of M and the second row gives the values of s. Thus, for the noise spectra from free-flowing traffic, M = 6.1 dB is the additive constant relating the D-weighted sound level to the A-weighted sound level and s = 1.2 dB is the corresponding standard deviation, around their mean, of the differences between the D-weighted and A-weighted levels. The diagonal of this matrix contains only zeroes. Since the matrix of M values is antisymmetrical [i.e., M(X,Y) = -M(Y,X)] and the matrix of s values is symmetrical [s(X,Y) = s(Y,X)], the lower half has been suppressed.

Table 6. Values of M, the average difference between a pair of ratings, and s, the standard deviation of these differences around their mean, for the outdoor LEQ free-flowing traffic noise spectra from the present investigation.

		B	C	D	E	MK6	MK7	ZWK	PNL	PNT	PSIL
A	M	4.6	7.9	6.1	4.1	12.9	5.4	18.9	12.7	13.2	-7.9
	s	1.9	2.9	1.2	.9	1.4	1.4	1.3	.8	1.4	1.0
B	M	--	3.3	1.5	-.5	8.4	.8	14.4	8.1	8.6	-12.5
	s	--	1.1	1.4	1.1	1.0	1.1	1.2	1.9	1.7	2.6
C	M	--	--	-1.8	-3.8	5.0	-2.5	11.0	4.8	5.3	-15.8
	s	--	--	2.1	2.0	1.7	1.8	1.9	2.7	2.3	3.5
D	M	--	--	--	-2.0	6.9	-.7	12.9	6.6	7.2	-14.0
	s	--	--	--	.6	.9	1.0	.7	.8	.6	1.5
E	M	--	--	--	--	8.8	1.3	14.8	8.6	9.1	-12.0
	s	--	--	--	--	.8	.8	.7	.9	1.0	1.5
MK6	M	--	--	--	--	--	-7.6	6.0	-.2	.3	-20.8
	s	--	--	--	--	--	.4	.4	1.3	1.4	2.0
MK7	M	--	--	--	--	--	--	13.6	7.3	7.9	-13.3
	s	--	--	--	--	--	--	.4	1.3	1.5	1.9
ZWK	M	--	--	--	--	--	--	--	-6.2	-5.7	-26.9
	s	--	--	--	--	--	--	--	1.1	1.2	1.8
PNL	M	--	--	--	--	--	--	--	--	.5	-20.6
	s	--	--	--	--	--	--	--	--	1.0	.9
PNT	M	--	--	--	--	--	--	--	--	--	-21.1
	s	--	--	--	--	--	--	--	--	--	1.7

Table 7 shows the values of M and s for the 32 spectra of noise from intersection traffic.

Inspection of the various values of s in Tables 6 and 7 shows that the more-frequently-proposed descriptors, such as A-, D-, and E-weighted levels, the three loudness levels, and the perceived noise level, are highly interrelated and a simple additive constant can be used to predict one rating from another with rather small uncertainty.

Table 7. Values of M, the average difference between a pair of ratings, and s, the standard deviation of these differences around their mean, for the outdoor LEQ intersection-traffic noise spectra from the present investigation.

		B	C	D	E	MK6	MK7	ZWK	PNL	PNT	PSIL
A	M	7.6	12.5	7.7	5.7	15.1	7.1	20.5	14.3	14.4	-8.7
	s	1.1	1.5	.7	.6	.9	.7	.7	.6	.7	.8
B	M	--	4.9	.1	-2.0	7.4	-.5	12.9	6.7	6.8	-16.4
	s	--	.4	.4	.5	.5	.8	.7	.9	1.0	1.9
C	M	--	--	-4.8	-6.9	2.5	-5.4	8.0	1.8	1.9	-21.3
	s	--	--	.8	.9	.7	1.0	1.0	1.2	1.3	2.2
D	M	--	--	--	-2.0	7.4	-.6	12.8	6.6	6.7	-16.4
	s	--	--	--	.1	.4	.5	.5	.6	.7	1.5
E	M	--	--	--	--	9.4	1.4	14.9	8.7	8.7	-14.4
	s	--	--	--	--	.5	.5	.5	.5	.6	1.4
MK6	M	--	--	--	--	--	-7.9	5.5	-.7	-.6	-23.8
	s	--	--	--	--	--	.4	.4	.7	.8	1.6
MK7	M	--	--	--	--	--	--	13.4	7.2	7.3	-15.8
	s	--	--	--	--	--	--	.1	.7	.8	1.3
ZWK	M	--	--	--	--	--	--	--	-6.2	-6.1	-29.3
	s	--	--	--	--	--	--	--	.7	.8	1.3
PNL	M	--	--	--	--	--	--	--	--	.1	-23.1
	s	--	--	--	--	--	--	--	--	.2	1.2
PNT	M	--	--	--	--	--	--	--	--	--	-23.1
	s	--	--	--	--	--	--	--	--	--	1.2

There is considerable redundancy in the additive constants listed in Tables 6 and 7 in that the additive constants relating all other frequency ratings to any given single frequency rating contain all the information necessary to relate other pairs of descriptors. Thus, from Table 6, it is seen that E = A + 4.1 and PNL = A + 12.7; therefore PNL = E + (12.7 - 4.1) = E + 8.6, as indicated further on in the table.

On the other hand, one cannot, in any simple way, combine standard deviations to predict the standard deviation of a particular pair of frequency ratings.

4.2 Functional Relationship Between Noise Ratings

We will now examine the feasibility of using other data, such as distance from the highway and traffic conditions, to reduce the uncertainty with which one noise rating can be predicted from another. Rather than empirically examine the residuals, $Y_i - X_i - M$, we will develop a functional relationship, between two noise ratings, that explicitly includes consideration of the influence of distance, traffic speed, and traffic mix.

The mean-square sound pressure due to an omni-directional, incoherent point source moving in a straight line, at uniform speed, past an observation point is

$$p^2 = P_o^2 \frac{D_o^2}{D^2 + S^2 t^2} , \tag{4}$$

where

D is the perpendicular distance from the observation point to the line of travel,

S is the speed at which the source is moving,

P_o^2 is the mean-square pressure at a reference distance, D_o,

and t=0 at the time when the source is closest to the observation point. It is assumed that there is spherical spreading in a non-absorptive medium and that the speed of travel is much less that the speed of sound in the medium.

The sound exposure due to the passage of this source is

$$\int_{-\infty}^{\infty} p^2 \, dt = \frac{\pi D_o^2 P_o^2}{SD} \tag{5}$$

The mean-square sound pressure due to a succession of such sources, moving past the observation point at arbitrary spacing, is

$$\overline{p^2} = \frac{\pi D_o^2 \, VP_o^2}{SD} \quad , \tag{6}$$

where V is the average flow rate (vehicles per unit time). The moving stream of traffic can be represented by an equivalent line source, the mean-square sound pressure falling off inversely with distance (i.e., the sound pressure level decreases 3 dB per doubling of distance away from the source).

In practice, the sound level from a real highway falls off more rapidly with distance that is indicated by Eq. (6). This occurs because of excess attenuation due to absorption by air, vegetation, etc. Equation (6) can be generalized to the form

$$\overline{p^2} = \frac{\pi D_o \, VP_o^2}{S} \; f(D_o/D) \tag{7}$$

where $f(D_o/D)$ represents not only the cylindrical spreading exhibited by Eq. (6) but also the effects of excess attenuation. Empirically, it has been observed that this function can be represented as a simple exponential function of the argument so that

$$\overline{p^2} = \frac{\pi D_o \, VP_o^2}{S} \left(\frac{D_o}{D}\right)^{\nu} \tag{8}$$

where $\nu=1$ corresponds to 3 dB per doubling of distance, $\nu=1.5$ to 4.5 dB per doubling of distance, etc.

A real highway may consist of a number of lanes carrying several classes of vehicles each traveling at various speeds. The average sound level at an observation point to the side of an infinitely-long, straight highway may be estimated by summing over a number of terms of the form of Eq. (8), yielding the following expression for the average sound level:

$$\mathrm{LEQ} = 10 \log \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \frac{\pi D_o \, V_{ij} \, Q_{ij}}{S_{ij}} \left(\frac{D_o}{D_j}\right)^{\nu_i} \right] \quad , \tag{9}$$

where

V_{ij} is the average volume flow rate (vehicles per unit time) of the i-th class of vehicles in the j-th lane,

S_{ij} is the average speed of the i-th class of vehicles in the j-th lane,

D_j is the perpendicular distance from the observation point to the acoustic center of the j-th lane (hereafter, and in all calculations in this report, the acoustic center of each lane is taken as the physical center of that lane),

D_o is a reference distance at which the source strength is defined,

$Q_{ij} = Q_i(S_{ij})$ is the average source strength of the i-th class of vehicles and is a function of the speed, S_{ij}, at which this class of vehicles is traveling in the j-th lane,

ν_i is the exponent which describes the rate of attenuation with distance for the i-th class of vehicles (it is a function of the class of vehicle because the characteristic sound spectra may be different for different classes of vehicles and because the differences in effective source heights may lead to different attenuations by ground cover),

I is the number of vehicle classes, and

J is the number of lanes.

Equation (9), for an infinitely-long straight highway, is consistent, for example, with the FHWA Highway Traffic Noise Prediction Model [20-23], that is used to predict the A-weighted average sound level along a highway.

Let us assume that Eq. (9) is valid for a particular frequency weighting and that measured values of LEQ and the relevant traffic parameters are available. Let us further assume that a similar equation can be written corresponding to some other frequency-weighted average sound level but with LEQ, Q_{ij}, and ν_i replaced by primed quantities, the primes indicating that the level, source strengths, and rates of attenuation are those corresponding to the other frequency weighting.

It is desired to predict LEQ' from measured values of LEQ and traffic parameters. In principle, this could be done by combining two equations of the form of Eq. (9) and then attempting to find values of $Q_i'(S_{ij})$, $Q_i(S_{ij})$, ν_i, and ν_i' that would make this expression fit the empirically-observed values of Δ = LEQ' - LEQ. While this could be done, using a non-linear fitting routine, the resulting expression would be complicated and difficult to use. We therefore seek means to develop a simpler empirical equation for predicting LEQ'.

The difference between the two ratings is obtained by combining two equations of the form of Eq. (9) to obtain

$$\Delta = LEQ' - LEQ = 10 \log \left[\frac{\sum_{i=1}^{I} \sum_{j=1}^{J} \frac{f_{ij} Q'_{ij}}{S_{ij}} \left(\frac{D_o}{D_j} \right)^{\nu'_i}}{\sum_{i=1}^{I} \sum_{j=1}^{J} \frac{f_{ij} Q_{ij}}{S_{ij}} \left(\frac{D_o}{D_j} \right)^{\nu_i}} \right], \qquad (10)$$

where f_{ij} is the fraction of the vehicles in the j-th lane that are of the i-th class. We will now make a number of assumptions to bring Eq. (10) into a more tractable form:

- o the equivalent lane concept of Appendix B is used to enable replacement of $\sum_j (D_o/D_j)^{\nu_i}$ by $(D_o/D)^{\nu_i}$, where D is the effective distance from a microphone location to the center of the fictitious equivalent highway and ν_i is an exponent that defines the rate of change of sound intensity with distance; similarly $\sum_j (D_o/D_j)^{\nu'_i}$ goes to $(D_o/D_j)^{\nu'_i}$, where the prime indicates that ν'_i may differ from ν_i,
- o all vehicles are assumed to be traveling at the same speed, S, regardless of lane or vehicle class,
- o all lanes are assumed to carry the same mix of traffic,
- o the source strengths for the i-th class of vehicles vary with speed in accordance with $Q_i = \alpha_i (S/S_o)^{\beta_i}$, where S_o is a reference speed and α_i and β_i are constants.

With these assumptions, Eq. (10) reduces to

$$\Delta = 10 \log \left[\frac{\sum_{i=1}^{I} f_i \alpha'_i (S/S_o)^{\beta'_i} (D_o/D)^{\nu'_i}}{\sum_{i=1}^{I} f_i \alpha_i (S/S_o)^{\beta_i} (D_o/D)^{\nu_i}} \right]. \qquad (11)$$

We now make the assumption that there are only two classes of vehicles: automobiles ($i = 1$) and trucks ($i = 2$). Since $f_1 + f_2 = 1$, we take $f_2 = f$ and $f_1 = 1 - f$ and write

$$\Delta = 10 \log \left[\frac{\alpha_1'(S/S_o)^{\beta_1'} (D_o/D)^{\nu_1'} \left[(1 - f) + f(\alpha_2'/\alpha_1')(S/S_o)^{\beta_2'-\beta_1'} (D_o/D)^{\nu_2'-\nu_1'} \right]}{\alpha_1(S/S_o)^{\beta_1} (D_o/D)^{\nu_1} \left[(1 - f) + f(\alpha_2/\alpha_1)(S/S_o)^{\beta_2-\beta_1} (D_o/D)^{\nu_2-\nu_1} \right]} \right], \tag{12}$$

where the term for automobiles has been factored out in both the numerator and the denominator. This expression can be expanded to yield

$$\begin{aligned} \Delta = {} & M_o + M_1 \log (S/S_o) + M_2 \log (D/D_o) \\ & + 10 \log \left[\frac{(1 - f) + f(\alpha_2'/\alpha_1')(S/S_o)^{\beta_2'-\beta_1'} (D_o/D)^{\nu_2'-\nu_1'}}{(1 - f) + f(\alpha_2/\alpha_1)(S/S_o)^{\beta_2-\beta_1} (D_o/D)^{\nu_2-\nu_1}} \right] , \end{aligned} \tag{13}$$

where

$$M_o = 10 \log (\alpha_1/\alpha_1), \tag{14}$$

$$M_1 = 10 (\beta_1-\beta_1), \tag{15}$$

and

$$M_2 = -10 (\nu_1 - \nu_1). \tag{16}$$

Inspection of the last term in Eq. (13) reveals that both the numerator and the denominator should be fairly close to unity since $\alpha_2/\alpha_1 \approx 1$, $\beta_2 \approx \beta_1$, $\nu_2 \approx \nu_1$, and similar approximations hold for the primed quantities. Accordingly, little error is introduced by the approximation $10 \log x = 4.34 \ln x \approx 4.34(x-1)$. With this substitution, Eq. (13) becomes

$$\begin{aligned} \Delta = {} & M_o + M_1 \log (S/S_o) + M_2 \log (D/D_o) \\ & + 4.34f(\alpha_2'/\alpha_1')(S/S_o)^{\beta_2'-\beta_1'} (D_o/D)^{\nu_2'-\nu_1'} \\ & - 4.34f(\alpha_2/\alpha_1)(S/S_o)^{\beta_2-\beta_1} (D_o/D)^{\nu_2-\nu_1} \quad . \end{aligned} \tag{17}$$

Using the approximation, $a^x \approx 1 + x\ell na$, which is valid for small x, Eq. (17) can be further reduced to

$$\Delta = M_o + M_1 \log (S/S_o) + M_2 \log (D/D_o)$$
$$+ M_3 f + M_4 f \log (S/S_o) + M_5 f \log (D/D_o), \quad (18)$$

where

$$M_3 = 4.34(\alpha_2'/\alpha_1' - \alpha_2/\alpha_1) \quad , \quad (19)$$

$$M_4 = 10[(\alpha_2'/\alpha_1')(\beta_2' - \beta_1') - (\alpha_2/\alpha_1)(\beta_2 - \beta_1)], \quad (20)$$

$$M_5 = -10[(\alpha_2'/\alpha_1')(\nu_2' - \nu_1') - (\alpha_2/\alpha_1)(\nu_2 - \nu_1)], \quad (21)$$

and a higher order term in f log (S/S_o) log (D/D_o) has been dropped.

