UMTA 79-25

REPORT NO. UMTA-MA-60-0099-79-3

NOISE RATING CRITERIA FOR ELEVATED RAPID TRANSIT STRUCTURES

Theodore J. Schultz

BOLT BERANEK AND NEWMAN INC.
50 Moulton Street
Cambridge MA 02138

REPRINT
MARCH 1980

INTERIM REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
URBAN MASS TRANSPORTATION ADMINISTRATION
Office of Technology Development and Deployment
Office of Rail and Construction Technology
Washington DC 20590

NOTICE

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

NOTICE

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

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTA-MA-06-0099-79-3		
4. Title and Subtitle: NOISE RATING CRITERIA FOR ELEVATED RAPID TRANSIT STRUCTURES		5. Report Date: Reprint March 1980
		6. Performing Organization Code
7. Author(s): Theodore J. Schultz		8. Performing Organization Report No.: DOT-TSC-UMTA-79-25
9. Performing Organization Name and Address: Bolt Beranek and Newman Inc.* 50 Moulton Street Cambridge, MA 02138		10. Work Unit No. (TRAIS): UM949/R9743
		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 Rail and Construction Technology Washington, DC 20590		13. Type of Report and Period Covered: Interim Report July-August 1978
		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
Cambridge, Massachusetts 02142

16. Abstract

This report examines the requirements for descriptors that would be suitable for rating elevated structure noise, reviews existing noise ratings, concludes that the only suitable candidates are the average sound level L_{eq} and the day-night average sound level Ldn, and examines and resolves the possible disadvantages of these choices. The report also reviews studies that have been made to determine the impact of rail transportation noise on the community, compares subjective response to rail noise with that due to road traffic and aircraft noise, and finds these responses to be nearly the same. Finally, the report delineates and illustrates application of the so-called Fractional Impact Method to assessment of the community impact of elevated structure noise.

17. Key Words	18. Distribution Statement
Noise, rail transportation noise, urban rail noise, community noise, noise ratings, noise impact, elevated structure noise	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	152	

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

PREFACE

This report presents the results of the first task of a five-task program dealing with the reduction of noise from elevated structures in use in U.S. rail rapid transit systems. This report was prepared by Bolt Beranek and Newman Inc. 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 Noise Abatement Program, which is being managed for UMTA at 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 the associated costs.

Dr. Leonard G. Kurzweil of the Transportation Systems Center served as technical coordinator for the efforts leading to this report. An advisory board constituted by the American Public Transit Association and headed by Mr. Theodore S. Gordon provided many useful comments which were taken into account gratefully in preparation of the final version of this report.

The author also is indebted to Dr. Kurzweil for his careful review and helpful suggestions, and to Dr. Eric E. Ungar of the author's company for his clarification and integration of some of the report's subject matter.

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

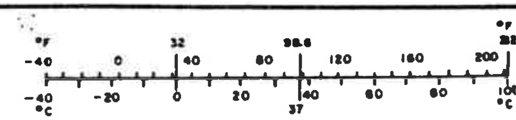


TABLE OF CONTENTS

TABLE OF CONTENTS *(Cont.)*

TABLE OF CONTENTS *(Cont.)*

LIST OF FIGURES

LIST OF FIGURES *(Cont.)*

LIST OF TABLES

SUMMARY AND INTRODUCTION

The purpose of this report is to recommend criteria for rating the noise radiated from elevated rapid transit structures during train passages, so that different types of structures can be inter-compared with respect to their noise impact on the immediate neighborhood or, alternatively, so that noise abatement programs for elevated structures may be developed on a rational basis. In developing these criteria, the report also summarizes information that is applicable to the rating of rail transportation noise in general.

The first chapter examines the requirements for a noise descriptor that would be suitable for rating elevated structure noise, and compares the existing noise ratings to determine which ones are acceptable. It turns out that the only suitable candidates are the average sound level, L_{eq}, and the day-night average sound level, L_{dn}. The chapter goes on to consider the possible disadvantages of these choices and resolves them. Supplementary background information is given in Appendices A, B, and C.

Chapter 2 reviews the existing studies that have been made to determine the impact of railway noise on the community, based on noise measurements and the results of interviews or questionnaires submitted to residents in the neighborhoods of rail lines to determine their annoyance. The subjective response to railway noise is compared with that due to road traffic and aircraft noise, and is found to be nearly the same.

Chapter 3 develops a method for assessing the community impact of elevated structure noise in terms of the so-called Fractional Impact Method, based on the results of numerous social surveys on noise, and widely used by EPA for environmental impact statements. Numerical examples are presented.

Note that for the purposes of comparing one kind of elevated structure against another, the background noise level in the absence of train passages is irrelevant and may be ignored. However, it has been accepted practice for years that, in evaluating or designing for a specific situation, one must take account of the background noise, because a noisy event that might go almost unnoticed in a bustling downtown district could be extremely intrusive in a quiet rural community. In the first case, the noise might generate little or no response, whereas in the rural situation, the community response might be violently negative.

In addition, there is the problem of balancing the extreme annoyance of a few rural residents against the moderate annoyance of many urban dwellers. The community impact computation procedure of Chapter 3 takes both of the foregoing matters into account.

Finally, despite some suggestion that railroad noise is somewhat less disturbing than other kinds of noise, it would not be prudent, in view of the larger expected number of train passages, to take credit for possible favorable attitudes toward railways when evaluating the impact of rapid transit noise.

Rapid transit noise should be evaluated, for the time being, according to the same criteria used for other transportation noise sources.

1. CRITERIA FOR RANK-ORDERING ELEVATED STRUCTURE TYPES ACCORDING TO COMMUNITY IMPACT

1.1 Introduction

Evaluation of the noise from elevated structures in rapid transit systems must be carried out in two different contexts, requiring two different noise ratings. In some cases, we are interested in comparing the noise of different kinds of elevated structures, one against the other. This comparison is best made in terms of the average maximum A-weighted sound level during a train passby, because such rating focuses upon the noise-generating *capability* of the structure. The rationale for this approach was developed for the Department of Transportation (DOT) in Ref. 1,* with respect to annoyance caused by wheel/rail noise of urban mass transit.

In other cases, we are interested in assessing how the noise of rapid transit trains on elevated structures compares with the noise impact on the community due to all *other* kinds of noise. For this purpose, in addition to the maximum passby level, we must take into account the number and duration of train passages, and put this information into a rating context that is general enough to accommodate all kinds of noise.

Until recently, there has been by no means complete agreement on the best way of describing the impact of community noise on people. Literally dozens of noise ratings have been proposed, for different purposes[2,3]. Some of these ratings are based only on the physical characteristics of the noise itself; other

*In this report, the references for each chapter or appendix are presented at the end of that chapter or appendix.

rating schemes attempt to include also the influence of situational factors. Despite their apparently quite different formulations, however, most of the ratings are highly correlated among themselves.

In the recent past, considerable attention has been given to *statistical* descriptors of community noise, because of the presumed importance of accounting for the fluctuations in loudness that typically characterize such noise. For example, the 10th and 50th percentile levels*, L_{10} and L_{50}, have been widely used for dealing with surface transportation noise.

Nowadays, however, the use of a *nonstatistical* noise measure, such as the average noise level, is rapidly gaining acceptance for evaluating various kinds of noise in certain applications. This chapter examines the reasons for this trend and explains why that kind of metric is the best currently available for DOT's purposes.

1.2 Requirements for a Suitable Noise Descriptor

Certain basic considerations affect the choice of an appropriate descriptor for environmental noise. These are summarized in the following statements:

- The effects of environmental noise on people can be discussed meaningfully only if the *total* noise exposure, regardless of individual noise sources, is considered.

---

*L_{10} and L_{50} are the A-weighted sound levels that are exceeded for 10% and 50% of the time, respectively, at a given location where the sound level fluctuates with time.

- The statement of long-term goals with respect to environmental noise must be made in terms of this total noise exposure.

For these purposes, the noise descriptor should conform to seven requirements, listed here in order of priority:

a. the measure of *total* noise exposure should be applicable in virtually all possible exposure conditions; it must apply to all kinds of noise sources and combinations of sources, so that the effects of different kinds of noise can be compared;

b. the measure should correlate well with the known effects of noise on people;

c. the required measurement equipment, with standardized characteristics, should be commercially available;

d. the noise exposure at a given location, expressed in terms of the chosen noise measure, should be predictable within acceptable tolerances from a knowledge of the physical events that produce the noise;

e. it should be simple, unambiguous, and easily understandable;

f. it should be usable for planning and monitoring, as well as for enforcement purposes;

g. the measure should be closely related to other existing methods currently in use.

These requirements are considered in the sections that follow.

1.3 Effects of Noise on People

The effects of noise on people fall into four categories:

- effects on hearing, such as temporary or permanent threshold shift
- interference with speech communication, either live or TV/radio, and with sleep
- task or work interference, and the
- effects on general well-being, leading to annoyance, complaints, and group or community actions.

(Other general psychological or physiological effects cannot be ruled out at present, but all the available evidence suggests that "...if noise control sufficient to protect a person from ear damage and hearing loss were instituted, then it is *unlikely* that the noise of lower level and duration resulting from this effort could directly induce non-auditory disease."[4/])

A comprehensive description of the effects of noise on people is given in Ref. 4.

1.4 Candidates for DOT's Noise Descriptor

As has been suggested above, a number of potential candidates are available as descriptors for measuring environmental noise. Some of these have been developed to rate the noise of a specific kind of source, such as the Traffic Noise Index (TNI) used for rating urban street traffic noise, or the Noise and Number Index (NNI), the Noise Exposure Forecast (NEF), and the Composite Noise Rating (CNR), all used in the assessment of aircraft noise near airports[2,5/]. Each of these ratings predicts reasonably well the subjective response to the kind of noise for which it was developed.

If a noise exposure descriptor must apply to *all* kinds of noise, however, these particularized ratings, validated only for specific noise sources, must be eliminated immediately.

Noise Pollution Level (NPL) is a descriptor that was deliberately introduced to deal with *both* road traffic noise and aircraft noise, though not necessarily in combination. However, in addition to it being rather complicated to measure NPL (less a drawback, nowadays, with the availability of measurement gear having self-contained computers), it is quite difficult to determine the NPL for *combinations* of noise sources. Moreover, NPL has had only moderate success in correlating with the effects of noise on people. Thus, despite its early apparent attractiveness, NPL has not come into general use.

Statistical descriptors, such as L_{90}, L_{50}, L_{10}, and L_1, have been used widely in the study of surface transportation noise. But, while these descriptors are useful in the assessment of noise exposure with "well-behaved" (i.e., quasi-Gaussian) statistics, they are quite unsuitable for railroad and aircraft noise, for example, which are characterized by discrete, individual noisy events of relatively infrequent occurrence. The reason is that, no matter how loud the noisy events may be, unless their cumulative duration lasts for more than 10% of the observation period, they will have no effect whatever on the value of L_{10}, L_{50}, L_{90} or any other of the statistical descriptors that concern noise of lower levels with greater cumulative duration.

This is illustrated in Figure 1.1, which shows how the 24-hour values of L_2, L_4, L_{33}, and L_{eq} (the time-averaged noise level) increase with increasing numbers of aircraft flyovers.

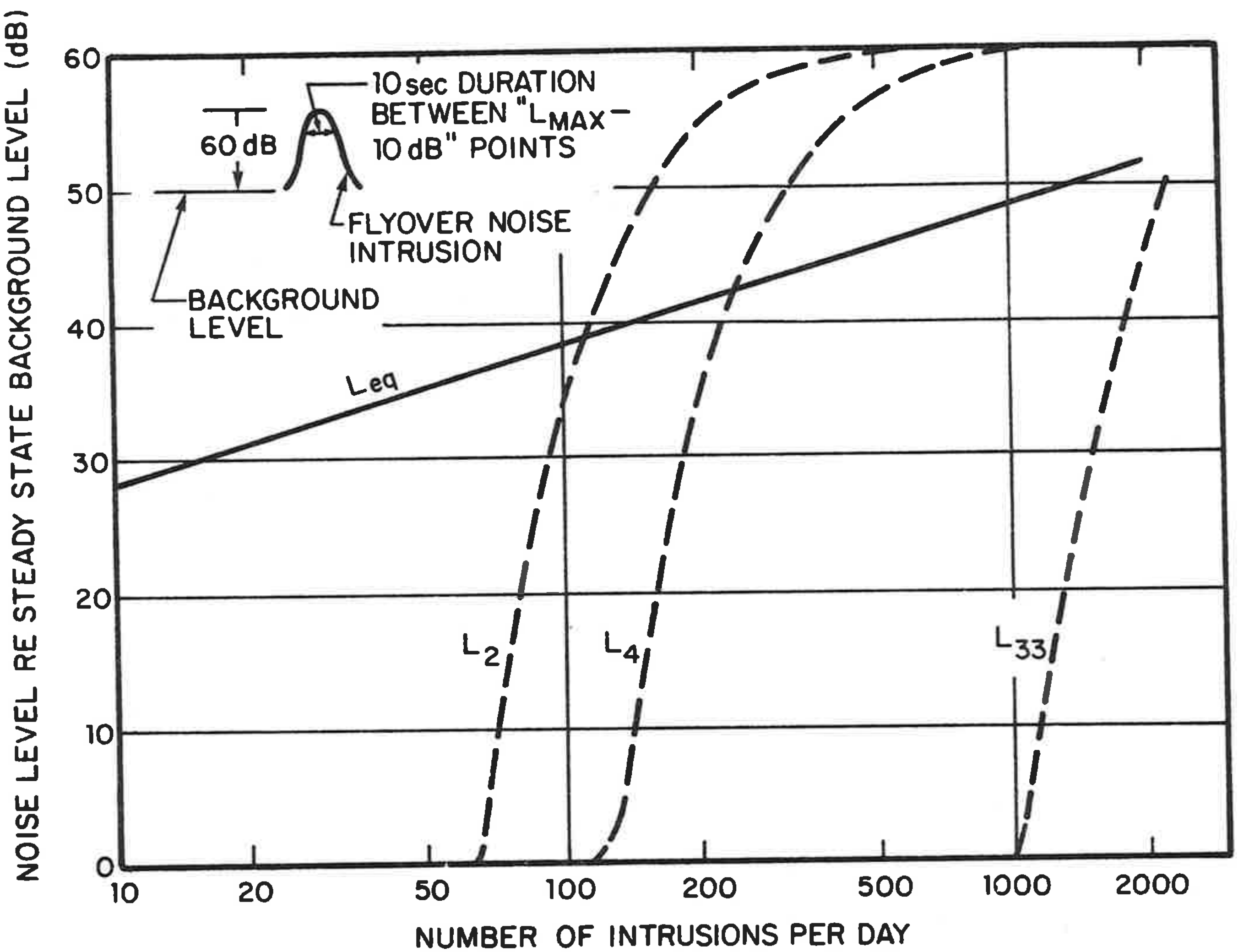


FIG. 1.1. GROWTH OF PERCENTILE-TYPE NOISE RATINGS VS AVERAGE SOUND LEVEL AS THE NUMBER OF NOISY EVENTS INCREASES.