Equation (18) was used for regression analysis of the differences in noise ratings as functions of traffic speed, effective distance from the highway, and equivalent fraction of heavy trucks. The effective distances from the highway were computed as indicated in Appendix B. The equivalent fraction of heavy trucks was computed from $f = f_3 + (Q_2/Q_3)f_2$, where f_2 and f_3 are the observed fractions of medium and heavy trucks, respectively, and Q_2 and Q_3 are the corresponding source strengths as computed from the equations defining the FHWA Reference Noise Emission Levels [16-19]. The reference distance used was D_o = 15 m, while the reference speed was S_o = 88.5 km/hr (55 mph). For the remainder of the analyses in this report, the A-weighted sound level was taken as the known noise rating and regression equations, of the form of Eq. (18), were derived to predict other ratings from the A-weighted level. The equations given could be combined to yield any rating in terms of any other rating (e.g., predict Mark VI Loudness Level from the D-weighted sound level) although the reliability of the prediction would not be well known.

In order to give the reader a better feel for the efficacy of regression equations of the form of Eq. (18), a series of figures have been included for the case of predicting the Mark VI Loudness Level [6,7] from the A-weighted level [2], based upon the data from the 71 recordings of noise from free-flowing traffic. Figures 1-5 show the difference Δ = MK6 - A, plotted versus log (D/D_o) for the COMSAT, I-95, B-W PKWY, GUDE DR., and RT. 28 sites, respectively. In any one of these plots, the points represented by a given symbol correspond to the (three or four) recordings made at a given session. The straight lines are regression lines, of the form $\Delta = M_o + M_2 \log (D/D_o)$, fitted to the data from a given recording session. It is seen that the lines on any given figure group rather closely. In Figure 6 a mean line is plotted for each of the five sites; these lines clearly illustrate marked differences among the five sets of data. As will become apparent below, these differences are mainly due to differences in traffic speed and mix, rather than to any particular site characteristics.

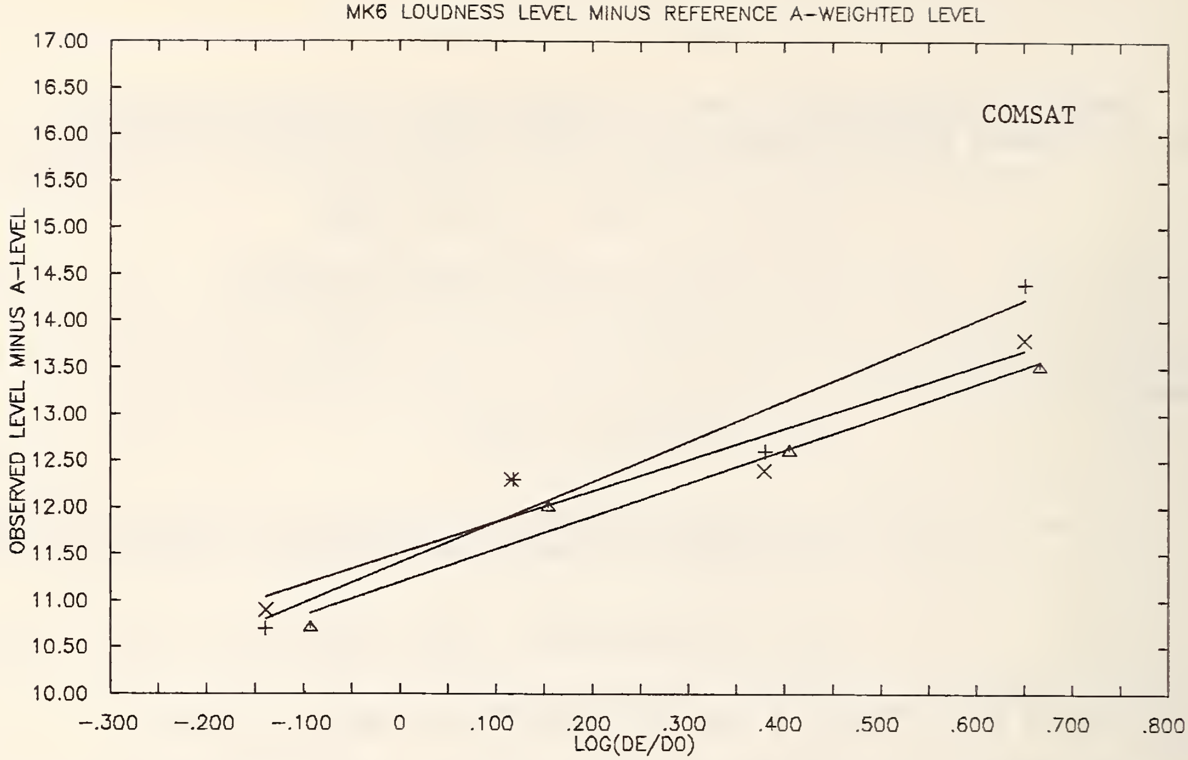

Figure 1. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the three recording times at the COMSAT site.

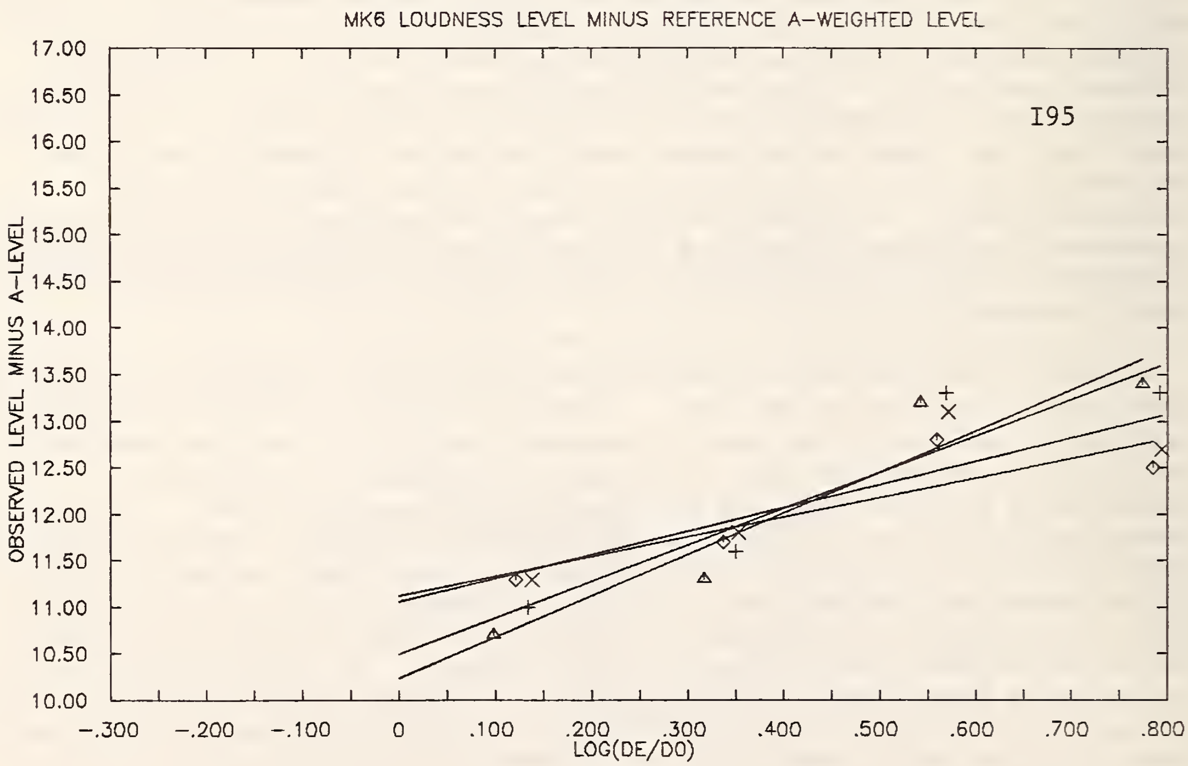

Figure 2. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the I95 site.

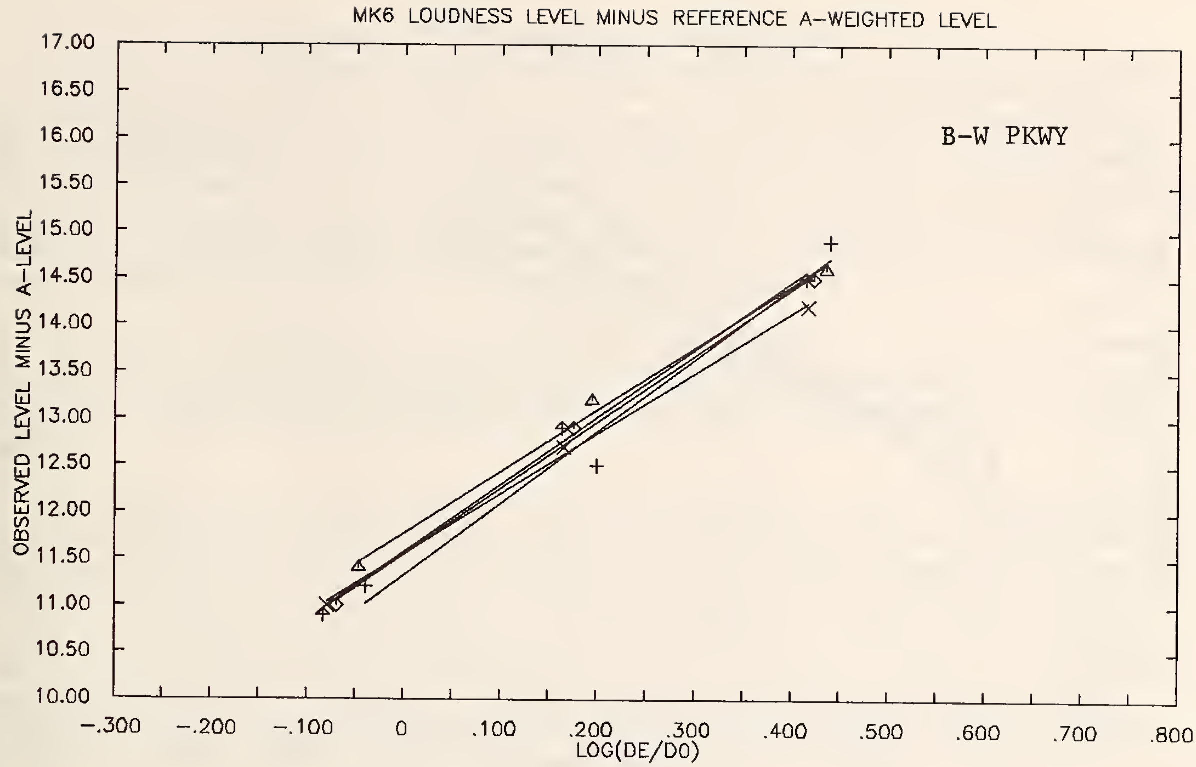

Figure 3. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the five recording times at the B-W PKWY site.

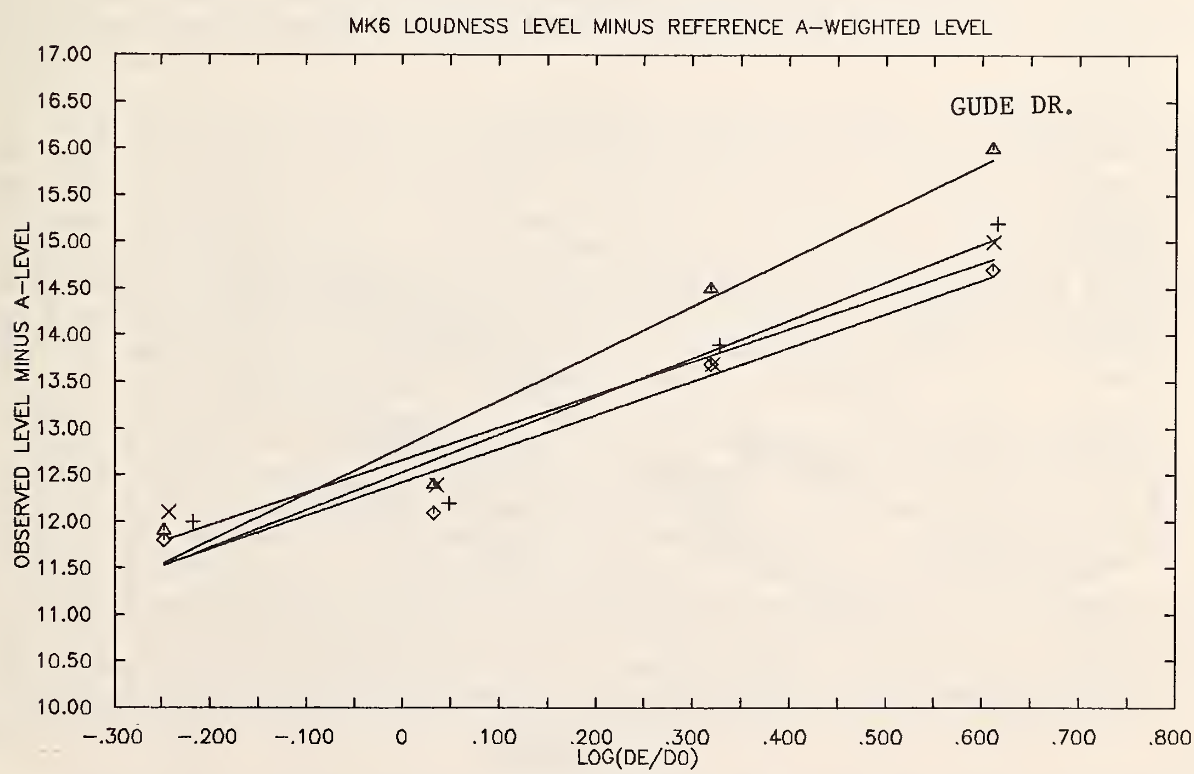

Figure 4. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the GUDE DR. site.

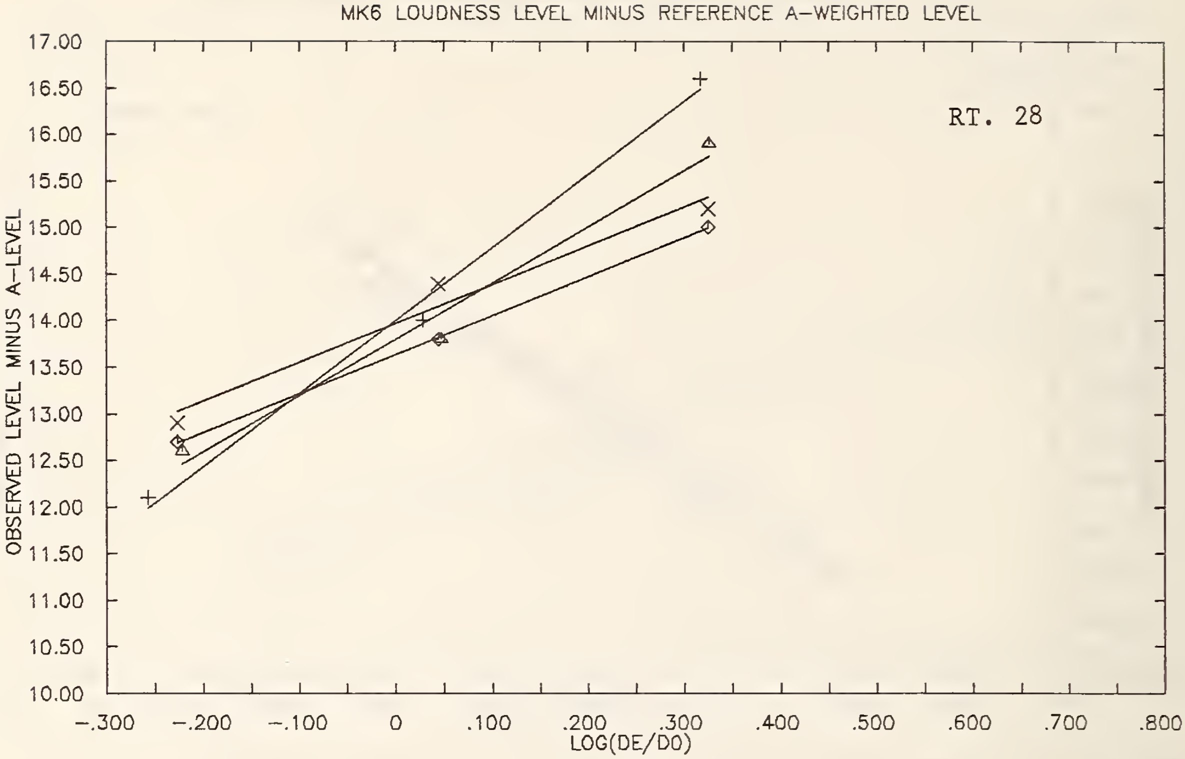

Figure 5. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the RT. 28 site.

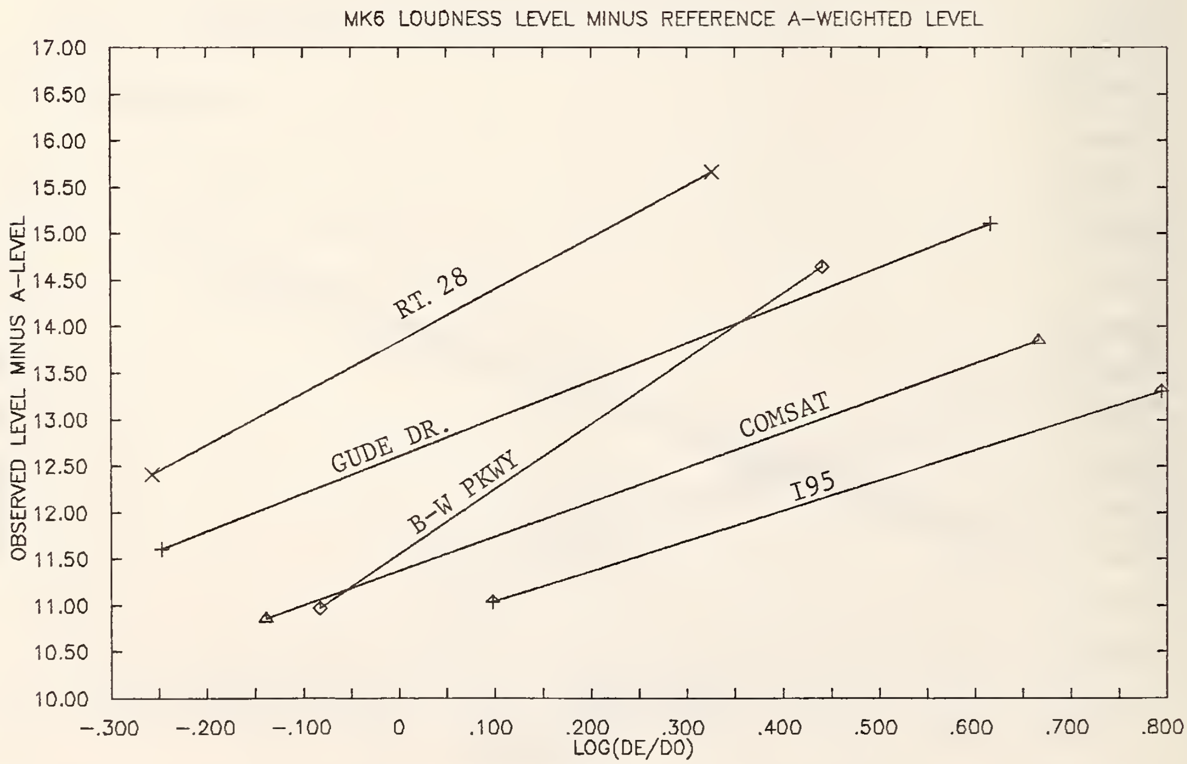

Figure 6. Average trends of the difference between the Mark VI Loudness Level and the A-weighted sound level, as functions of effective distance, for the five sites with free-flowing traffic.

Using the 20 lines from Fig. 1-5, the value of Δ was computed for $D = D_o$ for each recording session. These interpolated values are plotted in Fig. 7 versus the equivalent fraction of heavy trucks. It is seen that the twelve values corresponding to interstate traffic ($S \approx 88.5$ km/hr) lie rather closely along the regression line shown. The eight values corresponding to the slower traffic on secondary roads lie rather close to a different line, having a larger ordinate intercept and a slightly more negative slope.

In Fig. 8 the slopes of the 20 lines from Figs. 1-5 are plotted versus the equivalent fraction of heavy trucks. These slopes decrease with increasing truck traffic but show little evidence of dependence on traffic speed.

Equations of the form of Eq. (18) were fitted to all of the other noise ratings as functions of the A-weighted sound level. The resulting regression coefficients are shown in Table 8, along with the standard deviation of the residuals about the fitted curve. It is seen that the regression equations enable prediction of the noise ratings that would be likely to be used for traffic noise with standard deviations of 0.6 -0.8 dB, except for B-weighted and C-weighted noise levels, which are rarely used for predicting human response, and the Tone-Corrected Perceived Noise Level, PNT, which treats "spikes" in spectra in a very different way from that used by any of the other noise ratings. With the exception of these three ratings (B, C, PNT), the observed values for all 71 free-flowing traffic noise spectra were within ± 2.1 dB of the values computed using Eq. (18) and the regression coefficients shown in Table 8. (It should be noted that some of the regression coefficients obtained, especially for the cross-product terms (i.e., M_4 and M_5) do not lend themselves to ready interpretation from a physical point of view; these may be particularly influenced by the specific set of spectra used in this study.)

Figures 9 and 10 show the differences between the Mark VI Loudness Level and the A-weighted sound level plotted versus effective distance for the four recording sessions at the 355 & S. G. and the 355 & Q. O. sites, respectively. The mean curves for the two sites are compared in Fig. 11. The interpolated values at 15 m and the slopes of the regression lines show little, if any, systematic dependence upon traffic mix and hence plots corresponding to Figs. 7 and 8 are not included for intersection traffic. Since there is no relatively constant speed associated with stop-and-go intersection traffic, no terms involving speed were included in the regression analysis.

Table 9 gives the regression coefficients, and the associated standard deviation of the residuals, for the simple regression equation $\Delta = M_o + M_2 \log (D/D_o)$. The standard deviations of the residuals are in the range of 0.3 -0.6 dB for the noise ratings of most likely applicability to prediction of human response to traffic noise. For the D-weighted and E-weighted sound levels, the three loudness levels, and the two noisiness of levels, the observed values for all 32 spectra were within better than ± 2 dB the values computed using the M_0 and M_2 coefficients. Inclusion of terms (M_3 and M_5) involving traffic mix did not significantly improve prediction accuracies.

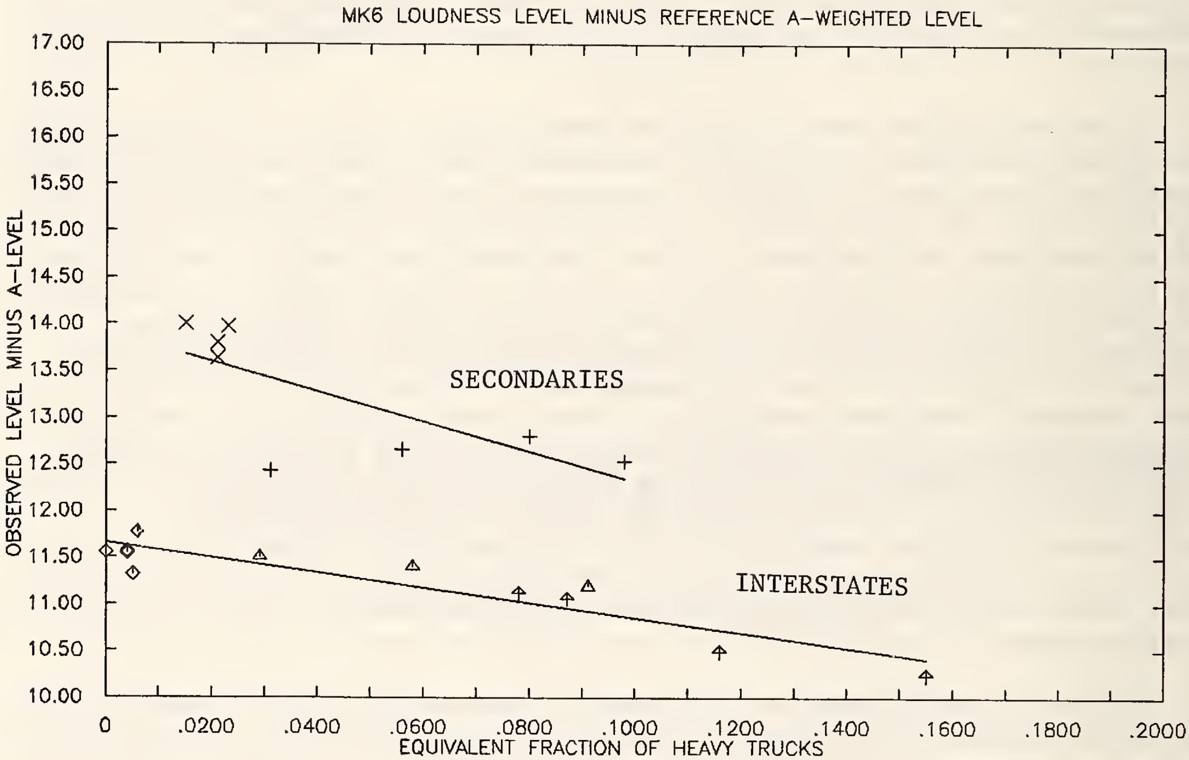

Figure 7. The difference between the Mark VI Loudness Level and the A-weighted sound level, each interpolated to an effective distance of 50 m, as a function of the equivalent fraction of heavy trucks. The lower line corresponds to the twelve recording times for interstate highways. The upper line corresponds to the eight recording sessions along the side of secondary roads.