(The L_{eq} descriptor is described and discussed in Section 1.5 below.) In each flyover, the noise is assumed to rise to a maximum level 60 dB above the prevailing background noise and to have a duration of 10 sec between the instants when the rising and falling noise level is 10 dB below the maximum, as shown in the upper left corner of the figure.

The curve at the right shows that the 24-hour value of L_{33} will not rise above the background noise level until more than 1000 flyovers have occurred; L_4 begins to respond when the number of intrusions exceeds about 120, while L_2 starts to exceed the background level with about 70 flyovers. For *fewer* noisy events, however, these statistical descriptors completely ignore the intrusions. Even L_1 would not respond to fewer than about 30 such events.

On the other hand, the value of L_{eq} increases gradually from the very first intrusion; the value of L_{eq} for a *single* event is 17 dB above the background noise.

A similar pattern would prevail for measurement of the noise of railroad or rapid transit passages.

Therefore, if the noise exposure descriptor must account for all kinds of noise, then *none* of the statistical ratings is adequate.

By a process of elimination we are left with a non-statistical measure of environmental noise exposure, the average sound level. No other noise exposure rating meets the primary requirement that it must account adequately for all kinds and combinations of noise sources. The next section describes two such measures, and the next following section (1.6) discusses the possible drawbacks of those measures for DOT's purposes.

1.5 Recommended Descriptor: Day-Night Average Sound Level[6,7,8]

The environmental noise descriptor that correlates best with the three categories of cumulative, long-term effects of noise on people, while fulfilling the seven conditions itemized in Section 1.2 above, is the long-term average sound level. (The average sound level is the constant level of sound that, in a given situation and time interval, would expose the ear to the same amount of acoustical energy as does the actual time-varying noise pattern.)

This measure has been widely used to relate individual and community reaction to aircraft and road traffic noise, to predict the likelihood and the severity of interference with speech and sleep, and to correlate hearing loss with noise exposure.

The average sound level* is defined as:

$$L_{eq} = 10 \log_{10} \left[\left(\frac{1}{t_2 - t_1} \right) \int_{t_1}^{t_2} 10^{L_A(t)/10} \, dt \right] , \qquad (1.1)$$

where $t_2 - t_1$ is the time interval over which the levels are evaluated, and $L_A(t)$ is the time-varying A-weighted sound level. For descriptions of the noise environment at various community

---

*In the past, the average sound level, defined above, has been called the "equivalent sound level," referring to the energy equivalence between the actual time-varying noise pattern and the steady noise level that confers the same acoustical energy. The term "equivalent" is so deeply engrained that the symbol L_{eq} continues in use even though most authorities have come to prefer to call the descriptor the average sound level. Proposed new ANSI terminology will symbolize average sound level as L_T, where T is the number of hours indicating the time period over which the average is taken.

locations, the time interval is usually the 24-hour day; the average sound level for this period is designated $L_{eq(24)}$; the parenthetical subscript is often omitted in practice.

For predicting long-term health effects, the value of $L_{eq(24)}$ for only a single day would be of little interest. Instead, the average $L_{eq(24)}$ over a yearly period is sometimes recommended. Because the value of a 24-hour average sound level is reasonably stable from day to day, it is not actually necessary to measure for a year to determine the annual average. (See Table 1.1 on the following page.)

For some environments, such as workplaces, offices, or schools, the 24-hour average sound level would be replaced by the average over the 8-hour work period, $L_{eq(8)}$, since that value would more accurately describe the impact of the noise on the people in such places; they go elsewhere for the rest of the 24 hours.

The simple concept of average sound level must be adjusted to account for the fact, revealed by most community response and public opinion surveys, that the same noise environment is considered more disturbing or annoying during the nighttime than during daytime. Not only do the requirements for undisturbed sleep and relaxation make a lower nighttime noise level desirable, but the exterior background noise level in most communities drops during the night by 10 dB or more and reduced activity inside homes contributes to a general lowering of interior noise levels. Consequently, intrusive noises are more disturbing during the night. To assess nighttime noise events in a way that accounts for their increased potential for causing disturbance, a weighting factor of

TABLE 1.1. REPEATABILITY OF L_{dn} AND L_{33} AT MONTHLY INTERVALS AT THE SAME LOCATION*.

Date	$L_{33(24)}$**	L_{dn}
7/24/68	60.8	69.7
12/17/68	59.5	67.6
1/21/69	59.5	67.2
2/21/69	60.0	68.8
3/19/69	59.8	68.1
4/15/69	62.8	70.2
5/20/69	59.5	67.5
6/17/69	59.5	67.0
7/16/69	58.8	67.1
8/19/69	58.0	67.3
9/16/69	60.5	68.2
10/21/69	58.0	67.2
11/25/69	60.8	68.7
Annual Range	4.8 dB	3.2 dB
Annual Average	59.8 dB	68.0 dB
Standard Deviation	1.27 dB	1.04 dB

*Reference 9.

**L_{33} evaluated for 24-hour period.

10 dB is applied to all nighttime noises; i.e., nighttime noises are treated as if they were 10 dB noisier than they actually are.

The 24-hour average sound level with a 10-dB nighttime penalty applied is called the day-night average sound level, L_{dn}, given by the following expression:

$$L_{dn} = 10 \log_{10} \frac{1}{24} \left[(15) \left(10^{L_d/10} \right) + (9) \left(10^{(L_n+10)/10} \right) \right], \quad (1.2)$$

where L_d and L_n stand for the daytime and nighttime* average sound levels, respectively.

1.6 Possible Disadvantages of Day-Night Average Sound Level

The preceding sections have presented a rationale for selecting the day-night average sound level as the noise descriptor of choice.** It seems appropriate to ask at once what potential disadvantages the day-night average sound level may have. Briefly, these are as follows:

a. the effect of pure tones in the noise is not accounted for;

b. some other weighting may be preferable to A-weighting;

c. rare loud events may not be adequately accounted for;

d. there is some question about the nighttime penalty used in calculating the day-night sound level;

---

*The daytime period is from 0700 to 2200; the nighttime period is from 2200 to 0700 hours.

**The reader may refer to Appendix A for a more detailed background on the average sound level.

e. the factor 10 multiplying the logarithm may be questioned.

These objections are discussed in the following paragraphs.

a. Pure Tones

One objection to the use of weighted sound levels is that some psychoacoustic judgment data indicate that the effects of tonal components in noise are sometimes not adequately accounted for by a simple sound level[10,11,12/].

It should be remembered, however, that this same disadvantage is shared by all other noise rating schemes, with the sole exception of EPNL, which is the basis for the Noise Exposure Forecast (NEF). In the current aircraft noise certification procedures[13/], the presence of tones is identified by a complex frequency analysis procedure. If the tones protrude above the adjacent broadband noise spectrum, a penalty is added to the directly calculated perceived noise level.

However, the complexities involved in accounting for pure tones are so great that the required resources exceed any practical limits for monitoring noise in the community. In addition, the pure tone corrections presently used for evaluating aircraft noise have not been validated for all types of noise, nor for all noise levels. Indeed, they appear *not* to be necessary for all noise levels.

FOR THE TIME BEING, IT IS RECOMMENDED THAT NO ATTEMPT SHOULD BE MADE TO INCORPORATE PURE TONE CORRECTIONS IN THE COMMUNITY NOISE RATING FOR ELEVATED RAPID TRANSIT STRUCTURES.*

---

*The most practical way of dealing with pure tone components in noise is for noise standards for new products to penalize the presence of tones in such a way that manufacturers will be encouraged to minimize them. Thus, ultimately they will not be a significant factor in environmental noise.

NOTE: This recommendation rests on the assumption that the (nearly) pure tones of wheel/rail squeal, since they are not structure-dependent, should NOT be taken into account in evaluating the noise from the elevated structure itself. However, in an inventory of elevated structures, it would be useful to indicate those structures for which wheel/squeal occurs.

b. A-weighting vs D-weighting

Several different frequency weightings have been proposed in the past for general use in the assessment of response to noise[2,3/]; they differ primarily in the ways sounds at frequencies between 1000 and 4000 Hz are evaluated. The A-weighting, standardized in current sound level meter specifications, has been widely used for transportation and community noise descriptions[5/]. For many noises, the A-weighted sound level is found to correlate as well with human response as much more complex measures, such as the calculated perceived noise level or the loudness level, both derived from detailed spectral analysis[14,15/].

On the other hand, some psychoacoustic research suggests that, at least for some kinds of noise signals, a different frequency weighting, that emphasizes the sensitivity in the 1000 to 4000 Hz frequency region, is more reliable[16/]. Various forms of this alternative weighting function have been proposed; all these variants are referred to here as "D-weighting." Unfortunately, none of these alternative weightings has progressed in acceptance to the point that a U.S. standard has been approved for commercially available instrumentation.

The D-weighting network was originally proposed in international standardization activities as a means to approximate the perceived noise level, for monitoring the noise produced by aircraft flyovers[13,17]. The original frequency weighting was specified to be the inverse of the 40 noy curve, used to compute perceived noise level. A request by ISO to the International Electrotechnical Commission (IEC) has resulted in a specification which approximates the inverse 40 noy curve[18]. This specification has been approved by member bodies of IEC and is in the process of being published as an IEC standard. In its vote on this proposed standard, the U.S. approved the standard *for use only in aircraft noise monitoring systems.*

Interest in possible alternatives to the A-weighting for use in direct measurement of noise has resulted in the establishment of Working Group S3-57, Auditory Magnitude, under Committee S3 of the American National Standards Institute (ANSI).

This working group is assessing the merits of various proposed frequency weighting functions, to see if any new network, such as D, has sufficient merit to warrant a new standard, in addition to the A, B, and C networks now incorporated in the ANSI standard for sound level meters.

No new network, including D, will be incorporated in the American Standard until the results of this working group activity are produced and voted on by the ANSI committees. At that time, if a new frequency weighting is proposed, an equipment standard to realize this response in commercial equipment will need to be developed. Considering the typical time scale for standards development, it is highly unlikely that a new frequency weighting will be incorporated in any ANSI standard for at least five years, if ever.

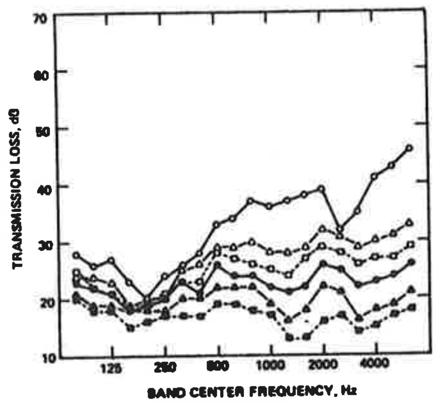
AT THE PRESENT TIME, THEREFORE, D-WEIGHTING IS NOT ACCEPTABLE FOR DOT'S PURPOSES, AND A-WEIGHTING IS THE ONLY SUITABLE CHOICE.

Sometimes the objection is raised that A-weighting does not adequately account for noises with most of the energy at low or very low frequencies, such as railroad locomotive noise. This objection is sometimes felt to be especially relevant to railroad noise heard indoors, because the transmission loss of the house wall, being less at low than at high frequencies, would increase the predominance of low frequencies in the spectrum.

With respect to such noises heard *outdoors*, there is no reason to suppose that any special consideration attaches to sounds comprised mostly of low-frequency energy. The A-weighting imitates the sensitivity of the human ear and thus gives a proper accounting of the contributions of all the different frequencies to the overall aural sensation.

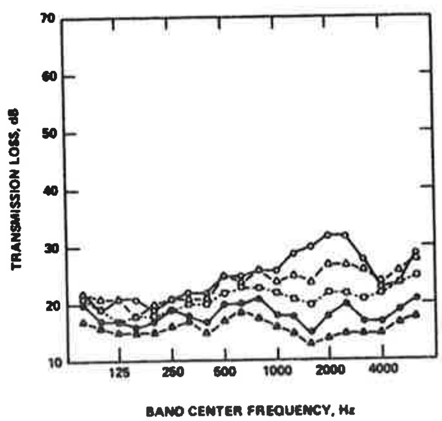
As for such noises heard *indoors*, the house attenuation from outdoors to indoors is limited by the windows and the leaks around them. For these elements, as shown by Figure 1.2, the transmission loss is nearly independent of frequency. Even sealed windows show very little frequency dependence. There is thus no significant enhancement of the low-frequency end of the spectrum, even with windows closed, and again the A-weighting is appropriate.

In any case, the objection stated above would *not* apply to the noise of rapid transit systems, because this noise is not particularly dominated by low-frequency energy. Figure 1.3, for example, shows (shaded in the upper portion) the envelope of octave-band sound pressure levels for a series of train passages on different kinds of elevated structures: steel girder bridge, slab viaduct, ballasted viaduct, embankment. The lower (shaded) part of the figure shows these same noise levels reduced by the mean attenuation for a series of unsealed closed windows, both locked and unlocked, see Figure 1.2.



Sound transmission loss vs frequency data for 6 x 5 ft picture window, glazed with 1 in. insulating glass, with perimeter cracks of controlled size.

Symbol	Test No.	Crack Size	STC
○	W-10-71	None, complete seal	34
△	W-20-71	1/32 in., half perimeter	29
□	W-19-71	1/32 in., full perimeter	26
●	W-18-71	1/16 in., full perimeter	23
▲	W-14-71	1/8 in., full perimeter	19
■	W-12-71	1/4 in., full perimeter	15



Sound transmission loss vs frequency data for 6 x 5 ft picture window, double-strength glazing, with perimeter cracks of controlled size.

Symbol	Test No.	Crack Width	STC
○	W-7-71	None, complete seal	29
△	W-21-71	1/32 in.	25
□	W-17-71	1/16 in.	21
●	W-15-71	1/8 in.	18
▲	W-16-71	1/4 in.	15

FIG. 1.2. TRANSMISSION LOSS OF TYPICALLY LEAKY WINDOWS WITH INSULATING GLASS (ABOVE) AND DOUBLE-STRENGTH GLAZING (BELOW). (From Ref. 32.)