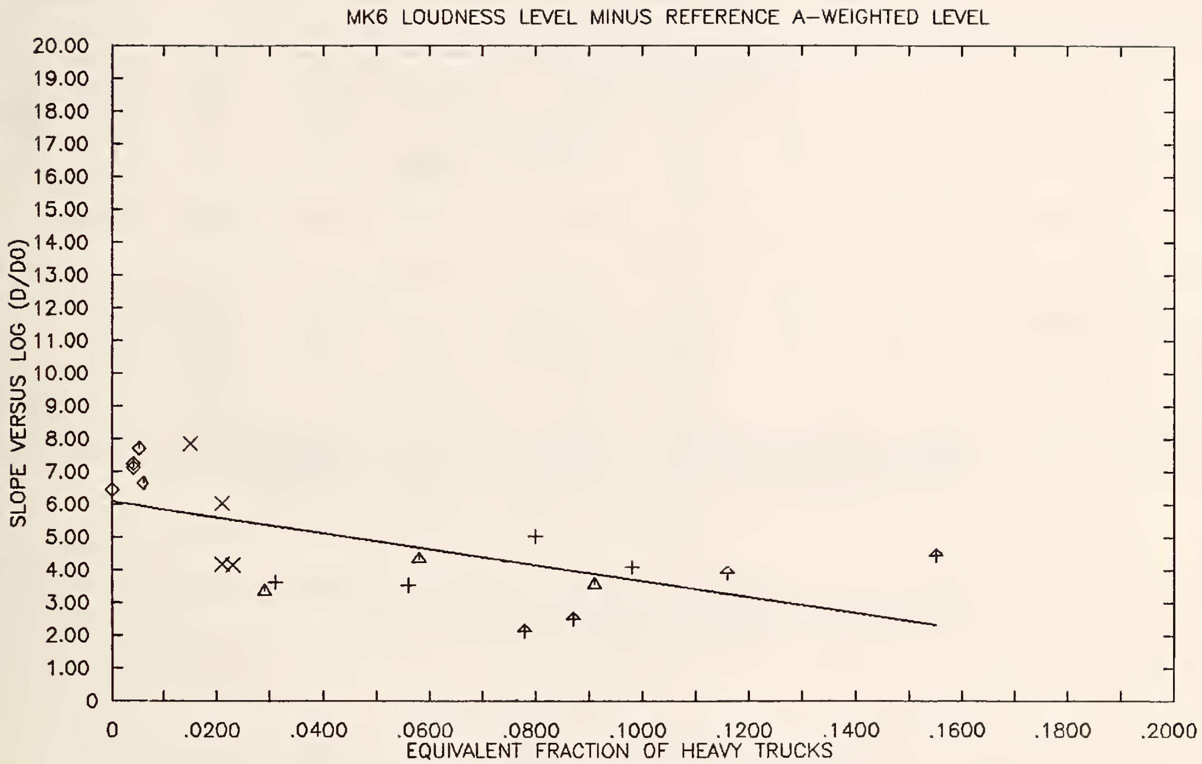

Figure 8. The slopes of the curves in Figs. 1-5 (i.e., the slopes of plots of the difference between the Mark VI Loudness Level and the A-weighted sound level as functions of the logarithm, to the base ten, of the ratio of the effective distance) as a function of the equivalent fraction of heavy trucks.

Table 8. Regression coefficients (for Eq. (18)), and associated standard deviations of the residuals, for predicting different noise ratings from the A-weighted sound level for free-flowing traffic.

Coefficient	Rating									
	B	C	D	E	MK6	MK7	ZWK	PNL	PNT	PSIL
M_0	3.2	5.3	4.5	3.2	11.9	4.4	17.6	11.6	11.3	-8.6
M_1	-19.6	-33.5	-15.0	-10.7	-16.0	-16.8	-18.2	-10.6	-16.1	-5.2
M_2	4.71	8.27	4.26	2.99	4.65	4.53	4.67	2.10	4.12	0.03
M_3	-8.34	-7.76	10.0	2.28	-8.97	-6.35	-0.83	15.1	16.9	20.6
M_4	-26.8	27.9	115.	32.1	64.8	83.4	121.	153.	148.	189.
M_5	-11.9	-18.5	-22.8	-16.1	-10.3	-16.8	-15.9	-20.6	-22.9	-20.5
s	1.1	1.4	0.7	0.6	0.7	0.8	0.7	0.6	1.0	0.6

In conclusion, the results presented above indicate that, in the case of both free-flowing and stop-and-go highway traffic noise, one frequency rating can be predicted from another rating, using simple regression equations, with standard deviations on the order of 1 to 2 dB. In addition, if the regression equations incorporate terms for traffic speed, traffic mix, and distance from the highway, these standard deviations may be reduced to 0.5 to 1 dB, depending on the particular frequency rating of interest. These uncertainties are less than those typically associated with noise measurements. Thus, for traffic noise the choice of which frequency weighting is utilized does not appear to be critical since dose-response relationships based upon a particular frequency weighting can easily be translated into equivalent dose-response relationships incorporating another frequency weighting without any significant loss of uncertainty.

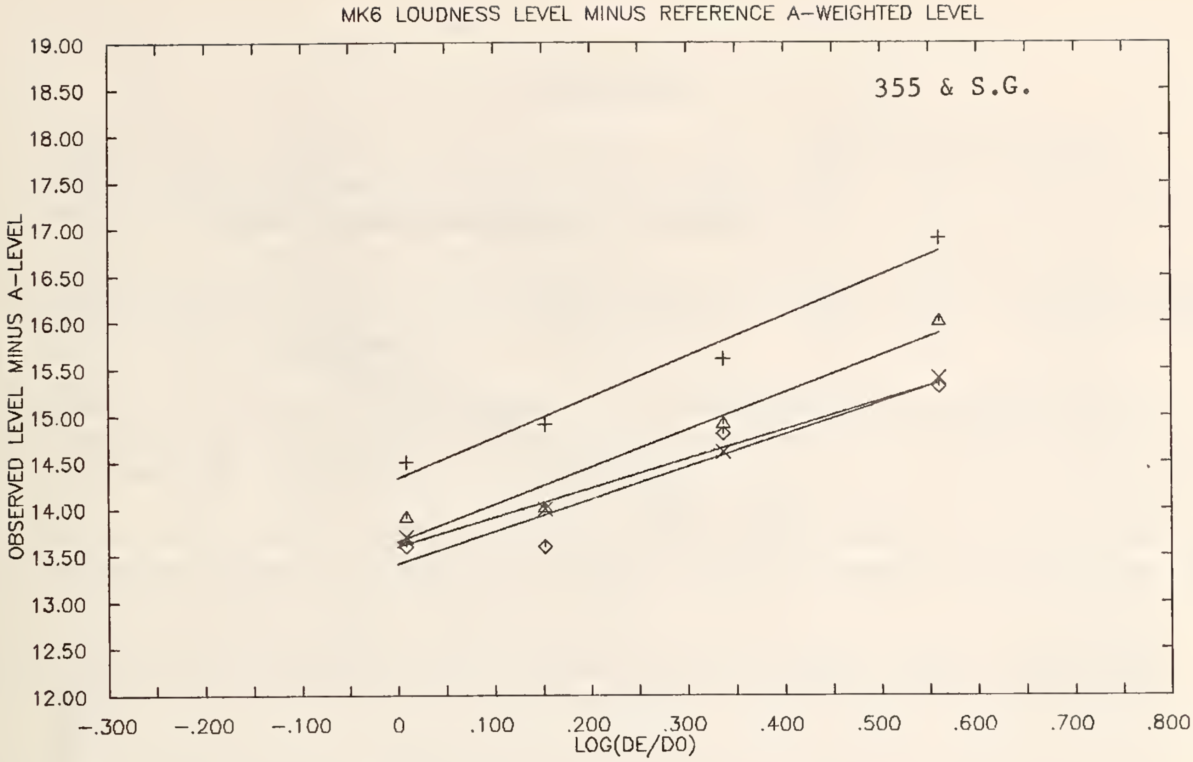

Figure 9. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the 355 & S.G. intersection.

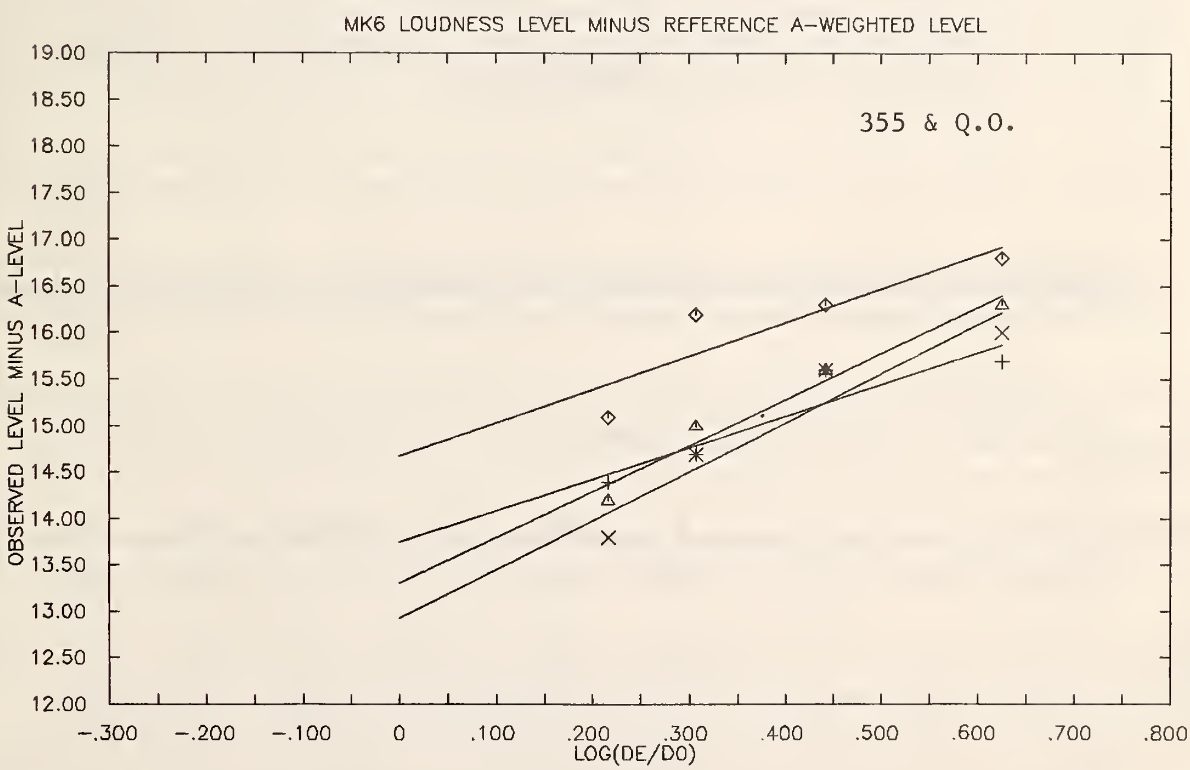

Figure 10. Difference between the Mark VI Loudness Level and the A-weighted sound level, as a function of effective distance, for the four recording times at the 355 & Q.O. intersection.

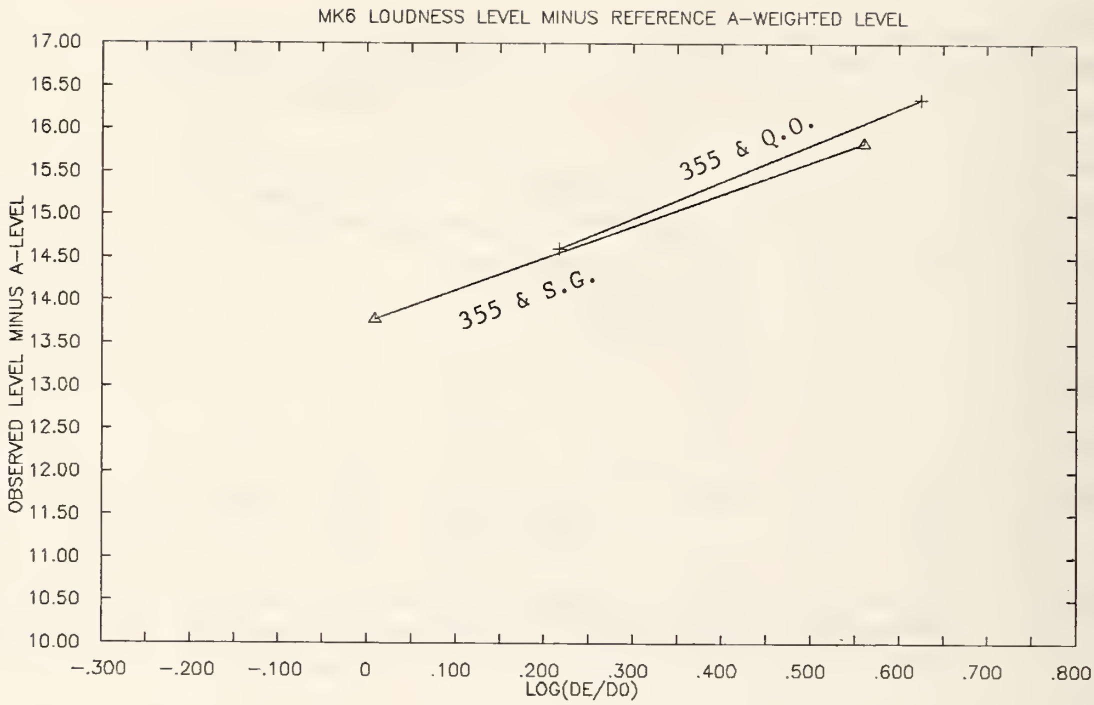

Figure 11. Average trends of the difference between the Mark VI Loudness Level and the A-weighted sound level, as functions of effective distance, for the two intersections.

Table 9. Regression coefficients (for first and third terms of Eq. (18)), and associated standard deviations of the residuals, for predicting different noise ratings from the A-weighted sound level for intersection traffic.

Coefficient	Rating									
	B	C	D	E	MK6	MK7	ZWK	PNL	PNT	PSIL
M_0	6.2	10.6	6.8	5.0	13.7	6.1	19.5	14.2	14.3	-7.8
M_2	4.2	6.0	2.7	2.2	4.0	2.9	3.1	0.5	0.4	-2.6
s	0.7	0.9	0.5	0.4	0.5	0.3	0.3	0.6	0.7	0.6

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Appendix A. Literature on Traffic Noise Spectra

This appendix contains a brief comparison of selected traffic noise spectra from the literature with some of the traffic noise spectra obtained in conjunction with the present investigation.

A.1 Literature Data

Many spectra have been reported for motor vehicle noise throughout the literature. For the purposes of this report, attention was given only to those studies which provide traffic noise spectra, rather than spectra for discrete, individual vehicle passbys. Included are typical traffic noise spectra corresponding to a variety of traffic conditions, including low- and high-speed cruise, stop-and-go traffic, arterial streets, freeways, passenger cars only, and mixed truck, bus, and automobile traffic. The traffic noise data reported in the literature were obtained from measurements performed at various distances from the roadways, ranging from 4 m to 30 m, although most reported spectra are for measurements performed at either 7.5, 15, or 30 m. Several references present spectra corresponding to L_{10}, the level exceeded 10 percent of the time; however, in most studies "average" spectra are reported where the averaging is of maximum levels, or some sort of average over time. In several of the reported studies, "average" is left undefined. With one exception, all the reported spectra are octave band levels.

The traffic noise spectra found in the literature are presented graphically in Figs. A1 through A4. The spectra have been grouped into L_{10} spectra (Fig. A2) and average spectra at distances of 7.5, 15, and 30 m (Figs. A1, A3, and A4, respectively). The literature reference from which each of these spectra was taken is indicated in the figure; a summary of the conditions under which each spectrum was measured is provided in Table A1. It will be noted that in some of the studies substantial variations in the level of the spectra occur. These differences in sound pressure level are due to the differences in vehicle speed, traffic volume, traffic mix, and averaging technique used in the various studies.

In order to allow easier comparison of the shapes of the individual spectra found in the literature, the reported band levels were normalized relative to the A-weighted sound level corresponding to each spectrum. This was done by computing the A-weighted level for each spectrum and then subtracting the A-weighted level from the level in each octave band. These normalized spectra are presented in Figs. A5 through A8. Comparison of these figures indicates that the shapes of individual spectra are generally similar regardless of the details of the traffic situation or measurement method. However, a comparison of individual spectra suggests that there will be source spectrum shape differences due to vehicle speed and traffic mix. The number of samples included in various studies is too small and in many cases the detail provided by individual references is not sufficient to allow for any general conclusions to be made.

The envelope defining the normalized spectra of Figs. A5 through A8 is presented in Fig. A9. Due to the emphasis placed on the middle frequencies by the normalization relative to A-weighted levels, the envelope of Fig. A9 displays its greatest range in the lowest and the highest octave bands. In

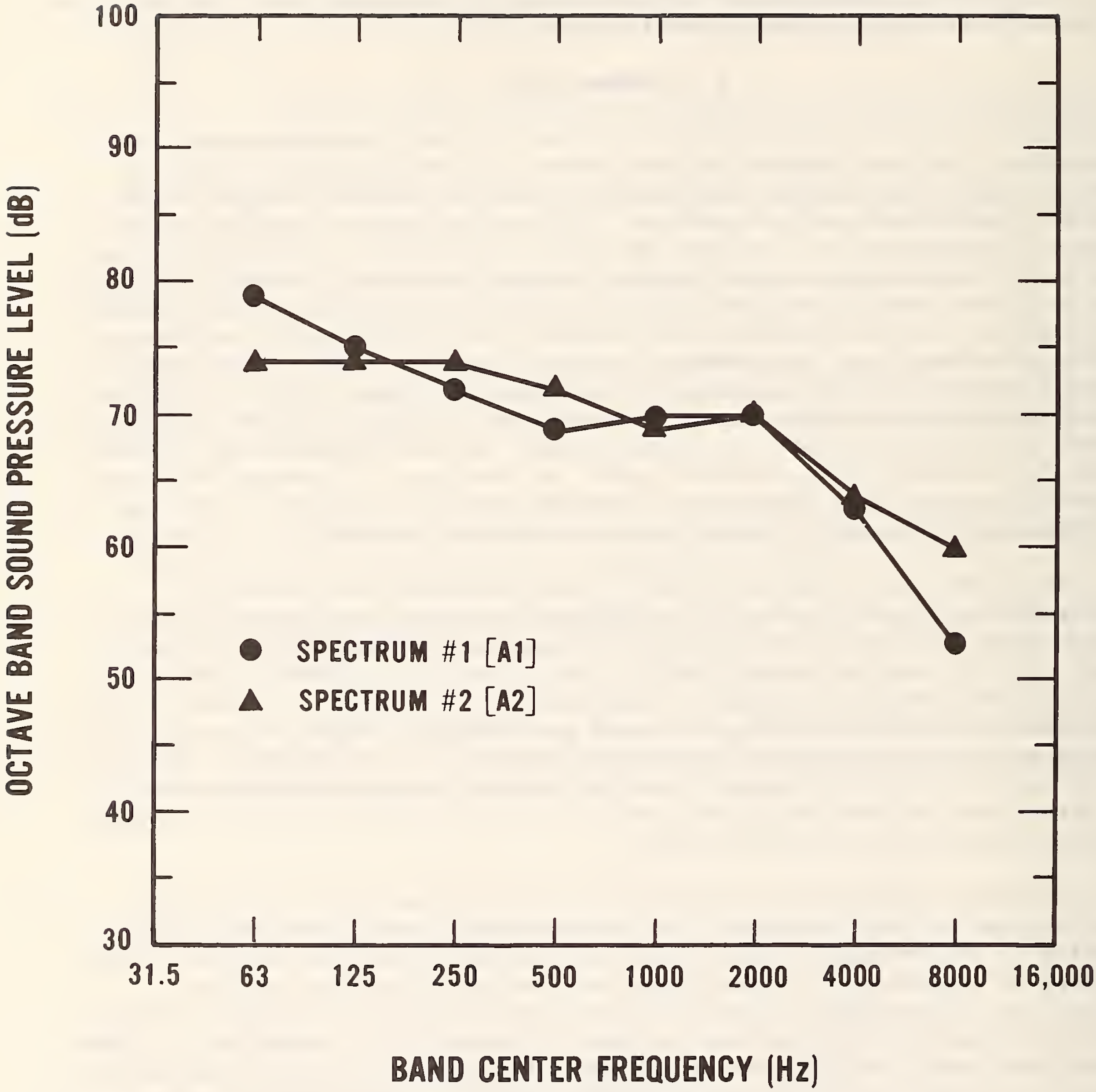

Figure A1. Published "average" traffic noise spectra at 7.5 m.

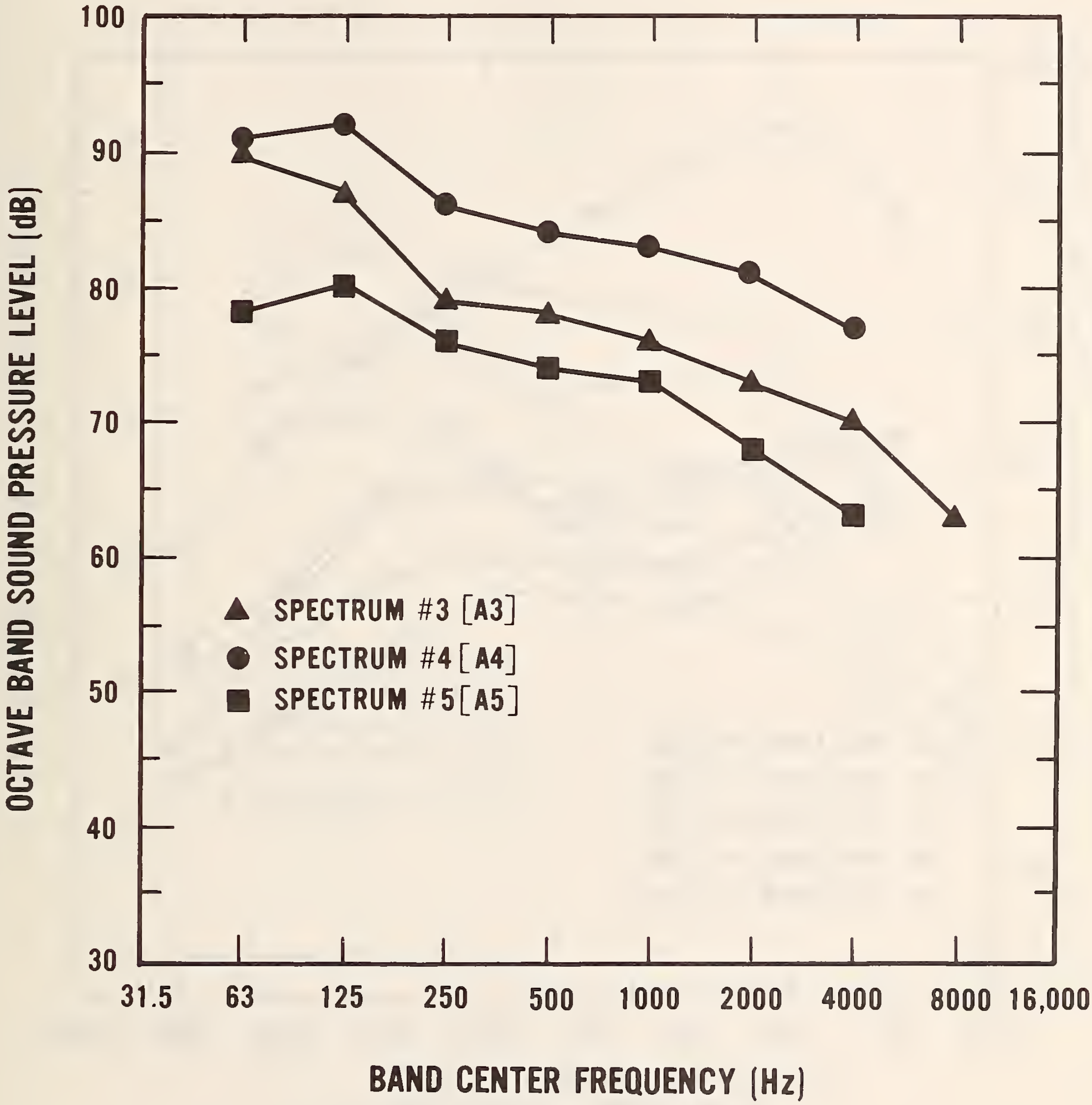

Figure A2. Published L10 traffic noise spectra at 4 to 25 m.

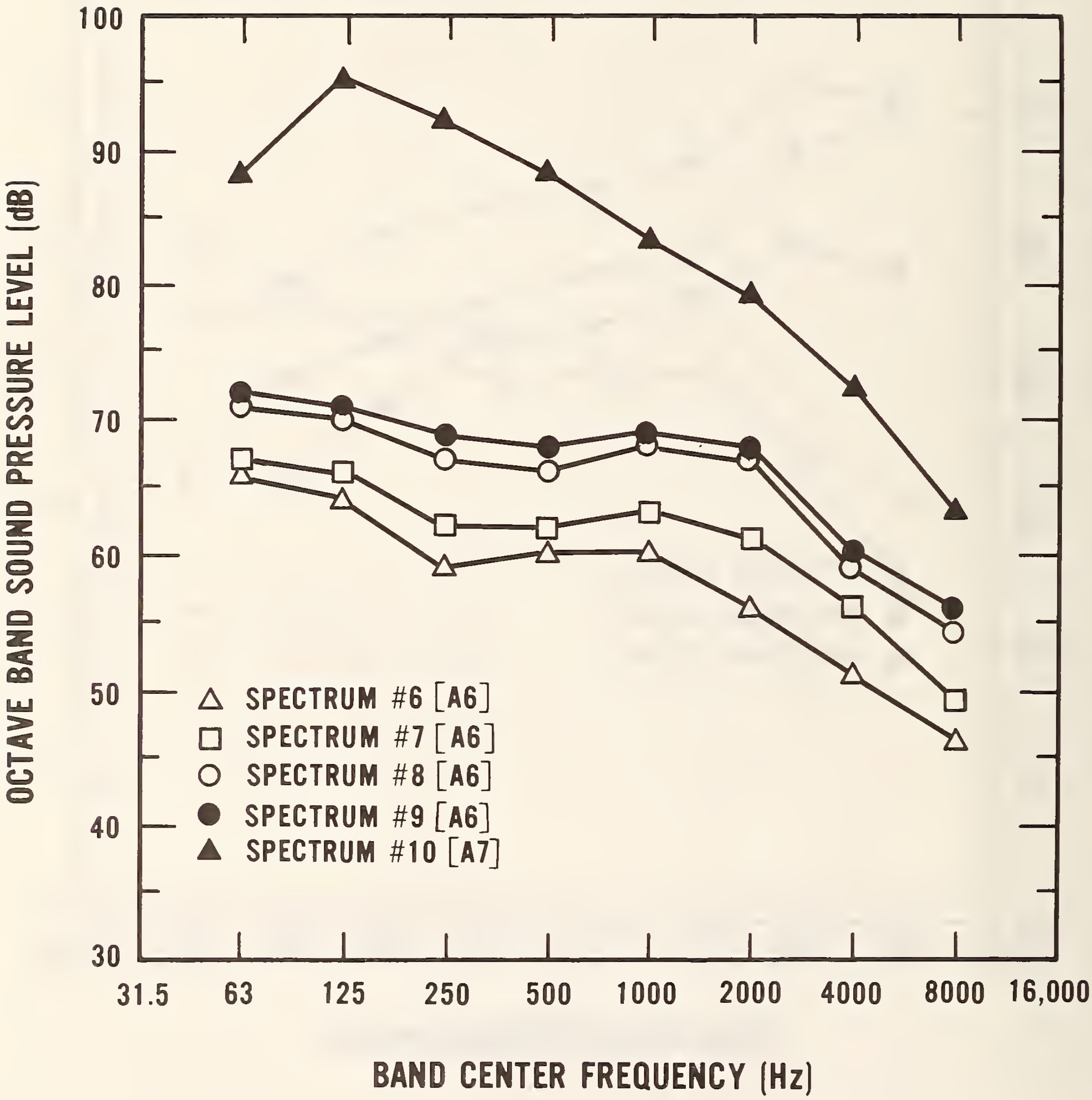

Figure A3. Published "average" traffic noise spectra at 15 m.