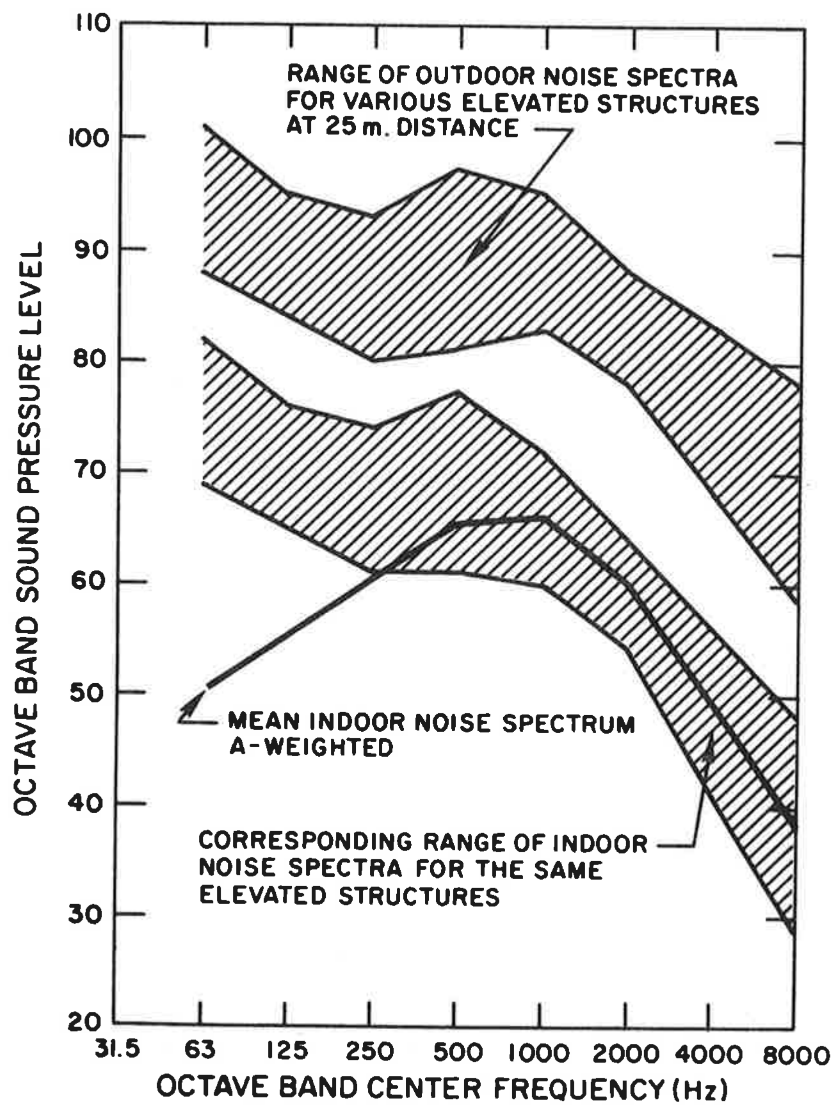


FIG. 1.3. THE A-WEIGHTED SOUND LEVEL CORRESPONDING TO THE NOISE OF RAPID TRANSIT TRAINS ON ELEVATED STRUCTURES HEARD INDOORS IS DOMINATED BY ENERGY IN THE 500 TO 1000 Hz RANGE.

This is, therefore, the range of *indoor* noise levels corresponding to the various elevated structures. The solid curve represents the mean of the indoor noise levels *with A-weighting applied*. The A-weighted indoor level is seen to be dominated, not by low frequencies, but by the frequency range from 500 to 1000 Hz. Only if the outside wall attenuation were *much* more frequency-dependent than is usually the case, and only for noises with *extreme* concentration of low-frequency energy, would this trend be significantly changed.

However, if the level of the noise is so great that it rattles glasses on shelves or pictures on the walls (as the result of structural vibrations induced by noise), or if structural vibrations from train passages give rise to such rattling, then an A-weighted sound level measured outdoors might not accurately reflect what the occupant of the dwelling hears, because the rattles are not accounted for. Although rattling is a commonly cited source of annoyance, rattling occurs in only a very small fraction of the houses exposed to noise from elevated structures, so that A-weighting may be expected still to be a valid measure for judging community noise exposure.

c. Rare Loud Events*

Sometimes the choice of L_{dn} as a measure of the impact of noise on a community is questioned because an *average* noise level reckoned over a 24-hour period may not be sufficiently sensitive to the effect of noisy events of short duration or infrequent occurrence.

This objection has some validity. The statement that "the average depth of the river is 2 ft" may conceal the existence

*These are not the same as impulsive noises, such as sonic booms, quarry blasting, and artillery fire.

of a pool deep enough to drown in. The restriction of noise exposure at a site to an average level of 65 dB may still permit quite loud, brief noises.

The Environmental Protection Agency (EPA) working group that recommended the adoption of L_{dn} was aware of this problem, but felt that the other advantages of L_{dn} were so great that it should be adopted by EPA anyway. Here is what they said:

> "A practical simple measure of environmental noise cannot and need not take into account secondary effects. Neglecting secondary details in the measurement and control of environmental noise does not mean that these details are not important or that attention should not be paid to them through other noise control measures. For example, one-time noise events, high instantaneous peak values, or objectionable discrete tones of individual sources must be separately controlled by emission noise standards. Standards for *cumulative* environmental noise exposure and *emission/certification* standards must complement each other. The emission or source standard can consider the details of the source characteristics and can employ methods of measurement, data analysis and interpretation appropriate for the characteristics of the particular noise or for effective noise control engineering on this noise source. However, it is mandatory that all detailed source standards can be translated into one common noise measure. Exposure to all kinds of noise can then be added in this common measure of exposure to give a measure of total accumulated noise exposure."[19]

While admitting the existence of the problem, it is important not to exaggerate the limitations of average noise levels in dealing with infrequent loud noises. For any neighborhood in which the background noise from all other noise sources is reasonably quiet (say, less than L_{dn} = 65 dB), the contribution to L_{dn} from a *single* noisy aircraft flight or railroad passage is readily detectable.

The average sound level for a single, triangular sound level pattern, such as the passby of a transit car, having a maximum value L_{max}, is given by

$$L_{eq} = L_{max} + 10 \log \frac{t}{2.3\ T} \quad , \tag{1.3}$$

where t is the duration in seconds of the passby period when the sound level is within 10 dB of L_{max} and T is the period, say, a day (equals 86,400 sec), over which the average is reckoned[20].

Thus, if t = 20 seconds, the second term in Eq. (1.3) is

$$10 \log \frac{20}{2.3 \times 86400} = -40 \text{ dB} \quad .$$

That is, the contribution to L_{dn} of a single daytime passby is 40 dB below the maximum passby level (30 dB below the maximum if at night) ; if there were no noise from any other source, the day's value of L_{dn} would be (L_{max} - 40) due to that single event alone.

For example, consider a neighborhood where the noise from all other sources is L_{dn} = 65 dB. A single nighttime passby with a maximum noise level of only 95 dB would represent an additional contribution to L_{dn} of 65 dB and, thus, would raise the day's L_{dn} to 68 dB. Such a change is readily measured. If the maximum passby level were 105 dB, the day's L_{dn} would increase to 75 dB.

Alternatively, if the value of L_{dn} is *limited* to 65 dB, then the duration of a 110 dB noisy event in the daytime period would be restricted to only 2.7 sec per day, even if there were no other contributants to the environmental noise. The allowed duration would be shorter if there were other noise sources or if it occurred during the nighttime.

IT APPEARS THAT AN AVERAGE SOUND LEVEL CAN BE TRUSTED TO ACCOUNT ADEQUATELY FOR EVEN A VERY FEW HIGH-LEVEL NOISE EVENTS PER DAY.

d. Nighttime Adjustment

In the formulation of the day-night average sound level, noises occurring between 2200 and 0700 are treated as though they were 10 dB louder than they actually are, in order to account for the presumed greater potential disturbance of people by nighttime noise. Similar adjustments have been applied in a number of other noise ratings.

These adjustments are assigned on the basis of results from complaint studies and social survey data that indicate a higher sensitivity to nighttime noise. Solid data to support the *amount* of the adjustment for this effect are hard to come by, however. The question is described in detail in Appendix B of this report.

FROM THE AVAILABLE EVIDENCE, IT APPEARS THAT AT VERY HIGH AND VERY LOW NOISE EXPOSURES, NO NIGHTTIME ADJUSTMENT IS WARRANTED. BUT IN THE RANGE OF NOISE EXPOSURE NEAR THE THRESHOLD OF ANNOYANCE, IT IS IMPORTANT TO TAKE INTO ACCOUNT THE INCREASED POTENTIAL FOR NIGHTTIME DISTURBANCE. THE BEST MEANS OF DOING THIS, AT PRESENT, IS TO USE A 10-DECIBEL ADJUSTMENT, AS IN THE DAY-NIGHT AVERAGE SOUND LEVEL.

The results of the social surveys* reviewed in Ref. 21 give support to this conclusion. They demonstrate remarkable agreement

---

*Unfortunately, no social surveys of rapid transit noise, complete with interviews to determine people's subjective response, have been completed at this time. Also, only four surveys on railway noise have been made, and they are not in agreement. (See Chapter 2.)

obtained in the community annoyance responses, from eleven social surveys dealing with different kinds of noise, when L_{dn} is used as the noise exposure descriptor.

Also, it may be recalled that HUD has, since the initial adoption of its noise policy in 1971, utilized a 10-decibel adjustment for nighttime noise in both the aircraft and non-aircraft interim noise standards.

e. Effect of Number of Events: Energy Summation or Other?

Equation 1.1 given in Section 1.5 for average sound level is appropriate for use when the available information about the noise is given in terms of a time-varying noise level $L_A(t)$. An equivalent equation can be used when the noise information is given in terms of the number, N, of similar noisy events of a certain average noise level[22/]:

$$L_{eq} = \overline{L_{eq}} + 10 \log_{10} N \quad , \tag{1.4}$$

where $\overline{L_{eq}}$ is the logarithmically averaged value of the several average noise levels, L_{eq}, for a number of individual events, each reckoned over the duration $(t_2 - t_1)$ of the individual event according to Eq. (1.1).

The question of concern here is whether or not the factor 10 for the second term of Eq. (1.4) is correct.

The preponderance of case histories and social surveys indicates that the response of a community to noise is affected not only by how loud the noise is but also by how *many* noisy events occur, e.g., by the total noise exposure in a specified time period. This is consistent with laboratory results of psychoacoustics experiments showing that the magnitude of sound and its duration seem to trade off on an energy-summation basis. On the assumption that community response is related to the total noise energy in a specified time period, a noise rating should sum events of equal magnitude as in Eq. (1.4), on the basis of 10 $\log_{10}$ N, where N is the number of events. Most noise rating scales, including L_{eq} and L_{dn}, follow this rule.

But is this a valid procedure, and, if so, why do some other rating methods use a different summation rule?

Three departures from the simple energy summation are represented in the British, German, and Dutch ratings[23/]. The first to gain prominence was the British Noise and Number Index (NNI) where the number of events is summed as 15 $\log_{10}$ N. The factor 15 was proposed as a result of analyses of a social survey conducted around Heathrow Airport in 1961[24/]. It has been shown by Galloway and Von Gierke[25/] (confirmed by Schultz[26/]), however, that the Heathrow survey results could be fitted equally accurately with a 10 $\log_{10}$ N summation.

In the German "StörIndex," $\overline{Q}$, a 13.3 $\log_{10}$ N summation is used. The justification for this choice is somewhat obscure, but it appears to have been chosen on the basis of certain psychoacoustic tests[27/]. The choice of 20 $\log_{10}$ N in the Dutch rating method is reported to have been selected on the basis of a social survey around Schiphol Airport[28/].

Thus, the factor, K, that multiplies the $\log_{10}$ N term has taken the following values in the several ratings discussed here: 10 (energy summation), 13.3, 15, and 20. Which is correct?

Considerable light has been shed on the choice of multiplier in the published analyses of a second social survey around Heathrow conducted in 1967[29/]. In these analyses, a number of correlations between community response and noise exposure were made with a forced variation in K from 2 to 22 for four different combinations of noise exposure. It was found that the degree of correlation was quite insensitive to the value of K, although some form of K log N is useful for assessing annoyance in the community.

In summary, psychoacoustic experiments indicate that magnitude, duration, and number of events should be combined on an energy basis. Sociological results indicate that energy summation is equally good for assessing community annoyance, although the results are somewhat insensitive to the actual form of the assessment of number of events, so long as some measure is used. IT SEEMS REASONABLE, THEREFORE, TO RETAIN THE ENERGY SUMMATION APPROACH (K = 10) IN ASSESSING COMMUNITY ANNOYANCE. THE INTERNATIONAL STANDARD SUPPORTS THIS POSITION[30/].

1.7 Unsuitability of "Percentile" Ratings

A noise rating based on a percentile, such as L_{10}, is completely unaffected by noise events whose cumulative duration in the observation period is less than that particular percent of the period, as was shown in Figure 1.1. Railway train passages and aircraft flights, for example, are never reflected in the the value of L_{10} because the total duration of those events is less than 10% of the day. For example, although Figure 1.4 shows that a statistical metric, like $L_{33(24)}$, and L_{dn} are very highly correlated for *general* urban noise situations, Figure 1.5 shows that these two descriptors are quite independent for aircraft noise situations, where L_{eq} accounts for the aircraft noise quite

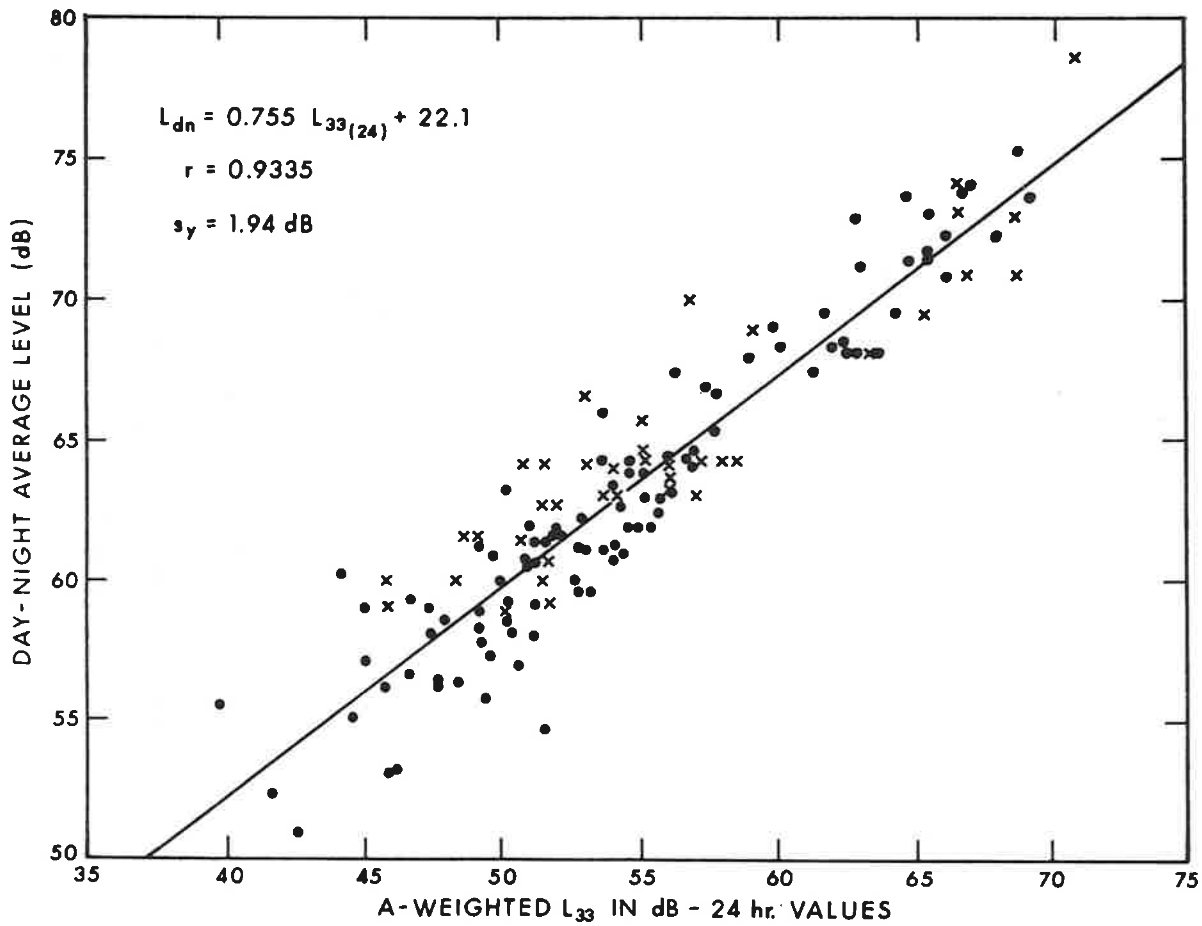


FIG. 1.4. CORRELATION BETWEEN L_{dn} AND L_{33} FOR 169 URBAN SITES *NOT* NEAR AIRPORTS OR RAILWAY LINES. (From page III-25 of Ref. 33.)