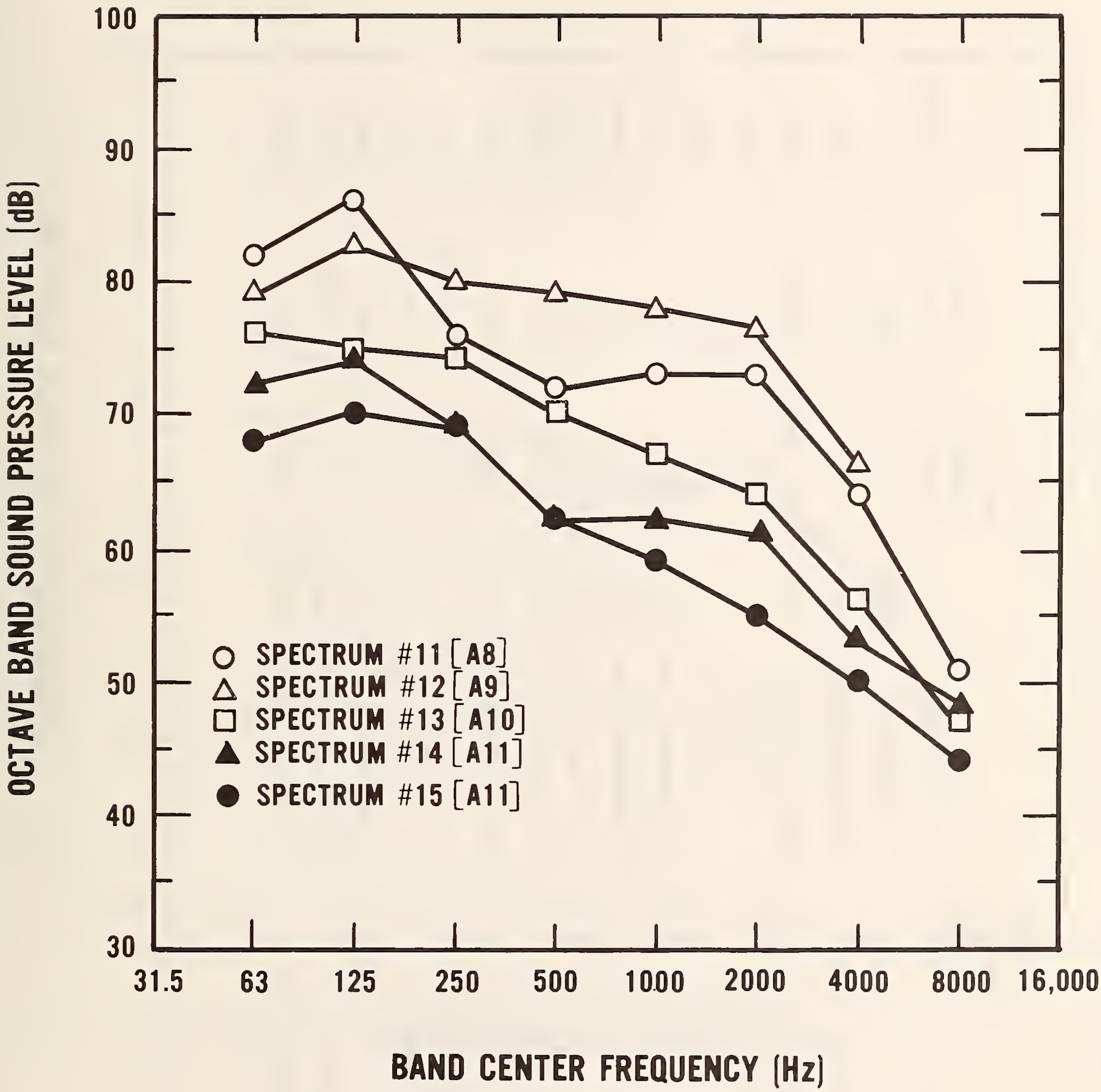

Figure A4. Published "average" traffic noise spectra at 30 m.

Table A1. Summary of conditions for the published traffic noise spectra.

Spectrum No.	Sound Level Metric	Distance from Roadway (m)	Traffic Mix	Vehicle Speed (km/hr)	Roadway Type	Country	Reference No.
1	N/A	7.5	Passenger Cars Only	64	N/A	USA	A1
2	Average (Unspecified)	7.5	Passenger Cars Only	105	N/A	USA	A2
3	L10-Average 5 sites	4-25	Cars, Trucks, Buses	Low Speed	Urban	Italy	A3
4	L10-Average 8 sites	10	Mixed Traffic	N/A	N/A	Netherlands	A4
5	L10	4	N/A	N/A	N/A	England	A5
6	Mean Level	15	Passenger Cars Only	48-64	N/A	Canada	A6
7	Mean Level	15	Passenger Cars Only	64-80	N/A	Canada	A6
8	Mean Level	15	Passenger Cars Only	80-97	N/A	Canada	A6
9	Mean Level	15	Passenger Cars Only	97-113	N/A	Canada	A6
10	N/A	12	N/A (Heavy Traffic	N/A	N/A	USA	A7
11	Average of Maximums	30	Cars and Trucks	80-113	Highway	USA	A8
12	Average of Range Maximums	30	N/A	N/A	Freeway	USA	A9
13	N/A	30	Passenger Cars Only	N/A	N/A	USA	A10
14	Average (Unspecified)	30	Passenger Cars Mostly	97	Freeway	USA	A11
15	Average (Unspecified)	30	Passenger Cars Mostly	48-56	Arterial	USA	A11

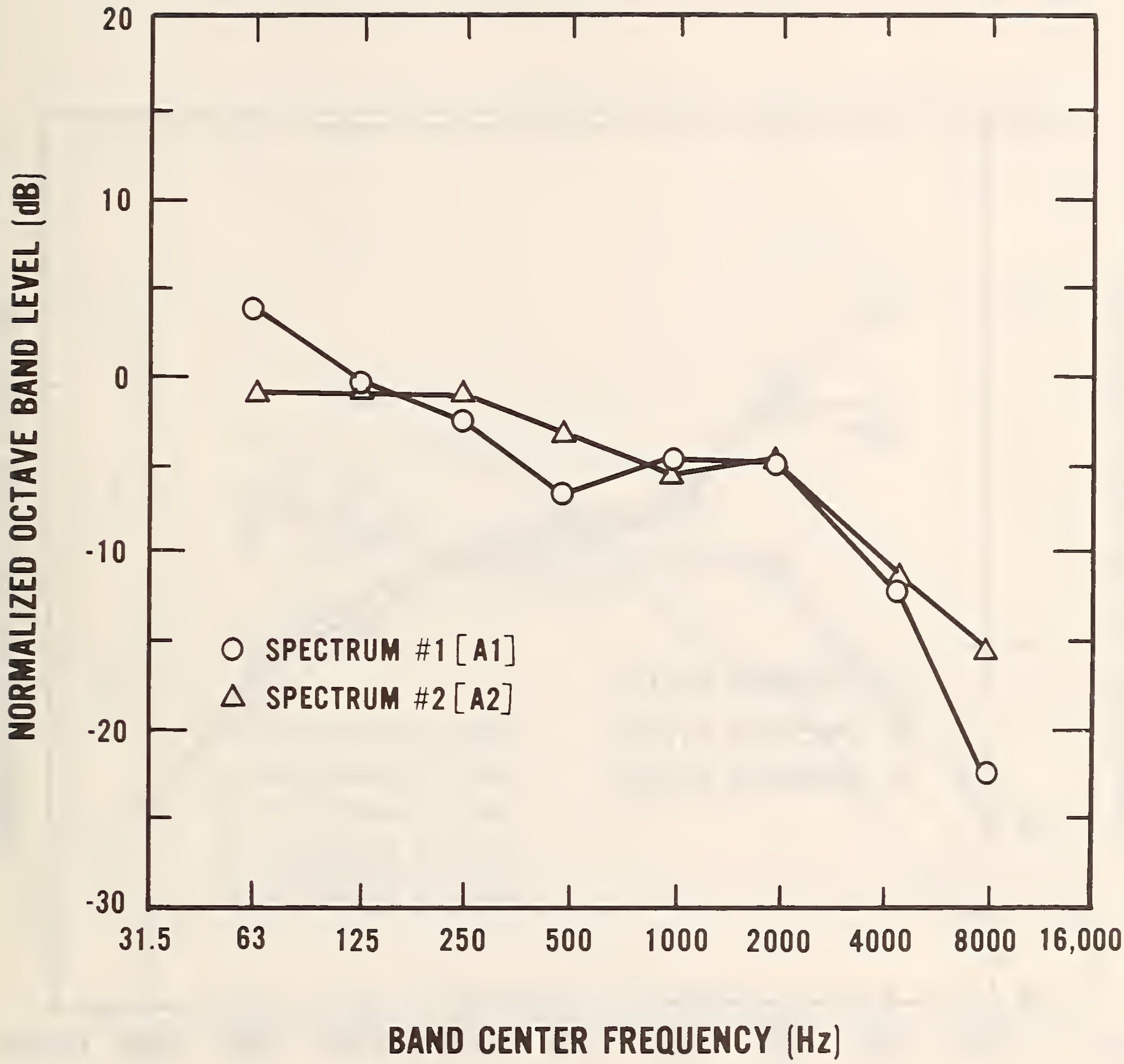

Figure A5. Normalized "average" traffic noise spectra at 7.5 m.

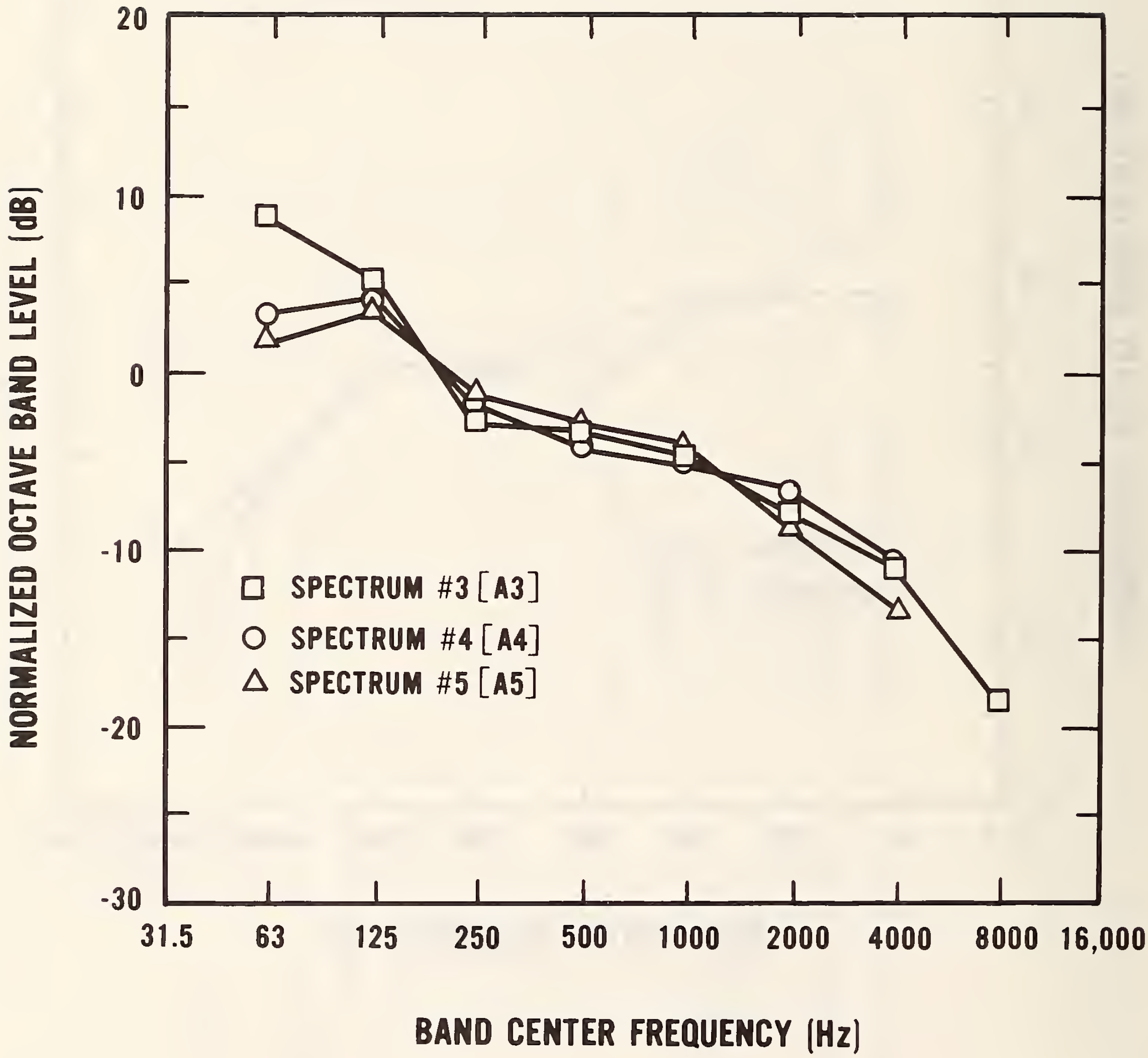

Figure A6. Normalized L10 traffic noise spectra at 4 to 25 m.

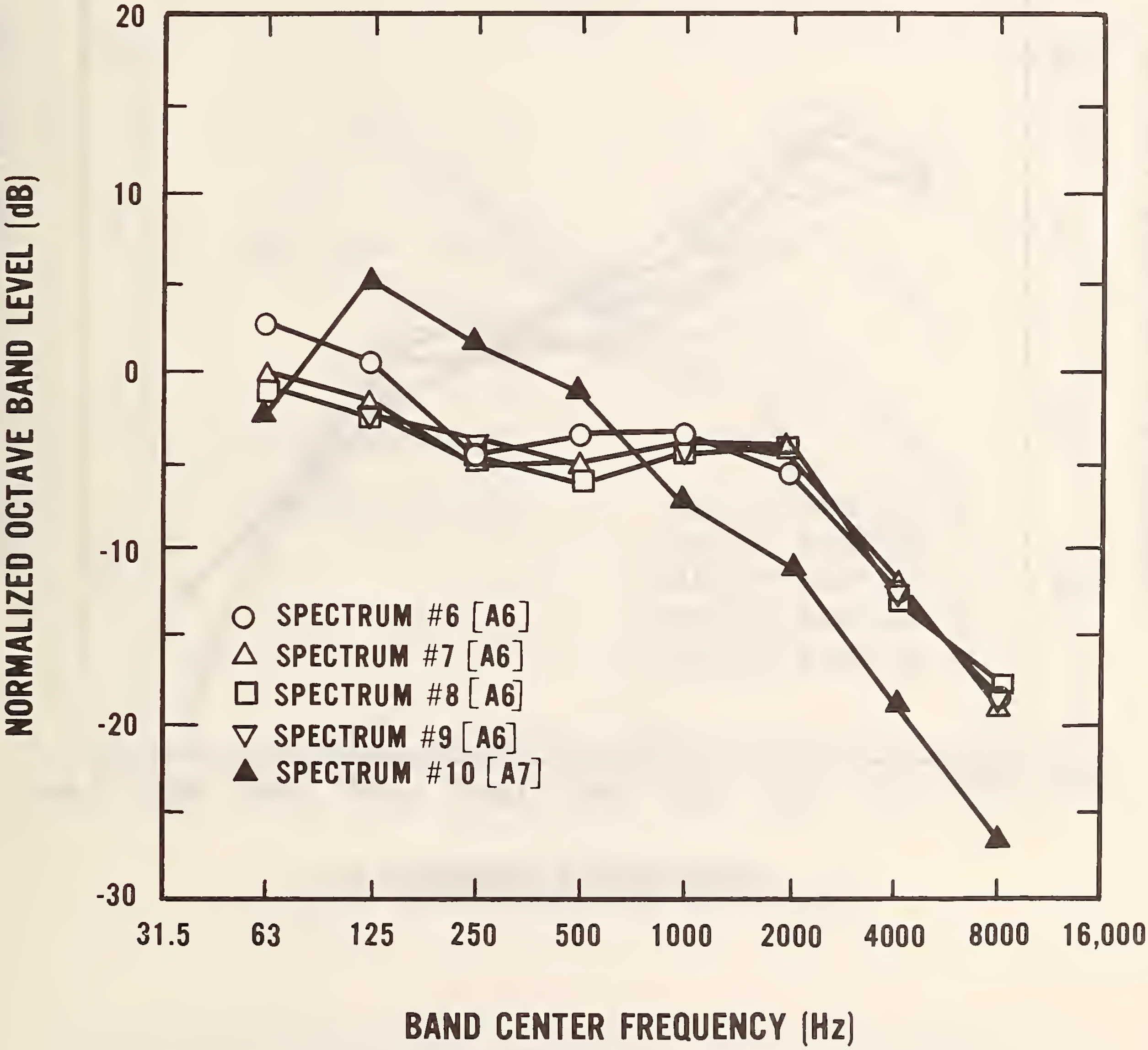

Figure A7. Normalized "average" traffic noise spectra at 15 m.

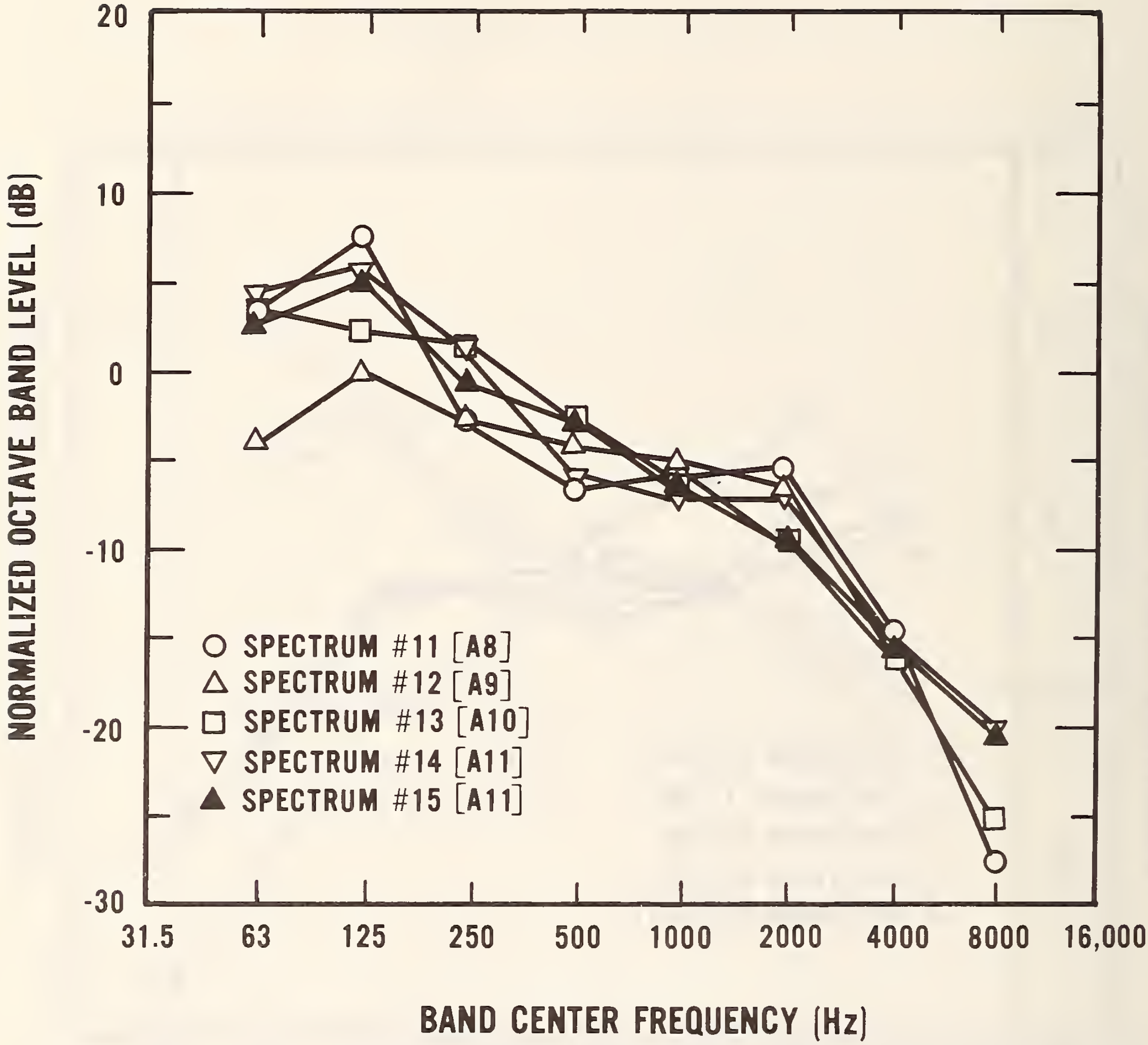

Figure A8. Normalized "average" traffic noise spectra at 30 m.

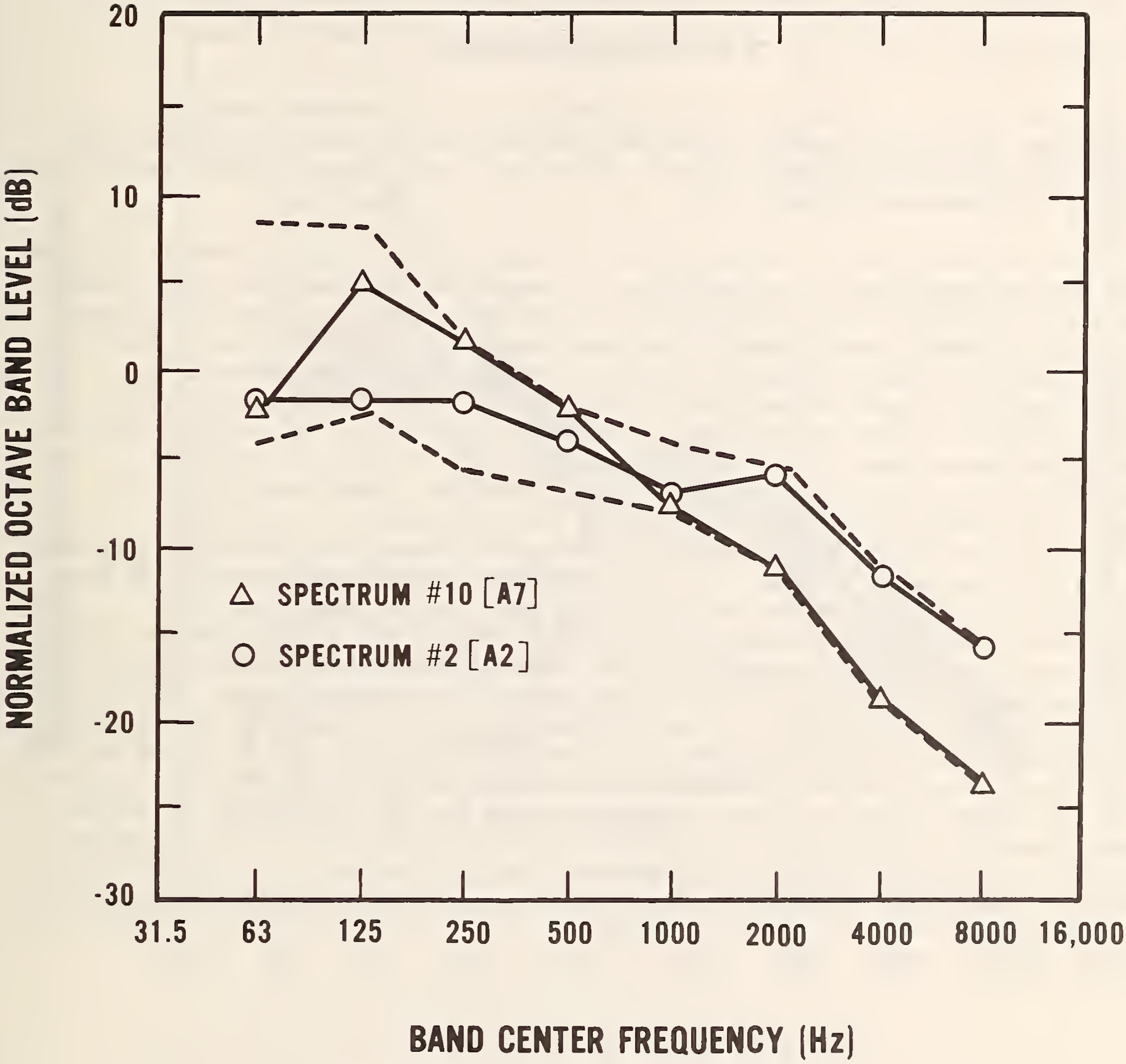

Figure A9. Range defined by normalized traffic noise spectra.

these bands, the envelope width is about 12 dB. In the middle frequency range, the width is as small as 5 dB. Within the envelope, individual spectra may vary in overall shape by an amount allowed by the limits of the envelope. As an example of this, two extreme spectrum shapes also are presented in Fig. A9.

A.2 Data from Present Study

As part of the present study, a library of 107 15-minute analog recordings of actual highway noise was obtained by the staff of the National Bureau of Standards at various times of day at seven sites. These recordings are fully documented in Ref. A12.

For the analyses in the main body of this report, the measured 1/3-octave band spectra were used. To facilitate a comparison between the traffic noise spectra obtained in the present study and those reported in the literature, octave band levels were computed for one recording, corresponding to the 15-m microphone position, at each of the seven sites used in the present investigation. These octave-band data, computed from the energy-averaged (LEQ) 1/3-octave band spectra and normalized relative to the corresponding A-weighted sound levels, are plotted in Fig. A10. Comparison with the published data (Figs. A5 through A8) indicates that these seven selected spectra are similar to those reported in the literature. For further comparison, the range defined by the individual normalized octave band levels of Fig. A10 is shown in Fig. A11 along with two individual spectra. As was observed with the corresponding plot (Fig. A9) for the published data, individual spectra may vary in overall shape within the envelope shown. To allow for a more direct comparison, the range of normalized octave-band levels for published data (Fig. A9) and the range from the current study (Fig. A11) are both shown in Fig. A12. It can be seen that the normalized octave-band level ranges established from the published data and from the selected data of the current study are very similar. The ranges are within 2 dB of each other over the entire frequency range, except in the 63, 125, and 8,000 Hz octave bands where the limits of the ranges differ by no more than 4 dB. To within a few dB, none of the published octave-band spectral shapes is excluded by the range of individual normalized octave-band levels from the data set collected in this study.

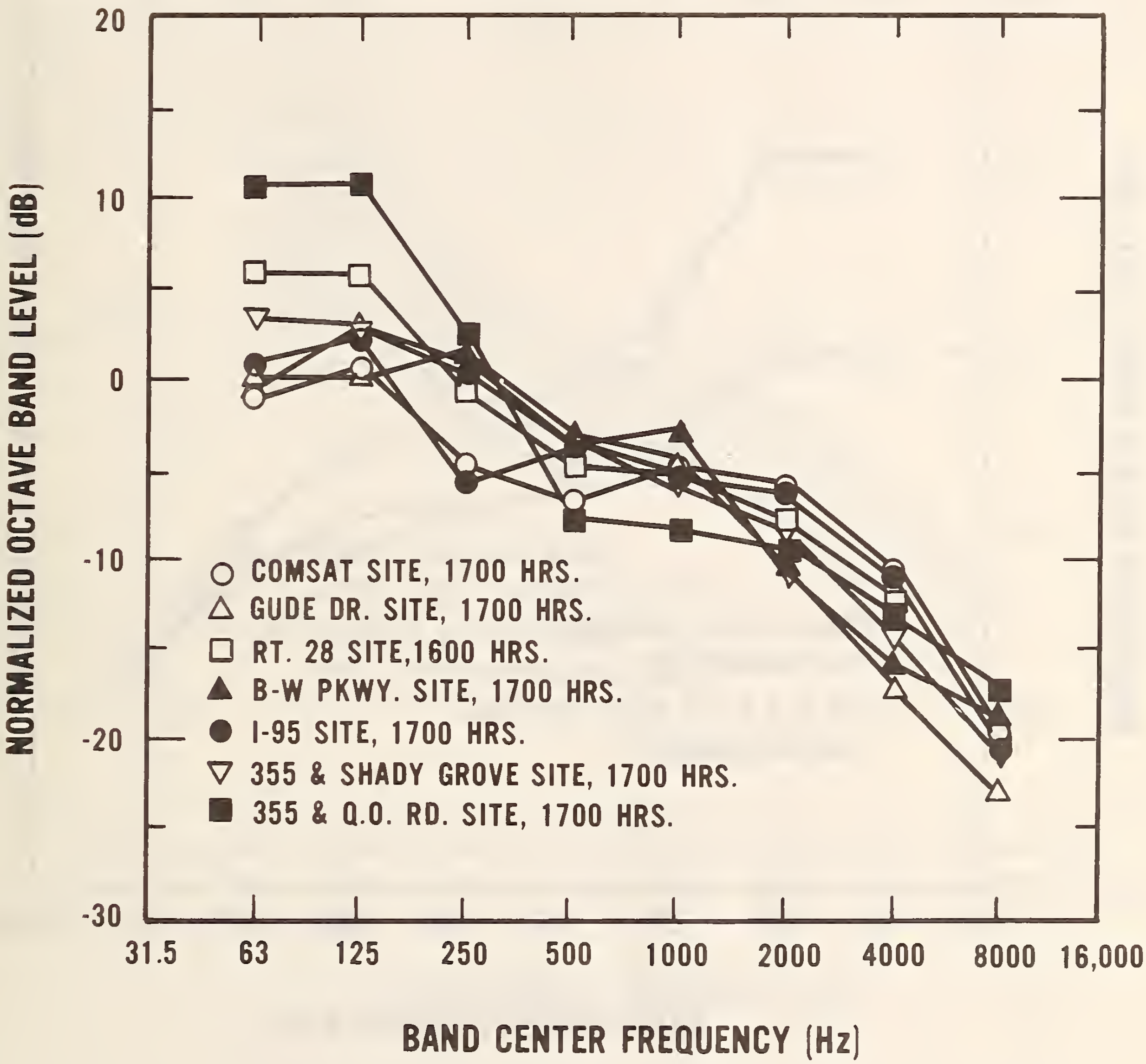

Figure A10. Normalized LEQ octave band spectra for each of the seven actual traffic noise recording sites of Section 2.1 at the 15-m microphone position.