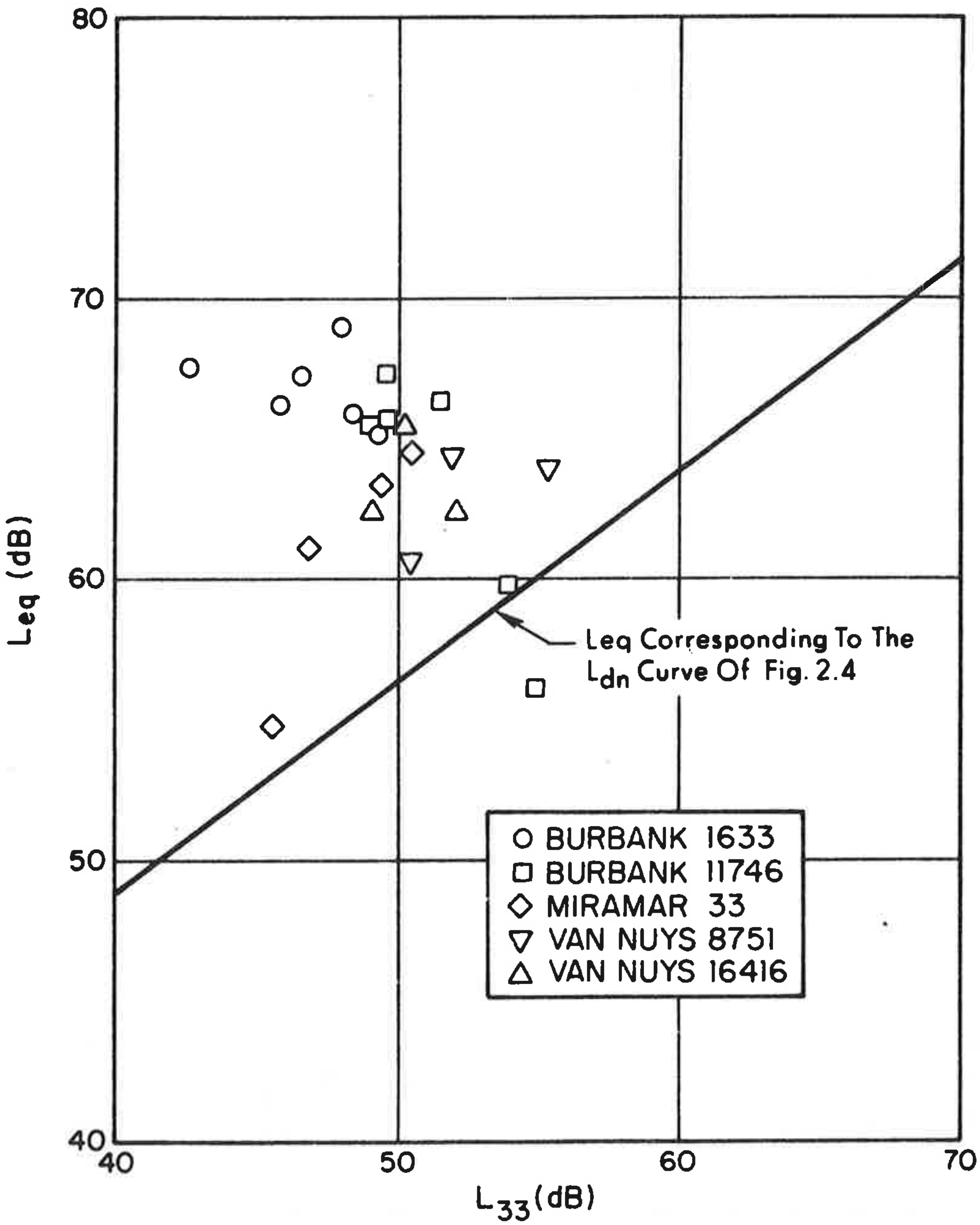


FIG. 1.5. CORRELATION BETWEEN L_{eq} AND L_{33} FOR AIRCRAFT NOISE.

well, but L_{33} ignores it. Figure 1.6 on page 31 shows similar behavior for railroad noise.*

In addition, with percentile noise ratings there is no convenient means of predicting the impact of *combinations* of noise sources at a site. For existing conditions, of course, the site noise may be measured, or the walkaway test[5] may be conducted. In either case, all sources of noise would be accounted for.

The difficulty is in combining *predictions* of future noise exposure from different sources. This is quite complicated, since it requires predicting a substantial part of the entire 24-hour cumulative statistical distribution for each source of noise, and combining these distributions, in itself a quite complicated procedure[31].

SINCE "PERCENTILE RATINGS" CANNOT COPE WITH SOME IMPORTANT KINDS OF NOISE, INCLUDING THAT OF RAILROADS AND RAPID TRANSIT, THEY ARE UNSUITABLE FOR EVALUATION OF THE NOISE OF ELEVATED STRUCTURES.

1.8 Conclusions

Based on the considerations presented in Sections 1.2 through 1.7, above, we recommend that the Day-Night Average

---

*Leq and Ldn are very highly correlated; for typical traffic volume distribution between day and night periods, they differ only by a constant. Therefore, their degree of correlation with the other noise ratings are practically identical.

Moreover, the percentile ratings L_{33} and L_{10} are very well correlated for aircraft and railway noise. The reason is that both ratings ignore those noises, and respond only to the commixture of all other, more continuous, noises, as discussed on p. 6. Thus, the results shown in Figures 1.4, 1.5, and 1.6 would be substantially the same if L_{10}, or even L_1, had been plotted instead of L_{33}.

Sound Level be used for the purpose of evaluating the noise of elevated rapid transit structures in the context of other kinds of noise in the community, and for assessing the "noise impact" on the community.

The reader will find further information relevant to the Day-Night Average Sound Level in Appendices A, B, and C of this report.

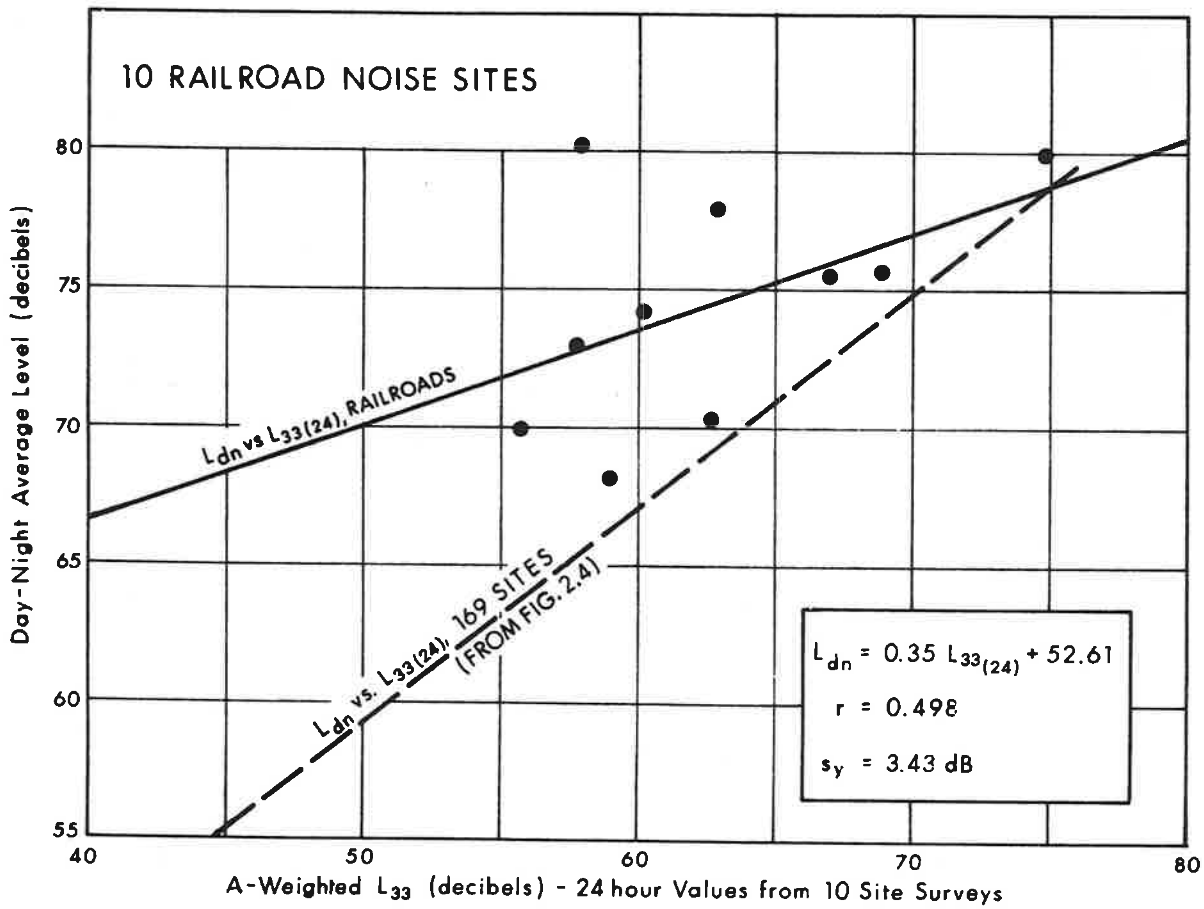


FIG. 1.6. CORRELATION BETWEEN L_{dn} AND L_{33} FOR RAILWAY NOISE.

References - Chapter 1

1. T. J. Schultz, "Development of an Acoustic Rating Scale for Assessing Annoyance Caused by Wheel/Rail Noise in Urban Mass Transit," Report No. UMTA-MA-06-0025-74-2, February 1974, prepared for Department of Transportation, Urban Mass Transit Administration, Office of Research and Development, Washington, D.C. 20591.

2. Theodore J. Schultz, *Community Noise Ratings*, Applied Acoustics Supplement No. 1, Applied Science Publishers Ltd., London, 1972.

3. Karl S. Pearsons and Ricarda L. Bennett, *Handbook of Noise Ratings*, NASA Report CR-2376, April 1974.

4. James D. Miller, "Effects of Noise on People," Report No. NTID 300.7, December 31, 1971, U.S. Environmental Protection Agency.

5. Theodore J. Schultz, "Noise Assessment Guidelines/Technical Background," Report No. TE/NA 172, U.S. Department of Housing and Urban Development, 1971.

6. "Impact Characterization of Noise Including Implications of Identifying and Achieving Levels of Cumulative Noise Exposure," Task Group 3, Henning von Bierke, Chairman, Report No. NTID 73.4, 27 July 1973, U.S. Environmental Protection Agency, Office of Noise Abatement and Control, Washington, D.C.

7. "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," Report No. 550/9-74-004, March 1974, U.S. Environmental Protection Agency, Office of Noise Abatement and Control, Washington, D.C.

8. H. von Gierke, "Noise -- How Much Is Too Much?", invited lecture at the Eighth International Congress on Acoustics, London, July 1974. Published in *Acoustics 1974*, Chapman and Hall, London, 1975.

9. D. Aubrée, S. Auzou and J.-M. Rapin, "Étude de la gêne due au Trafic Automobile Urbain" (Study of Annoyance Due to Urban Automotive Traffic), no report number, June 1971, Annexe 4: Catalogue des Caracteristiques du Bruit aux Divers Points de Mesure (Catalogue of Noise Characteristics at Various Measurement Locations), Centre Scientifique et Technique du Bâtiment, Paris: Table S-11 to S-23.

10. Karl S. Pearsons, Dwight E. Bishop and Richard D. Horonjeff, "Judged Noisiness of Modulated and Multiple Tones in Broad-Band Noise," *J. Acoust. Soc. Am.*, 45 (3), 742-750, 1969.

11. Karl S. Pearsons, "Combination Effects of Tone and Duration Parameters on Perceived Noisiness," Bolt Beranek and Newman Inc. for Langley Research Center, National Aeronautics and Space Administration, Washington, D.C., NASA CR-1283 (BBN Report 1701), February 1969.

12. Karl S. Pearsons and Richard J. Wells, "Judged Noisiness of Sounds Containing Multiple Pure Tones," *J. Acoust. Soc. Am.*, 78th Meeting, San Diego, CA, November 4-7, 1969.

13. ISO Recommendation R507, "Procedure for Describing Aircraft Noise Around an Airport," 2nd Edition, June 1970.

14. J. H. Botsford, "Using Sound Levels to Gauge Human Response to Noise," *Sound and Vibration*, 3 (10), October 1969.

15. Reference 5, pages 50-65.

16. Karl D. Kryter, *The Effects of Noise on Man*, Academic Press, New York and London, 1970; Chapter 9.

17. ISO Recommendation R1761, "Monitoring Aircraft Noise Around Airport."

18. IEC Document IEC 29C (Central Office) 26.

19. Reference 6, pages vi-vii.

20. Reference 6, page A-8.

21. Theodore J. Schultz, "Synthesis of Social Surveys on Noise Annoyance," *J. Acoust. Soc. Am.*, 63 (8), August 1978.

22. W. J. Galloway, "Community Noise Exposure Resulting from Aircraft Operations: Technical Review," Report No. AMRL-TR-73-10g, July 1974, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

23. Reference 20, pages 31-34.

24. *Noise — Final Report*, Cmnd. 2056, July 1963; Her Majesty's Stationery Office, London.

25. W. J. Galloway and H. E. von Gierke, "Individual and Community Reaction to Aircraft Noise; Present Status and Standardization Efforts," Paper No. INC/C4/P9, International Conference on the Reduction of Noise and Disturbance Caused by Civil Aircraft, London, November 1966.

26. Reference 2, page 49.

27. W. Bürck, M. Grützmacher, F. J. Meister and E. A. Müller, "Fluglärm," Göttingen, May 1965.

28. C. Bitter, "Noise Nuisance Due to A [illegible]art," Collque sur la définition des exigences humaines á l'égard du bruit, Paris, November 1968.

29. "Second Survey of Aircraft Noise Annoyance around London (Heathrow) Airport," H.M.S.O., April

30. ISO R 1996-1971: "Acoustics - Assessment of Noise with Respect to Community Response".

31. P. M. Nelson, "The Combination of Noise from Separate Time Varying Source," *Applied Acoustics*, 6 (1), 1-22, 1973.

32. H.J. Sabine, M.B. Lacher, D.R. Flynn, and T.L. Quindry, "Acoustical and Thermal Performance of Exterior Residential Walls, Doors and Windows," U.S. Department of Commerce, National Bureau of Standards, NBS Building Science Series 77, November 1975.

33. T.J. Schultz, W.J. Galloway, and P.W. Hirtle, "Noise Assessment Guidelines — Technical Background (revised)," Bolt Beranek and Newman Inc., Report No. 3415, February 1977. Prepared for Department of Housing and Urban Development under Contract No. H-2243R. To be published as a HUD Technical Report.

2. REVIEW OF STUDIES ON IMPACT OF ELEVATED STRUCTURE (OR SIMILAR) NOISE ON THE WAYSIDE COMMUNITY*

2.1 Introduction

Before embarking on any noise abatement program, it is essential to have a means of rating the noise in terms of the disturbance it creates. The reason is that, strictly speaking, we are not so much interested in abating the noise, itself, as in reducing the amount of unfavorable community response (e.g., activity interference or annoyance) it causes. If possible, the noise rating should be one-dimensional, so that all the improvements developed during a noise-abatement program can be evaluated along a single, continuous scale, and thus can be rank-ordered as to their effectiveness in reducing disturbance.

2.2 Developing a Rating of Acceptability for Community Noise

The method usually used to develop a rating of acceptability for noise from a specific source is to combine the results of a large-scale social survey with those from a corresponding program of outdoor noise measurements[3/], both surveys being carried out in areas strongly impacted by the noise source in question. Comparison of these results permits one to determine what aspects of the noise are most important in generating annoyance, and then to develop a rating that combines assessments of the relative severity of these various aspects, to be used as a tool for evaluating different degrees of exposure to this noise. Finally, one can select a maximum acceptable value for the rating, based on economic and political considerations as much as on the technical

---

*Chapter 2 of this report is largely based on Ref. 1, along with added material from Ref. 2.

results of the surveys, that corresponds to the maximum exposure that the average person, weighing cost against comfort, will find acceptable.

For example, in the development of the Noise and Number Index[3/], currently used in the United Kingdom for evaluating the noise from aircraft, nearly 2,000 people were interviewed in the area within ten miles of London's Heathrow Airport, covering a rather wide range of severity of exposure to aircraft noise. Extensive measurements of the noise in that area were also made at about the same time. The subjects' responses to a series of 42 questions indicated that their annoyance is determined by only two aspects of the noise: namely, the average peak noise level during aircraft flybys and the number of flight events occurring per day. The Noise and Number Index (NNI) was accordingly formulated as the sum of two terms:

$$NNI = \overline{PNL} + 15 \log N - 80 \quad , \tag{2.1}$$

where N is the total number of aircraft operations heard during a specified period (e.g., one day or one night);* and

$\overline{PNL}$ is the average, over the N aircraft operations, of the maximum Perceived Noise Level occurring during the flybys.

Since the survey indicated no appreciable annoyance until the sum of $\overline{PNL}$ and 15 log N exceeded 80, this number was subtracted from the sum, so that annoyance would be expected at locations where the values of NNI are greater than zero.

*Note that the definition of N as the number of operations actually "heard" smuggles into the rating the concept of the background noise!

Similar studies of aircraft noise, coupling social surveys with noise measurement programs, have been carried out in Sweden, France, Germany, Switzerland, The Netherlands, a second time in London, and the United States, each leading to a noise rating slightly different from the others[3]. For assessing the noise of roads and street traffic, surveys combining interviews and noise measurements have been conducted in England, Austria, Denmark, France, Belgium, Sweden, Switzerland, Canada, and the United States[3]; again, the ratings developed in these studies and currently used to assess the impact of road noise are somewhat different. But in any case, at least for the noise of air and road traffic, rationally developed rating schemes exist, and they are similar, if not identical, from one country to another.*

---

*One particular noise related problem has not, however, received much attention, i.e., the problem of secondary radiation. By this is meant radiation into the interior of the buildings due to ground vibration set up by the passage of heavy surface vehicles, such as trucks or trains. In general, vibration in the audio frequency range is rapidly attenuated in the ground as one moves away from the source. However, low-frequency vibration that is not well attenuated can lead to rattling of china, glassware, or windows.

It is clear that it would be extremely difficult to put an evaluation of such secondary "rattling" on a firm quantitative basis, and its consideration is beyond the scope of this report. It is suggested, however, that because of the relatively indirect structural coupling for mechanical vibration between the elevated structure and the nearest buildings, the impact of the airborne sound usually may be felt as serious before significant secondary radiation due to building vibration becomes disturbing. Thus, it is not likely that a noise rating scheme which copes successfully with the airborne noise will permit significant disturbance from "rattling." Note that this approach would not work for evaluating the impact of vibration from trains in tunnels!

Unfortunately, at the present time no surveys have been completed that deal with the noise of rapid transit at all, either with track on grade or on elevated structures.* Thus, it will be necessary to rely on the results of several social surveys dealing with railroad noise, as representing the most nearly similar situation.

In the recent past, there have been published the results of four studies dealing explicitly with rail noise and combining social surveys with noise measurements: two in England, and one each in France and Japan. Although the first British survey was little more than a pilot study, never carried to completion, the other three present valuable data. Indeed, a portion of the Japanese survey concerns the New Sanyo Line of Shinkansen, for which most of the track is carried on elevated concrete structure. Unfortunately, the Japanese results cannot be relied on for decisions about community response to noise in American communities, because of the great cultural and architectural differences between Japan and the United States (see below, Section 2.6.1).

The results of these four railway noise surveys are summarized in this chapter, in chronological order.

---

*A Japanese survey on rapid transit noise is currently being made, some of it applying to elevated structure, but only the noise data have been analyzed, so far.

2.3 The British Pilot Study

A promising study was begun by Walters in England, in 1968; he attempted to evaluate the annoyance caused by the noise of high-speed electric trains passing in direct view of residences[4,5], but the results of the early phases of that study were inconclusive and the study was apparently never completed. The preliminary results suggested that people's annoyance decreases as their distance from the tracks increases, though the dependence was neither strong nor consistent. (As an example of this inconsistency, people living at 70 m distance expressed more annoyance than those at 45 m, according to one set of interviews.)

There was a suggestion that people living in high background noise from other sources (children, dogs, etc.) are *more* sensitive to the railway noise than people in quieter locales, contrary to our usual expectations! This implies that in conditions of persistent noisiness, people experience an increased, rather than reduced, sensitivity to the occasional extra noise of the railroad. A similar trend was found in the French survey (see Section 2.4.1).

Another unexpected feature of the preliminary results was how surprisingly unannoying the railway noise turned out to be: there were quite a few houses where train passages (57 in the daytime, 30 at night, at about 85 mph) produced levels of 90 dB(A) just outside the bedroom windows, yet the inhabitants did not seem to be unduly concerned about the noise. The British study (very tentatively) concluded that the external noise level must exceed 95 dB(A) during train passages before serious annoyance becomes evident: this implies houses within 30 meters of the track!*

Because these results were tentative, mostly qualitative, and not quite consistent with those from the other surveys, we do not give much weight to them here.

2.4 The French Survey[7/]

A combination of social survey and physical noise measurement survey has been completed (1973) in France, near Paris. After a series of interviews to identify the important aspects of the annoyance due to train noise, a questionnaire was designed and administered to nearly 350 subjects living in different locations where the train noise had previously been measured. Their responses were coded and punched onto cards for computer analysis.

The 90 questions were divided into three groups, one (38) evaluating different aspects of the annoyance, another (37) bearing on attitudes towards noise in general, towards trains, and towards the neighborhood, and the third (15) being descriptive questions about the subject and his house.

The responses to the questions were initially screened to select the most reliable indicators of annoyance; all but three manifestations of annoyance were discarded. These were the different ways in which an individual can respond to the noise

---

*For comparison, HUD's *Noise Assessment Guidelines* would find a housing site to be "Clearly Unacceptable" if the median peak-sound-level during train passages exceeds 75 dB(A), and "Normally Unacceptable" if it exceeds 60 dB(A). These limits are based on ten or more train passages during the night; the guidelines permit progressively higher noise levels (up to 10 dB increase) for fewer nighttime operations[6/].

stimulus:

- With a statement that the noise interferes with an activity like reading;
- With a judgment about the noise, itself ("It is intolerable");
- With overt action to change the situation (like moving away or soundproofing the house).

Both the elementary annoyances and a constructed overall rating were compared with various noise parameters measured outside the home of the interviewee for possible correlation, to discover which noise parameters or group of parameters would be most successful in predicting annoyance due to the train noise, and also to define the maximum acceptable exposure to train noise for the average person.

The noise measurements at the various sites were analyzed to derive a number of parameters that were expected to be useful for predicting annoyance, as follows:

• rate of increase of noise level	in dB(A)/sec
• maximum noise level during train passage, L_{max}	in dB(A)
• duration of audible train noise	in sec
• duration of maximum level, L_{max}	in sec
• duration of level within 10 dB of L_{max}	in sec
• rate of decrease of noise level	in dB(A)/sec
• ambient noise level	in dB(A)

equivalent noise level, L_{eq}* (over 24 hours) in dB(A)

2.4.1 Some results

Only 40 persons failed to mention train noise among the three most noticeable sources of noise in the neighborhood; and of the remaining 304 persons, 62% cited the train noise as the source of greatest annoyance.

More than half the people interviewed (54%) said that, of all the kinds of noise made by trains, the noise that they notice most is that of the train passage itself, that is, the wheel/rail noise.** Next in order of importance (34%) were the noises of shunting, including switching, locomotives, braking, and the impact of cars; naturally, these noises were cited more frequently in locations near Paris. About 5% of the people also mentioned the noise of horns, whistles, and bells, and the noise of work on the tracks during the nighttime.

Not all of people's activities are equally sensitive to disturbance by train noise: there was little or no annoyance expressed about interference with reading or daytime relaxation, but great annoyance about disturbance of television listening and conversation; radio listening held an intermediate position in this respect.

Eighty-four percent of the people interviewed stated that their visitors frequently comment on the noise of the trains.

---

*The equivalent noise level, L_{eq}, (also called the average sound level) is the level of a constant sound which, in a given situation and time period, has the same sound energy as does the time-varying sound. L_{eq} has already been defined mathematically by Eq. (1.1) on p. 10.

**Note that this may *not* be true of rapid transit noise!

While 43% of the subjects said that the noise keeps them from opening the windows in hot weather, 55% said they open the windows in spite of the noise.

It made a great deal of difference in the expressed annoyance whether *all* the rooms of the dwelling face onto the tracks or there is a least one room that does *not* face the tracks and, therefore, can be regarded as a haven of escape from the trains. For people whose rooms all face the tracks, it hardly mattered how loud the train noise is; more than 80% of these people regarded the train noise as the most disturbing neighborhood noise, whatever its absolute level in decibels. For people with at least one sheltered room, there was found a gradual increase of disturbance with increase of maximum noise level during a train passage, from 35% at 67 dB(A) to 100% at 88 dB(A). If the occupant has an "escape room," his annoyance, on average, is the same as that of an occupant without an escape room living where the railroad noise is 4 dB quieter.

No influence of individual variables such as age, sex, socioprofessional category, etc. was found.

Significant correlations were found between the expressed annoyance and the noise parameters of Table 2.1, listed in order of importance.

Neither the number of trains alone (as reflected in the traffic volume or the total duration of train passages) nor the peak noise level during a train passage alone gave the best prediction of annoyance. Instead, the best prediction* was given by the

*Although all these numbers seem low, a correlation coefficient of 0.33 is, in fact, a rather good correlation, as survey results go, concerning subjective response to noise *alone*. Considerably improved prediction is usually found when attitudinal variables are also taken into account or when averaging over large groups of subjects. (See important further discussion in Appendix D.)

TABLE 2.1 CORRELATION BETWEEN ANNOYANCE AND VARIOUS NOISE PARAMETERS.

Parameter	Correlation Coefficient
L_{eq} for 24 hours	0.33
Logarithm of traffic volume	0.30
Total duration of train passages	0.26
Ambient noise	0.23
Maximum noise level	0.22
Maximum noise level of noisiest type of train	0.20
Distance from track	0.12

Equivalent Noise Level, L_{eq}, whose value increases when either the number of trains or the noise of the trains increases.

No correlation was found between annoyance and the rate of increase or decrease of the noise level (i.e., startle is not very important); nor (surprisingly) with the difference between the ambient noise level and the maximum noise of train passages; to the contrary, notice the positive correlation with ambient noise, implying greater annoyance with train noise where the noise from other sources is higher (as found in the British pilot survey by Walters).

2.4.2 Increase of annoyance with increasing noise level

A customary way of evaluating the subjective response of a community to noise of a certain kind is to measure the noise to which the people in the neighborhood are exposed* and then ask certain statistically selected individuals a series of questions concerning how they feel about the neighborhood and the noise that they hear. The questionnaire often includes an annoyance scale, such as the following:

HOW ANNOYING WAS THE NOISE IN YOUR NEIGHBORHOOD DURING THE PAST YEAR?
1 Not at all. 2 Slightly. 3 Moderately. 4 Very. 5 Extremely.

The subject is asked to place himself at the appropriate step along the scale. Sometimes, the number of steps on the scale is different, ranging from four to eleven in different surveys; and sometimes only the end steps on the scale are given names.

The seven-step annoyance scale used for the French railroad survey was as follows:

"D'un point de vue général le bruit des trains est à votre avis:

* 1 * 2 * 3 * 4 * 5 * 6 * 7 *

1 ↓ très supportable; 7 ↓ tout à fait intolérable

This corresponds in English to:

"From a general point of view, in your opinion the noise of the trains is:

* 1 * 2 * 3 * 4 * 5 * 6 * 7 *

1 ↓ quite tolerable; 7 ↓ altogether intolerable

*See the cautionary remarks on this topic in Appendix D.