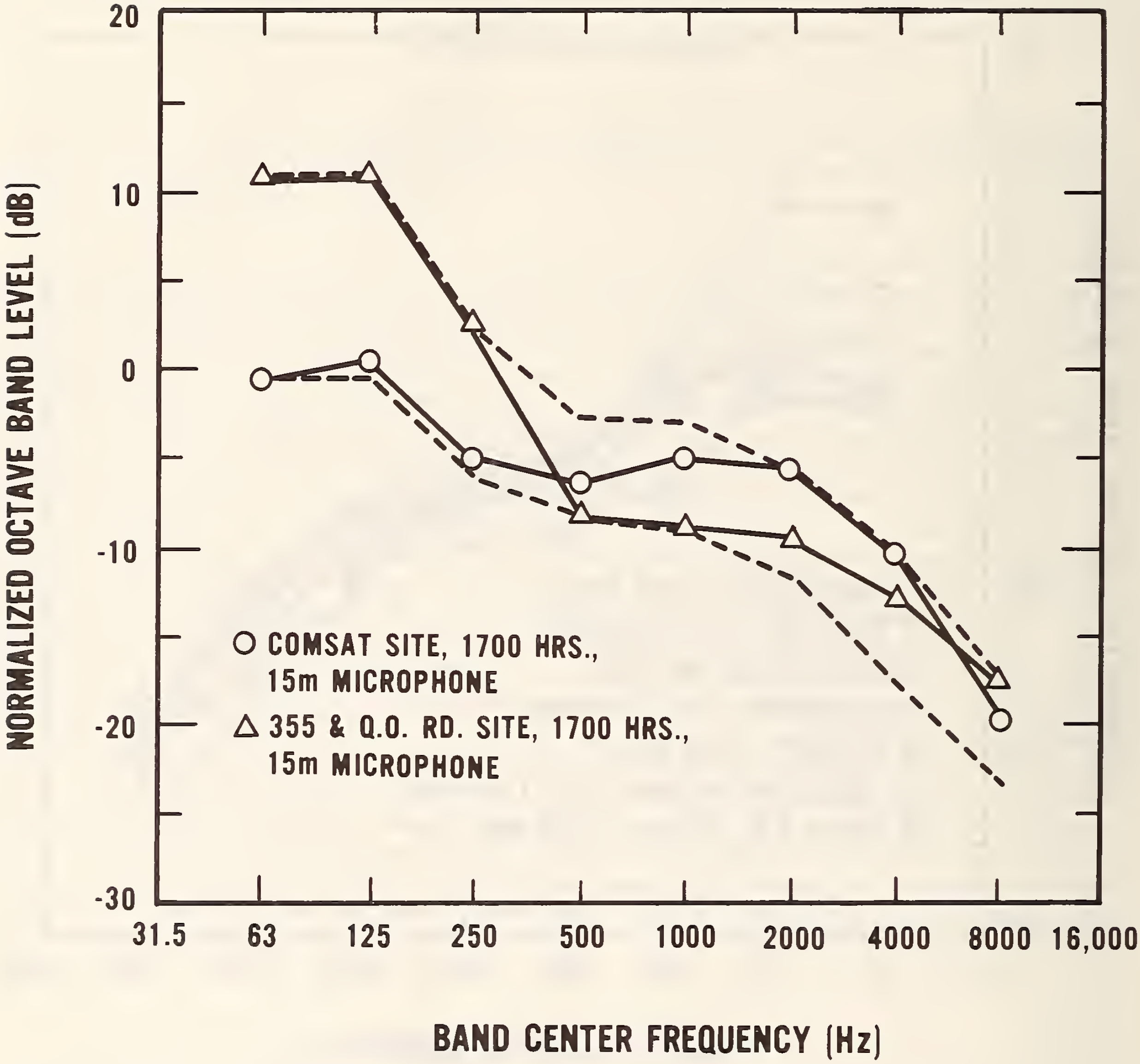

Figure A11. Range of normalized octave band levels for each of the seven actual traffic noise recording sites of Section 2.1 at the 15-m microphone position.

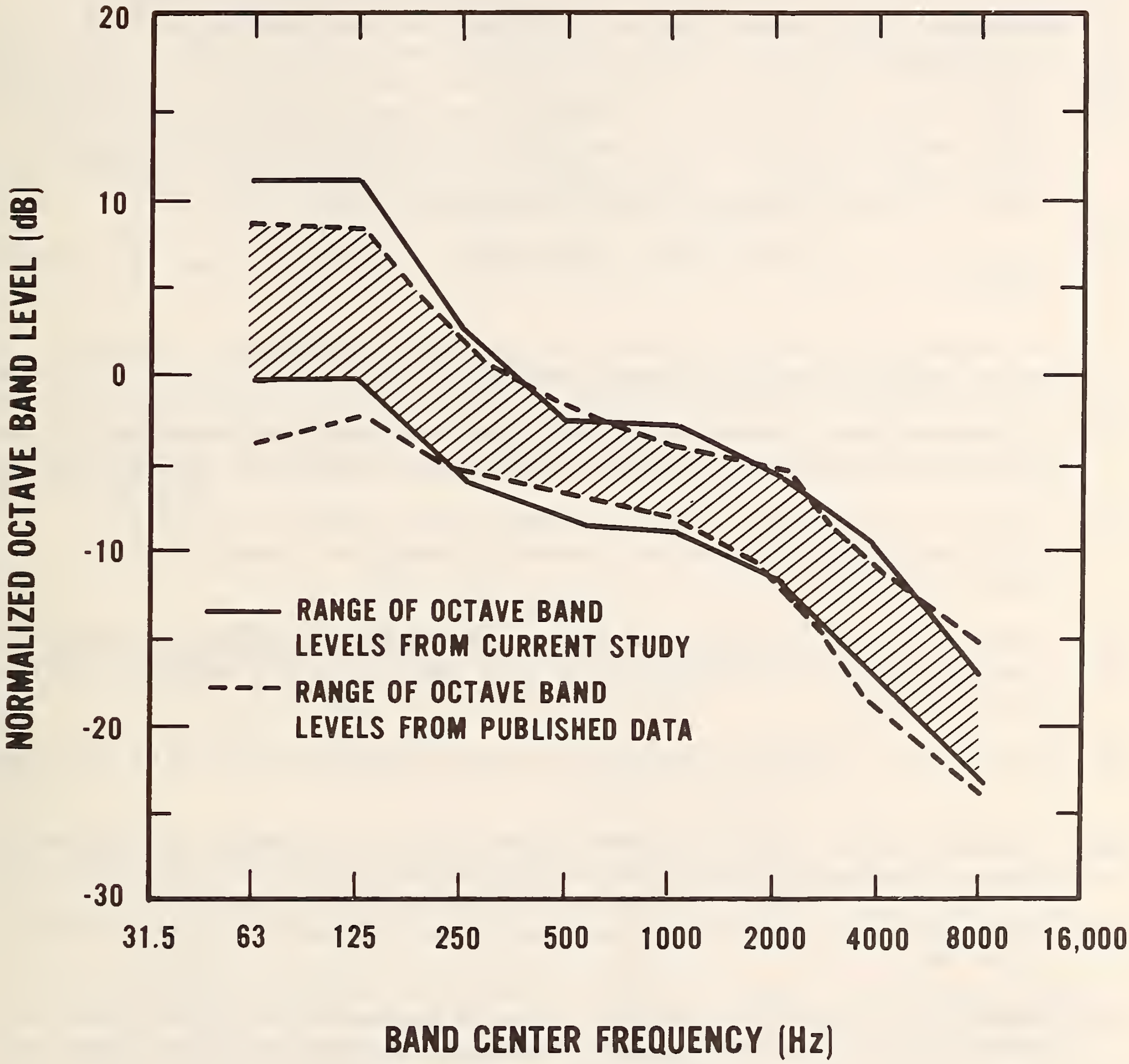

Figure A12. Comparison of ranges of normalized octave band levels for the published data of Fig. A9 and for the data of Fig. A11 from the current study.

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Appendix B. Equivalent Lane Concept

In order to establish the "effective location" of a highway such that a plot of sound level versus the logarithm of distance (from the "effective location" to the point of observation) will, ideally, be a straight line, one hypothesizes a single virtual lane into which all the traffic is placed. The resultant average sound level is given by

$$LEQ = 10 \log \left[\left(\frac{D_o}{D} \right)^{\nu} \sum_{i=1}^{I} \sum_{j=1}^{J} \frac{\pi D_o V_{ij} Q_{ij}}{S_{ij}} \right], \tag{B1}$$

where D is an effective distance from the point of observation to the center of the virtual lane, ν is an effective average exponent, and all other variables are as defined in Sec. 4.2. In order to obtain the values for D and ν, one requires that Eqs. (9) and (B1) yield the same average sound level, thus obtaining

$$\left(\frac{D}{D_o} \right)^{\nu} = \frac{\sum_{i=1}^{I} \sum_{j=1}^{J} \frac{f_{ij} Q_{ij}}{S_{ij}}}{\sum_{i=1}^{I} \sum_{j=1}^{J} \frac{f_{ij} Q_{ij}}{S_{ij}} \left(\frac{D_o}{D_j} \right)^{\nu_i}}, \tag{B2}$$

where $f_{ij} = V_{ij}/(\Sigma\Sigma V_{ij})$ is the fraction of total traffic corresponding to the i-th class of vehicles and the j-th lane. By selecting a reasonable value for ν, Eq. (B2) yields the effective distance, D. The value obtained for D is very insensitive to the value selected for ν.

In computing effective locations of virtual lanes in the present study, the values of f_{ij} were obtained from traffic counts and classifications made from the video recordings obtained simultaneously with the audio recordings. The values of S_{ij} were obtained from radar observations of traffic speed obtained simultaneously with the audio recordings. The A-weighted "source strengths" for three classes of vehicles (automobiles, medium trucks, and heavy trucks) were taken from the FHWA Highway Traffic Noise Model (Refs. 20-23 in Sec. 5).

If all of the data required for Eq. (B2) are not available, simplified expressions can be used, sometimes with little loss of accuracy. The most obvious first step is to assume that all vehicles are traveling at the same speed, regardless of lane or vehicle class. If all values of S_{ij} are the same, Eq. (B2) reduces to

$$\left(\frac{D}{D_o}\right)^{\nu} = \frac{\sum_{i=1}^{I} \sum_{j=1}^{J} f_{ij}\, Q_i}{\sum_{i=1}^{I} \sum_{j=1}^{J} f_{ij}\, Q_i (D_o/D_j)^{\nu_i}} , \qquad \text{(B3)}$$

where Q_{ij} has been replaced by Q_i since it is assumed that all lanes of traffic are running at the same speed. If it is further assumed that all lanes are carrying the same mix of traffic, Eq. (B3) can be simplified to

$$\left(\frac{D}{D_o}\right)^{\nu} = \frac{J \sum_{i=1}^{I} f_i Q_i}{\sum_{i=1}^{I} \left\{ f_i Q_i \sum_{j=1}^{J} (D_o/D_j)^{\nu_i} \right\}} , \qquad \text{(B4)}$$

where

$$f_i = \sum_{j=1}^{J} f_{ij} \qquad \text{(B5)}$$

is the fraction of vehicles in a given class, regardless of the lane. Equation (B4) should be reasonably accurate when all lanes, in both directions, are carrying roughly the same volume and mix of traffic. If it can further be assumed that $\nu_i = \nu =$ a constant, independent of the class of vehicle, Eq. (B4) reduces to

$$\left(\frac{D}{D_o}\right)^{\nu} = J \left[\sum_{j=1}^{J} (D_o/D_j)^{\nu} \right]^{-1} \qquad \text{(B6)}$$

independent of the mix of traffic or the source strength, Q_{ij}, of the various classes of vehicles.

In the present report, values of D_e were computed using Eq. (B2) but with the simplification that all lanes in a given direction were assumed to carry the same mix and speed of traffic. The values for ν_i and ν were all taken as 1.5, as in the FHWA Highway Traffic Noise Model.

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5. AUTHOR(S)

Daniel R. Flynn and Simone L. Yaniv

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

A series of calculations was performed to ascertain how well one frequency-weighted rating, such as weighted sound level, loudness level, or perceived noise level, may be predicted from another such rating. A total of 103 average sound level spectra, measured at several distances from different types of highways, were used in these calculations. It was found that knowing a single noise rating, such as the A-weighted sound level, enables one to predict other outdoor ratings in this set of 103 spectra with a standard deviation of the order of 1 to 2 dB. If, in addition, traffic speed and mix and the distance to the highway are taken into account, these standard deviations can be reduced to 0.5 to 1 dB, depending upon the particular noise rating of interest. Equations are given for predicting one rating from another; the associated standard deviations are presented as a measure of how well any given rating can be predicted from a single measured, or otherwise known, noise rating. It is concluded that it is not very critical which frequency-weighting procedure is used in conjunction with highway noise criteria since one descriptor can be predicted from another with a rather small statistical uncertainty. Thus, if human response criteria, or stimulus-response relationships, have been developed in terms of one frequency-weighting procedure, these may be translated into equivalent criteria expressed in terms of a metric that is easier to measure or predict.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

acoustics; environmental pollution; highway noise; motor vehicle noise; noise; noise control; sound; traffic noise; transportation noise.

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Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NBS, NBS annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NBS under the authority of the National Standard Data Act (Public Law 90-396).

NOTE: The principal publication outlet for the foregoing data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St., NW, Washington, DC 20056.

Building Science Series—Disseminates technical information developed at the Bureau on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

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