The French survey results, plotted vs. Day-Night Average Sound Level in terms of the percentage of people at each noise level who are highly annoyed (i.e., respond in the top three steps of the annoyance scale), agree quite well with the results of other surveys concerning the noise of aircraft, road traffic noise, and urban street noise[8/].

Figure 2.1 compares the results of the French railroad survey against the mean of the curves resulting from eleven other noise surveys[8/]. The shaded area represents the range of those curves.

It is seen that for most of these surveys, few people are highly annoyed when the Day-Night Average Noise Level (L_{dn}) is below 50 dB, about 25% are highly annoyed when L_{dn} = 70 dB, and 50% are highly annoyed when L_{dn} = 80 dB.

2.5 The Japanese Survey[9,10/]

In connection with the planning for new railroad lines in Japan, a survey was made in July 1972 to determine the effects of Shinkansen (the high-speed "bullet train") noise on people living between 10 and 200 meters from the tracks. Noise measurements and interviews were carried out along both the Tokaido Line (opened to traffic for eight years) and the new Sanyo Line (opened only four months before the survey).

The Tokaido Line covers the 515 km distance between Tokyo and Osaka in 3 hrs 10 min at a top speed of 210 km/hr; more than half the track is constructed on embankment roadbed; there are about 200 trains per day. The New Sanyo Line covers the 161 km distance between Osaka and Okayama in one hour, at a top speed of 210 km/hr; most of the track is carried on an elevated concrete structure; there are about 80 trains per day. In both

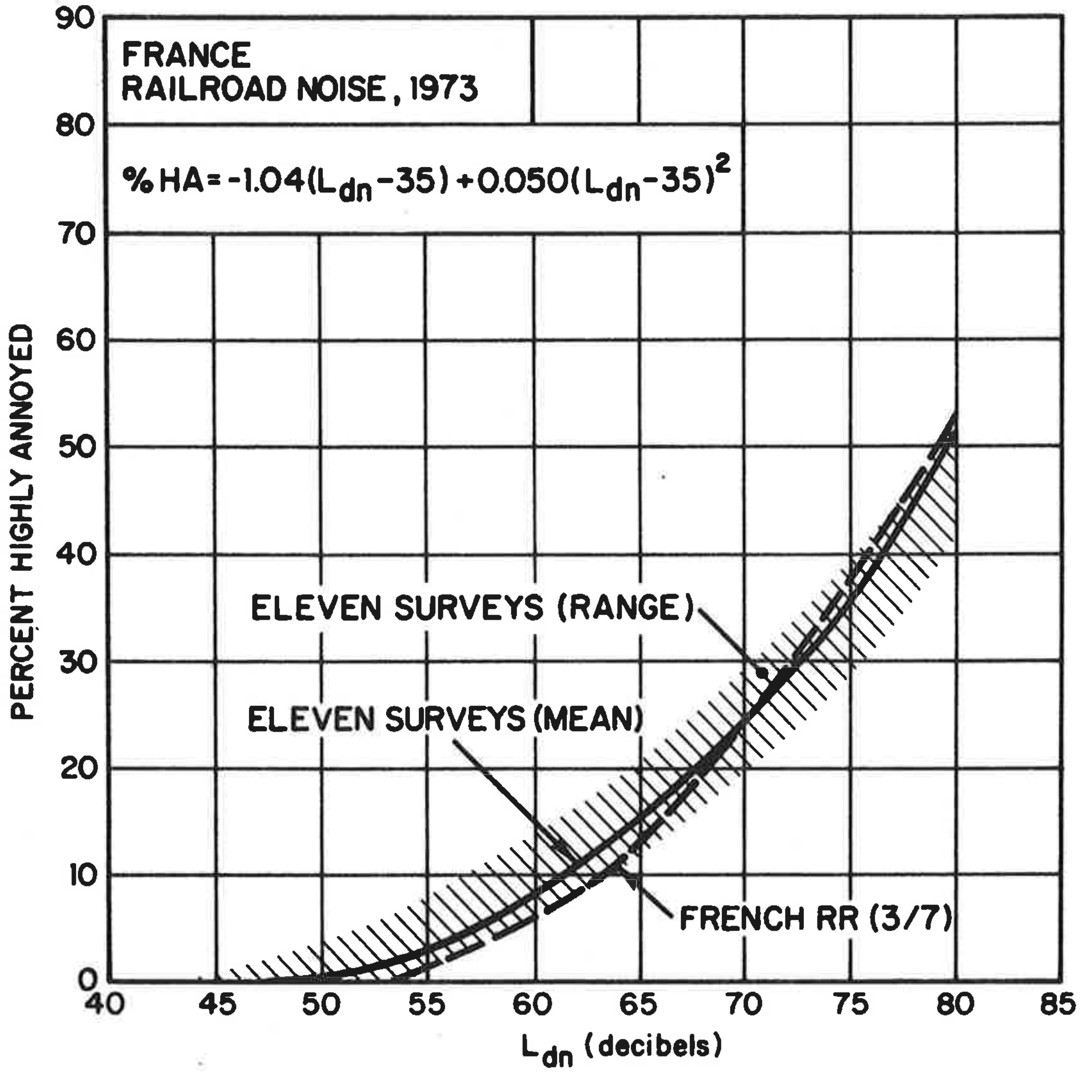


FIG. 2.1. COMPARISON OF PERCENT OF POPULATION HIGHLY ANNOYED (% HA) BY RAILWAY NOISE IN FRENCH SOCIAL SURVEY WITH THE RANGE AND MEAN OF "PERCENT HIGHLY ANNOYED" IN ELEVEN OTHER SOCIAL SURVEYS.

lines, the makeup of the trains is very much the same (12 or 16 cars) and the trains run at prescribed speeds along each section of the track; consequently, the reported noise levels at any given location show little variation (±1 dB) from train to train.

It was intended that the survey area should extend far enough away from the tracks that the train noise impact would be negligible, so that a continuous range of noise exposure, from extreme to none at all, could be investigated. However, within this distance the houses were separated rather widely and, because of budget limitations, the number of samples was restricted. Consequently, the survey was not as detailed (in terms of noise exposure) as desired. The final number of samples was 182 for the New Sanyo Line (87 within 50 m of the tracks) and 242 for the Tokaido Line (150 within 50 m), altogether 424 subjects. More than 80% of the informants were housewives.

In order to avoid focusing only on the railroad noise, the interview included general questions about the living environment; the 52 questions can be divided into five categories:

1. Conditions with respect to the house. } 16 questions
2. Information about the informant and his/her family. }
3. Feelings about the neighborhood. (14 questions)
4. Effects of the noise of the trains. (17 questions)
5. Sensitivity of the informant to noise in general. (5 questions)

The relations between five-step Likert scales,* describing the direct effects of train noise on the community, and the maximum A-weighted levels of train noise during train passages were obtained from the response data; also, the maximum train noise levels that correspond to "neutral points"** along the various disturbance scales were determined. In addition, relations were found between the percent of positive responses (indicating disturbance) to a question and the maximum level of train noise at the location.

A-weighted sound pressure levels of train noise were recorded outside each informant's residence, during the interview period, at the same distance from the track as the house wall facing the track. (Distances were measured from the centerline between the two tracks.) The noise parameter retained for comparison with people's annoyance was the maximum level attained during a train passage. Since this level will be different for trains on the near track than for trains on the far track (about 8 dB at 10 m, 5 dB at 100 m, and 0 dB at 200 m), the question arose whether to use the near-track maximum levels or an energy-average of the maximum levels from *both* tracks to characterize the noise exposure; the latter was adopted.

---

*A Likert scale is a well-known type of psychological measure of human response, ranging from favorable to unfavorable, to some kind of stimulus, that is, a kind of annoyance scale. It is a response scale in which the separate scores for response categories of a set of questions, all representing a particular attribute, are summed to form a composite rating. By using a set of questions rather than a single question, greater reliability in the measurement of the attribute is claimed.

**A neutral point is the boundary on the Likert scale between the response "not disturbed" and "sometimes disturbed."

2.5.1 Effects of the train noise

Effects of the train noise may be divided into three categories: noise, vibration, and radio-wave interference. Although these must be dealt with separately from the physical viewpoint, the neighbors of the railway track are likely to lump them together as disturbance from the trains. Moreover, all three effects behave similarly in their dependence on distance from the tracks. Consequently, the noise survey also included questions on "house vibration" and "TV picture flicker," and the responses were treated like those concerning train noise.

Table 2.2 gives, for ten of the individual annoyance scales and three of the combination scales, the relationship between the maximum noise level during a train passage and the percent of positive (disturbance) responses to the question; it also shows the neutral point that indicates the transition from "no disturbance" to "some disturbance" along the Likert scale for the activity in question.

It is rather surprising at first glance, that these neutral points identifying the *onset* of disturbance should correspond to such high noise levels [73 to 86 dB(A), except for interference with radio/TV-listening]. Nearly one-third of the informants in the French survey gave "intolerable" responses when L_{eq} reached 70 dB(A)! It is particularly puzzling in view of the phrasing of the questions, which seem to require a positive response even for rare occasions of disturbance ("Have you *ever* been wakened..."). It may be that the English translation of the questions fails to give the exact flavor of what was asked. On the other hand, it may be that the well-known Japanese tendency to give a polite reply to all questions biased the interview so that a positive (unfavorable) response was withheld out

TABLE 2.2 RELATIONSHIP BETWEEN PROPORTION OF POSITIVE RESPONSE TO EACH ITEM AND PEAK LEVELS OF TRAIN NOISE

Item	Line	Positive Response in % 60	50	40	30	20	10	Neutral Point of Scale
Single-Question Scales								
				dB(A)				dB(A)
Disturbance of falling asleep (30)	NSL	82	78	75	71	67	--	78
	NTL	87	84	82	80	77	75	85
Awaking from sleep (31)	NSL	80	77	74	71	69	66	77
	NTL	87	85	82	79	76	73	85
Interference with telephone (32)	NSL	79	76	73	70	67	64	78
	NTL	81	79	77	74	72	69	78
Interference with listening to TV or radio (33)	NSL	71	67	64	61	--	--	68
	NTL	72	68	65	62	--	--	69
Startle (35)	NSL	84	81	77	74	71	68	81
	NTL	88	85	83	80	77	75	86
Interference with conversation (36)	NSL	77	74	72	70	67	65	74
	NTL	80	77	75	73	71	69	77
Bothering children (43)	NSL	79	75	71	67	62	58	77
	NTL	87	84	81	78	75	72	85
Disturbance of children's study (44)	NSL	82	79	76	74	71	68	82
	NTL	88	86	84	81	79	77	85
Annoyance	NSL	72	69	66	--	--	--	69
	NTL	77	73	70	--	--	--	73
				m				m
House vibration (37)	NSL	61	77	94	108	124	138	79
	NTL	78	104	130	160	--	--	93
TV picture flicker (34)	NSL	89	112	140	160	--	--	118
	NTL	103	133	160	190	--	--	125
Combined-Question Scales								
				dB(A)				dB(A)
Interference with sleep (30,31)	NSL	80	78	75	72	69	66	78
	NTL	87	84	82	79	76	74	85
(Speech Interference) Disturbance of hearing (32, 33,36)	NSL	75	72	69	66	63	60	73
	NTL	78	76	73	70	68	65	76
Disturbance of children's life (43,44)	NSL	82	80	77	74	71	69	77
	NTL	89	87	84	82	79	76	85

NSL: New Sanyo Line
NTL: New Tokaido Line

of consideration of the interviewer, except in locations where the disturbance is very severe. A further consideration is that, for low traffic volume, a value of 70 dB(A) for L_{eq} would imply a considerably higher value for the maximum noise level during a train passage.

For DOT's purposes, it is unfortunate that the only complete noise survey involving trains mostly on elevated structure (New Sanyo Line) should have been done under cultural circumstances so different from those in North America. The attenuation of railroad noise from outdoors to indoors in a typical Japanese house is an estimated 18 dB less than in a typical North American house; thus, the results of the Japanese survey are not applicable to community response in regions with much higher house attenuation, such as North America. Moreover, the phrasing of the questionnaire for the Japanese survey ("Have you *ever* been disturbed by...etc.") seems to be coaxing an annoyed response. These two facts probably contribute largely to the great differences between the results of this Japanese railroad noise survey and the other surveys mentioned above: the Japanese appear to be much more highly annoyed for the same noise exposure. Moreover, the Japanese responses to the noise of ordinary railroads and of road traffic differ similarly from the results of other surveys in Europe and North America.

Thus, we do not recommend using the data from the Japanese railroad noise survey for assessing noise from elevated structures in the United States.

It is worth noting, however, that the Japanese survey confirms the existence of the "escape room" effect. Moreover, the best correlation between the noise exposure and the subjective response was found for noise ratings that account for both the average maximum noise level during a train passage and the number or duration of the passages, thus lending support to the average noise level rating, L_{eq}.

2.5.2 Japanese laboratory study of the noisiness of trains

In connection with the Japanese social survey described in the previous section, a laboratory study was conducted in parallel, to try to define how the perceived noisiness (as opposed to expressed annoyance... though presumably there must be some relation between noisiness and annoyance!) depends on various parameters of the noise pattern during train passages[11]. The tests were carried out by presenting to trained observers a series of simulated and recorded train noises, having a variety of different peak levels, peak durations, rise and decay times, etc. These signals were alternated with a "Comparison Noise" whose level could be adjusted until the test noise and the comparison noise sounded equally loud.

It turned out that a satisfactory rating for the noisiness of train passages depends only on (1) the maximum A-level during the train passage, and (2) the duration of the passage, thus lending support to the results of the survey.

2.6 Second British Survey on Railroad Noise Annoyance

A nationwide social survey on the response to railroad noise has just recently been carried out at 403 locations with 1453 respondents along the 11,288 miles of railroad routes in Great Britain. The data are still being analyzed at this time, though some preliminary results have already been reported[2,13,14]. Since the data are preliminary, the numerical results may be subject to modifications in the final reports of the study, though the general conclusions will probably not be changed.

Using an analytical model of railroad noise prediction, the survey was designed to provide an equal distribution of subjects at the different noise levels while maintaining a suitable probabililty sample design.

The train noise was estimated, rather than being measured, for most of the 40,000 houses used in the survey. The estimation procedure was based on an empirical mathematical model, with corrections for the distance from the track, the speed of the trains, the effect of cuttings and embankments, and the shielding effect of houses on the noise levels. The corrected level thus found is the noise level resulting from the noisiest train type (usually the fastest) using the nearest track. Actual noise measurements made at 400 houses during the survey suggest that the estimation procedure may have overestimated the actual noise by more than 5 dB in 30% of the cases, and underestimated the actual noise by more than 5 dB in 5% of the cases. Further analysis is continuing, in order to study these matters.

The following noise quantities were measured at the reference sites:

1. The maximum A-weighted sound level reached during the train passby.

2. The mean A-weighted sound level during the loudest part of the train passby.

3. The maximum noise level generated by the rail/wheel interaction (this could normally be distinguished from the locomotive noise for diesel-hauled trains).

4. The acoustic energy emitted during the train passby, normalized to a standard time of one hour, $L_{eq\ 1h}$. That is, it was assumed that each passby was the only noise event in each hour.

Measures 1 — 3 were read visually from a level recorder trace. Measure 4 was obtained using a noise dosimeter.

From the noise measures at the reference sites, the calculated noise levels at the houses of the interviewed subjects, and the traffic volume for trains of different types, the following noise measures were determined for each site:

a. the logarithmic mean value for all trains at each sites for Measures 1, 2, 3, above;

b. the 24-hour L_{eq};

c. the 18-hour L_{eq} (0600-2400);

d. the day-night level (L_{dn});

e. the community noise equivalent level (CNEL);

f. the number of trains exceeding a level of 68 dB(A) (for an approximate calculation of NNI assuming L_A = NPL - 12) and their logarithmic mean level;

g. the number of trains exceeding the measured (or estimated) background level and their logarithmic mean level;

h. the highest level recorded from any train;

i. the number of train passbys used for these calculations;

j. the total number of trains per day.

The analysis of the social data has concentrated on the types of disturbance arising from railroad noise; the relationships between the different noise ratings and annoyance; the independent effect of the number of noisy events on annoyance; local neighborhood factors affecting annoyance; individual attitudes affecting annoyance; the relative annoyance caused by railroad and road traffic noise; and the number of people living in high noise levels from railroads.

The activity most greatly disturbed is talking in the garden. Also of concern is disturbance of conversation indoors with the windows open, and the startle effect.

An annoyance index was formed from the responses to five questions dealing with: (10b)* whether the subject is *at all* bothered, disturbed, or annoyed; (11b) how the subject feels about the amount of noise from trains; (17b) *how much* the noise bothers or annoys him on a four-stepped scale, all steps named, from "not at all" to "very much"; (43b) the subject's rating of the amount of railroad noise at his house, on a ten-point scale with the end-points named "No noise at all" and "The worst imaginable amount of railway noise;" and (61) how the subject feels about the noise of all trains on a seven-step scale with the end-points named "Definitely Satisfactory" and "Definitely Unsatisfactory."

This index was correlated against the various noise ratings to see which gives best prediction of community response. None of the ratings gave better correlation than $L_{eq(24)}$.

In attempting a preliminary estimate for an acceptable level of railway noise, it developed that a great deal depends on the assumed shape of the curve relating noise exposure and annoyance, that is, whether is it linear of curvilinear. This choice also influences estimates of the effects of attitudinal factors on the subjective response. (That is, some of the variance that could not be explained by the noise exposure in past surveys

*The numbers in parentheses here correspond to those used in the survey.

and that had to be attributed to attitudinal variables, may have resulted from the fact that a linear regression was fitted to data that require a curve.)

It is claimed that the annoyance results of this British survey agree closely with the data from the French railroad survey, based on Figure 7 of Ref. 2, reproduced here as Figure 2.2. If one looks at the neighborhood mean annoyance score for a given noise exposure, there is, indeed, reasonable agreement. But if one looks for the percentage of people in the neighborhood who are highly annoyed, there is considerable disagreement. The reason lies in the very different names given to the top steps of the annoyance scales in the two surveys: "Definitely unsatisfactory" vs "Altogether intolerable." To evaluate high annoyance in the *same* way on these two scales, and to find that the resulting curves overlie one another is clear evidence that the results are *not* the same.

Figure 2.3 shows this comparison, assuming $L_{dn} = L_{eq(24)} + 4$, which corresponds to about 17% of the daily traffic volume at night (2200-0700), on average. The top three steps out of seven were counted as highly annoyed in the French survey, because of the extreme name given to the top step[8/]; the top two out of seven steps were counted as highly annoyed for the British survey, because no other count is possible from the published data. According to the arguments presented in Ref. 8, a more consistent reckoning of high annoyance in the British survey would be to count the mean of the responses in (1) the top two and (2) only the top step. This would lower the curve for Question 11b considerably, and would decrease the apparent agreement between the French and British studies. The reason for this disagreement between British and French railroad surveys is not known. It may become clearer in subsequent analysis of the British survey data.

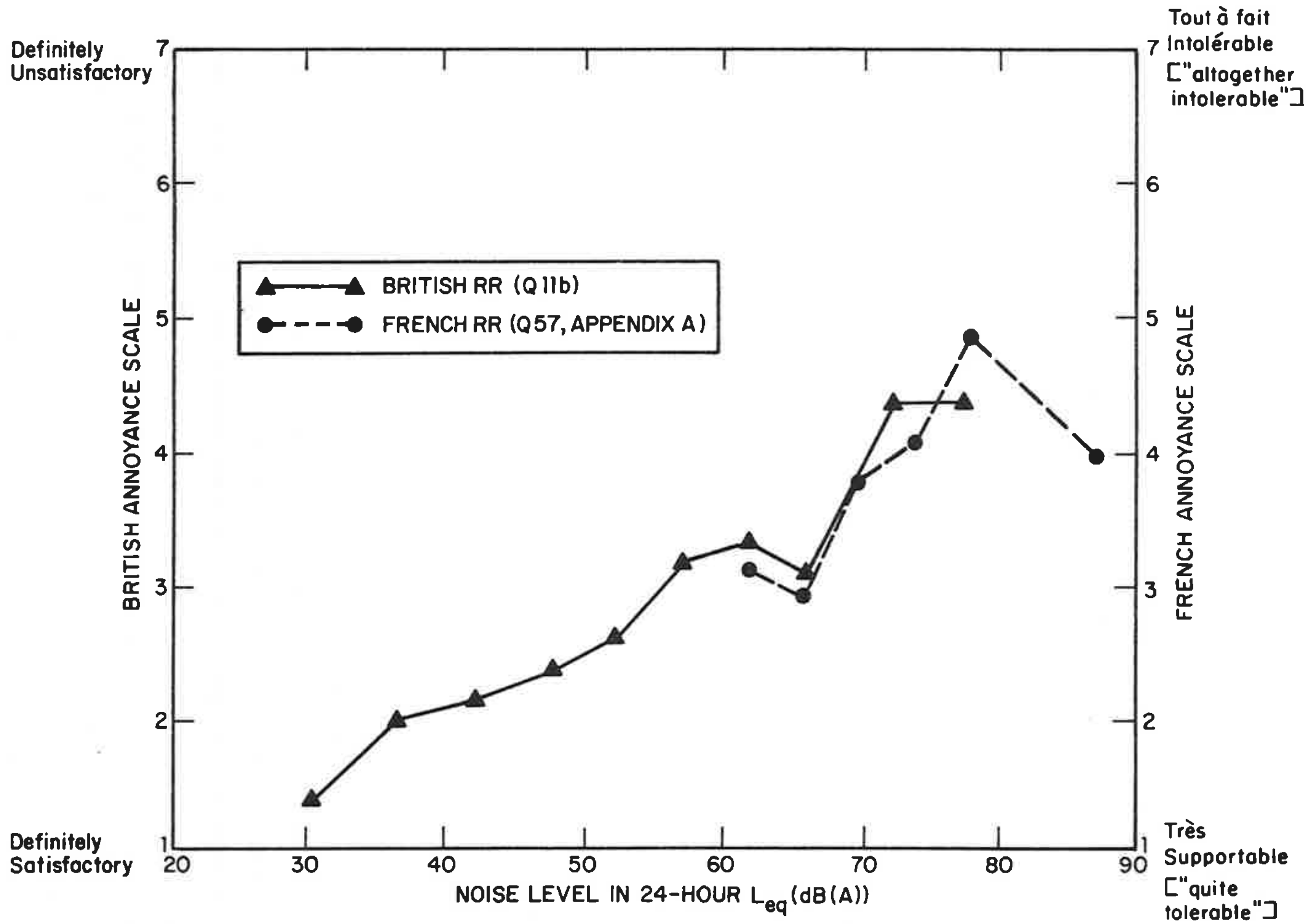


FIG. 2.2. COMPARISON OF MEAN ANNOYANCE SCORES FOR FRENCH AND BRITISH RAILWAY NOISE SURVEYS.

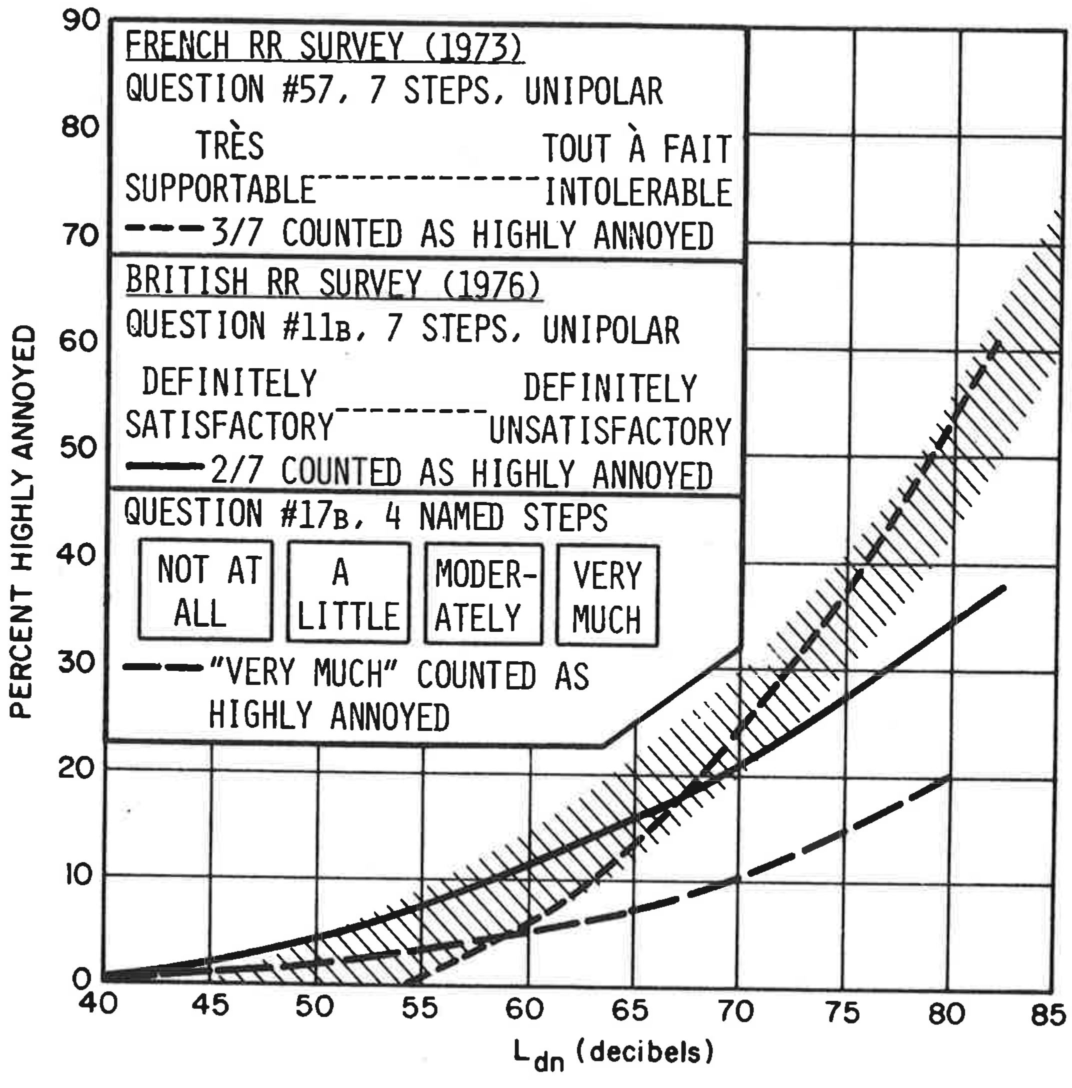


FIG. 2.3. COMPARISON OF "PERCENT HIGHLY ANNOYED" FOR FRENCH AND BRITISH RAILWAY NOISE SURVEYS. THE SHADED AREA REPRESENTS THE RANGE COVERED BY THE AVERAGE RESPONSE CURVES FROM ELEVEN SURVEYS DEALING WITH TRANSPORTATION NOISE (SEE CHAPTER 3).

2.7 Is the Noise of Railroads Less Annoying than Other Kinds of Noise?

There is a belief widely held, nowadays, that people are not annoyed by railway noise as much as by noise of the same level from, say, road traffic or aircraft. This fact is to some extent "documented" in the literature by the relative scarcity of papers dealing with the subject of railway noise. The same belief was mentioned explicitly in the [British] Wilson Report[12/] and is confirmed by private communication with acoustical scientists in Europe. (See also Section 2.3 above, and Ref. 13.)

It is not clear whether this lack of concern (if, indeed, it exists) comes about because railways have been around for so long that people have grown to accept their noise; or because people still cherish railroads as a reminder of a happy earlier era; or because the railway (operating over a fixed path on a strict schedule) is not a source of fear nor surprise, but a token of dependable service; or because the only people strongly impacted are those situated next to the right-of-way and they are comparatively few; or because there has been a long-term migration of noise-sensitive people away from rail lines.*

*The Japanese railroad survey compared responses to the Tokaido Line (opened to traffic for eight years) with the New Sanyo Line (opened only four months before the survey). To elicit the same annoyance response, the train noise levels had to be 5 to 6 dB higher on the older Tokaido Line than on the newly opened Sanyo Line. This difference would be 3 dB greater if the traffic volumes were taken into account (say, with L_{eq}). This difference is presumably due to some kind of "adaptation" of the people near the Tokaido Line, in the eight years of its operation. Since the *individual* residents, who lived there before the operations began, say that they have *not* become habituated, it must mean that the *neighborhood* has adapted: that is, the sensitive people have moved away.

Whatever the cause, there has been no *widespread* public complaint; and, until recently, very little research effort has been undertaken to develop a suitable rating for railway noise.

The data from the recent surveys on railroad noise, however, permit preliminary comparisons of community response to transportation noise of different kinds.

The results of the French railroad noise survey do *not* suggest a different community response to railroad noise than to road and aircraft noise, as shown in Figure 2.4. Furthermore, although the annoyance responses from the Japanese "bullet train" survey are significantly greater than the responses from most European noise surveys, the Japanese responses to the noise of their ordinary trains and to road traffic are quite similar to their response to the noise of the bullet train.

Based on the preliminary results given in Ref. 2, the second British railroad noise survey tenatively concludes "that railway noise may be less annoying than road traffic noise and certainly is no more annoying than road traffic... the application of road traffic criteria to railway noise would protect railway areas from noise at least as much as they protect road traffic areas."

The British report also points out, however, that the greater annoyance due to road traffic noise may be a seasonal effect, since the London road traffic survey (with which they compared their railway data) was conducted at a warmer time of year (late spring) than their railway survey. "If people have their windows open more and expose themselves more to noise in the spring they may conceivably report more annoyance in the spring."

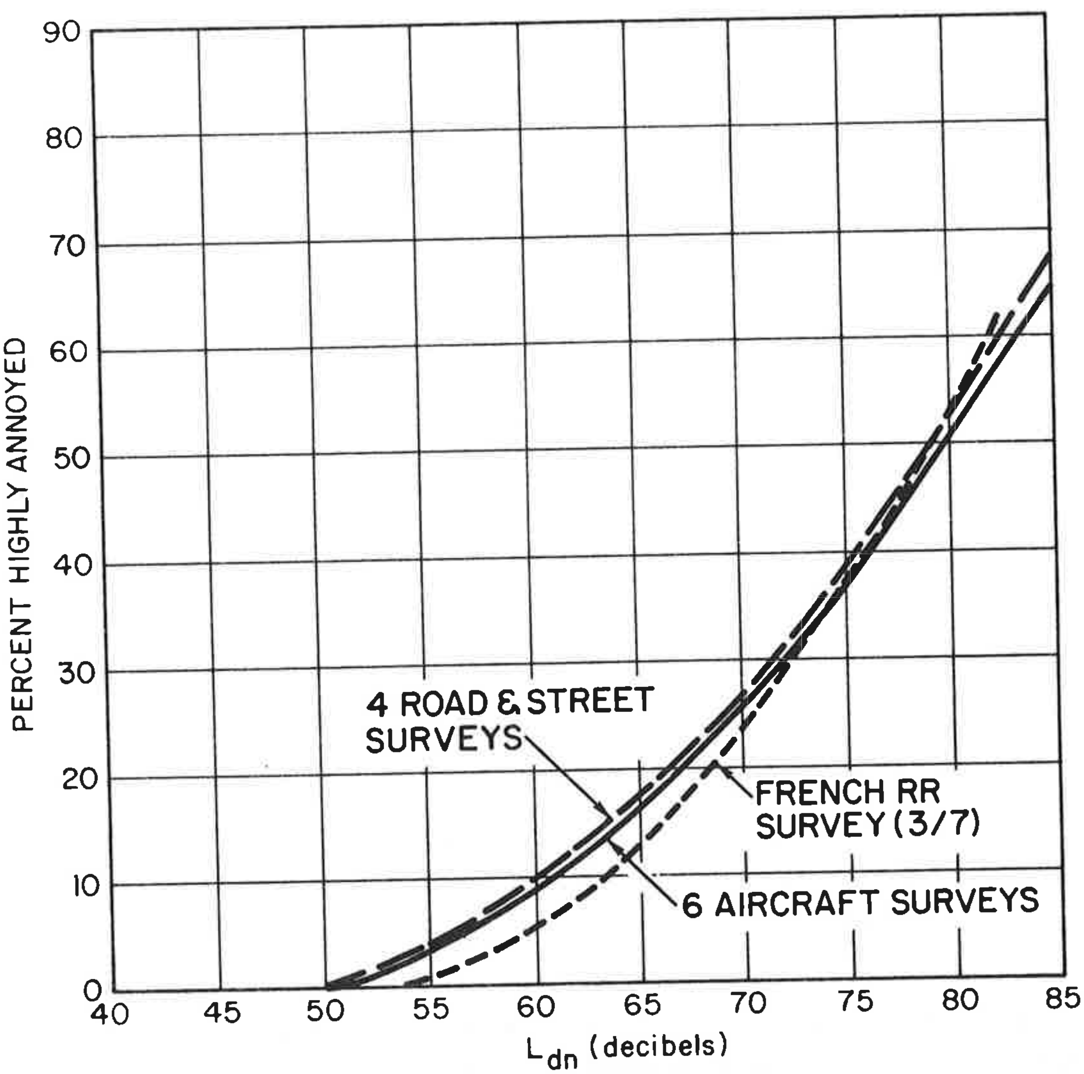


FIG. 2.4. COMPARISON OF "PERCENT HIGHLY ANNOYED" FOR NOISE OF AIRCRAFT, ROAD TRAFFIC, AND RAILWAYS.

There is a further hint in the recent British railroad noise survey that may suggest a plausible explanation for the apparent pardox about attitudes toward train noise. This has to do with the effect of the number of trains. For the same level of train passage noise, there is more annoyance in areas with numerous (more than 223) train passages than where the number of trains is few.* (See Ref. 2, Figure 6.)

Thus, if the number of trains is very small, "nostalgia for the good old days" may generate a favorable response to railroad noise, as suggested above. However, when the number of train passages is much greater, as in a rapid transit system, this affection may disappear and the favorable attitude toward trains may even reverse.

The best currently available information suggests that people's annoyance due to railroad noise follows essentially the same trend as for other kinds of transportation noise; and, in view of the expected large number of train passages, it would *not* be prudent to take special credit for possible favorable attitudes toward railways when evaluating the impact of rapid transit noise.

2.8 Consensus of Social Surveys on Railroad Noise

The general conclusion from the five studies described above is that, as far as the noise impact itself is concerned — that is, leaving attitudes and dwelling exposure out of account — the best correlation with expressed community annoyance is

---

*If the noise were measured in terms of L_{eq}, instead of maximum passby noise level, this difference might be automatically accounted for!

achieved when both the maximum noise level during train passages and the train traffic volume are taken into account; this can be done either explicitly, with separate terms for each variable (the NNI is an example, but not the best!), or by the use of L_{eq}, which embodies both variables. The prediction of annoyance is equally good either way.

However, for the purposes of evaluating a specific component of the noise (e.g., wheel squeal, wheel-rail noise, etc.), the most important parameter will be the maximum noise level during a train passage, since no attempt at trade-offs (with ambient noise, duration or traffic volume, for example) is contemplated for most tests.

The studies considered above have dealt mainly with the explicitly expressed annoyance of people impacted by railway noise. A number of the surveys included studies of interference with specific important activities such as sleep, conversation (in person or on the telephone), listening to radio or television, etc. It is shown in Ref. 8, Figures 10 to 23, that the curves relating serious interference with these activities to the day-night average sound level are very similar to the curves of percent highly annoyed population vs noise level.

Readers of a draft of this report called our attention to three recently reported studies, dealing with rather special aspects of activity interference by noise; one of them actually concerned the noise of elevated rapid transit trains. None of them suggests a significant change from the conclusions reached on the basis of the surveys previously considered here.

One study[15/], conducted in a public school in New York City, was undertaken to determine the relationship between high-intensity, uncontrollable, unpredictable noise and students' reading deficits in a real-life setting. It was concluded, based on a comparison of reading scores of classes on the noisy side of the building with those on the quiet side, that students on the noisy side scored worse than students on the quiet side. The mean reading scores of the classes on the noisy side lagged three to four months behind those on the quiet side.

The noise in question was that of elevated trains, running parallel to the building at about 220 ft distance. It was stated that the average noise level during the six-hour teaching period, in the absence of train passages, was 59 dB(A), and that when a train passed, the noise level rose to 89 dB(A), "which required the teacher to scream in order to be heard by a student sitting 16 feet away." Classes on the noisy side were said to be interrupted for an interval of 30 seconds every 4½ minutes, on average. The report implies that this is an example of serious noise impact.

A noise exposure of 89 dB(A) for 30 seconds out of every 4½ minutes corresponds to an average noise level of 79.5 dB(A). It will be seen in Chapter 3 (Table 3.1) that 79.5 dB(A), increased by 12 dB to translate from indoors to outdoors, corresponds to a noise impact of 288%, a very severe condition, indeed. Thus, the rating scheme proposed in Chapter 3 of this report gives a plausible assessment for the extreme condition existing in that school.

Noise measurements, made in the same schoolroom by an independent team for different purposes, range from 75 to 85 dB(A) with one window open by 1 to 1½ feet, depending upon the train speed. Thus, the 89 dB(A) noise level reported during train passages appears to be the correct measure of the noise exposure.

The second paper[16/] reports the effect of teletype noise on the accuracy of subjects doing a proofreading task in a laboratory study. The noise levels were "typical" [i.e., 66 to 70 dB(A) at the subject's ears]. This study produced clear evidence of noise interference, in contrast to the earlier similar studies of task interference, which have yielded small or equivocal results. Here, the noise group overlooked 25% more errors than a control group who worked without the teletype noise; however, the variation among the individual performances was so large that the power of the test was said to be only about 0.25.

The results of this study are interesting, but not directly applicable to the evaluation of elevated train noise; its most relevant contribution to DOT's purposes is the concluding paragraph of the paper:

> "In spite of current interest in noise as one aspect of a deteriorating environment, the use of realistic noise levels and meaningful tasks is still uncommon. Without theories capable of making accurate generalizations from one situation to another, the use of laboratory analogues must be recognized as a hazardous practice. Investigators interested in the practical applications of their research must attempt to design experiments which duplicate, as nearly as possible, conditions as they occur in real life."

It is for this very reason that the conclusions of the present report are based entirely on observations of people's responses in real-life situations, and not on laboratory studies.

The third paper[17/] dealt with the effect of railway train noise on sleep. This was a field study, in which the physiological responses of sleeping subjects (EEG, EOG, EMG, EKG, and plethysmograph data) were recorded for subsequent comparison with recordings of the train noise, analyzed to determine L_{eq}. Comparisons were also made of the sleep disturbance caused by road traffic noise with the same values of L_{eq}.

The fact that there was the same *percentage* of disturbances for both road and rail noise suggests that people do not become more conditioned to rail than to road noise. However, the total *number* of sleep disturbances was three times greater for road traffic than for rail noise at the same value of L_{eq}. (Note that it required about three times as many road vehicle passages as train passages to generate the same value of L_{eq} because the peak noise level during a train passage is so high.) Thus, the *number* of occurrences of noise is an important factor in sleep disturbance. The percentage of awakenings increased with increases in the peak noise level for peak levels exceeding 52 dB(A) [indoors; corresponds to 64 dB(A) outdoors, windows open]. Awakenings did not occur for noise levels lower than 52 dB(A) and no sleep disturbance of any kind occurred for levels below 45 dB(A) (indoors).

The results of the study suggest that, although sleep disturbances increase in number both with increasing peak noise level and increasing number of noisy events, the combination of levels and number of events embodied in the L_{eq} rating (energy equivalence) is not the best combination for rating sleep disturbance.

A fourth recent paper[14] reports further results from the second British survey, described earlier in this report on the basis of Ref. 2. These new results appear to contradict some of the conclusions of the French paper described above. For example, the British survey found that the number of nighttime train passages contributes nothing to the amount of disturbance once the peak noise levels have been accounted for, suggesting that nighttime annoyance is sensitive only to peak levels. It must be remembered that the subjects' response models were quite different in the two studies: the French survey inferred sleep disturbance based on measured physiological variables, while the British survey questioned the subjects about disturbance of various kinds, including sleep.

An interesting finding is that people were considerably less disturbed by overhead electrical routes than by other types; third-rail electrified routes were only slightly less annoying than diesel routes. No explanation has been found for this difference.

The study found that "on average, at least in Britain, most people find other noise sources [e.g., aircraft and road traffic] are somewhat more disturbing than railway noise." The size of the difference in reaction is not clear, however; it depends on the surveys being compared, the noise level at which the comparison is made, and the assumptions made in the comparisons, and the country. Moreover, the surveys of aircraft noise with which the railway responses were compared adopted a method of counting high annoyance that surely exaggerates the negative response (for discussion, see Ref. 8, Part Two, Section II.A); and finally, the railroad noise survey was conducted in the wintertime when windows are mostly closed, whereas the aircraft and road traffic surveys were conducted in spring and summer, the open-window season. The conclusion that people are especially tolerant of railway noise is yet to be firmly established.

Based on all the information presently available, *the maximum A-weighted sound pressure level during a train passage* is the best choice for evaluating the efficiency of various noise control measures for elevated rapid transit structures.* The ultimate success of a specific noise control measure as it reflects the impact of the elevated train noise on the community, can be assessed in terms of the reduction of maximum A-weighted sound level during a train passage. But to assess the impact of the rapid transit system on the community, either in a restricted neighborhood or over the entire system, it is necessary to take into account the size of the impacted population and the noise level relative to the background noise that exists in the absence of the train passages, as described in Chapter 3, below.

Some train noises, such as the engine noise of the locomotives (or other traction units), the noise of warning signals (whistles, horns, bells, etc.), and the noise of shunting in the yard, present difficulties. Practically no study has been done on the effects of these noises, by themselves, on the community; and for some wheel/rail interaction noises, such as flange impacts, passage over switches, etc., very little information is known. These noises, however, are not intrinsic to elevated structures, and, therefore, are not regarded as important to the present study and are not considered further in this report.

---

*It is worth noting that International Standard 3095 (1975) "Measurement of Noise Emitted by Railbound Vehicles" of the International Standards Organization, Geneva, gives first priority to A-weighted sound levels for measuring the noise outside *all* kinds of railbound vehicles, with octave-band analysis permitted for diagnostic purposes.

2.9 Conclusions

We recommend for all monitoring of elevated train structure noise, and for assessing the effectiveness of noise control measures for elevated structures, that A-weighted sound pressure levels be used to rate the noise and that A-weighted noise level reductions be used to assess the merit of the noise control measures.

We recommend that the relevant parts of international or national standards be used for carrying out such evaluations, as follows:

For the exterior noise generated by the train as a whole or by individual cars or other items of rolling stock:

a. ISO International Standard 3095 (1975), "Acoustics-Measurement of Noise Emitted by Railbound Vehicles"*

b. ISO Draft Proposal DP 1996/1 (1978), "Acoustics-Description and Measurement of Community Noise Environments. Part 1: Basic Quantities and Procedures."

For the interior noise, affecting both passengers and operators, generated by the train as a whole or by individual cars or other items of rolling stock:

c. ISO International Standard 3381 (1977), "Acoustics-Measurement of Noise Inside Railbound Vehicles."

---

*The requirements for microphone positions given in this standard are modified, in this report, for use with elevated structures (see Section 3.6, below).

9. Toshio Sone, Kono Shunichi, Nimura Tadamoto, Kameyama Shunichi, and Kumagai Masazumi, "Effect of High-Speed Train Noise on the Community Along a Railway," *J. Acoust. Soc. Japan*, 29 (4), 214-224, April 1973. (Translation available from BBN as Technical Information Report #87, August 1973.)

10. T. Nimura, T. Sone, and S. Kono, "Some Considerations on Noise Problem of High-Speed Railway in Japan," *Proceedings of INTER-NOISE 73*, 22-24 August 1973, Copenhagen, Denmark, Paper #D22Y17.

11. Shunichi, Kono, Toshio Sone and Tadamoto Nimura, "A Study on Noisiness of a Train Noise," *J.Acoust. Soc. Japan*, 29 (4), 225-?, April 1973.

12. *Noise — Final Report*, Cmnd. 2056, July 1963; Her Majesty's Stationery Office, London.

13. J.M. Fields and J.G. Walker, "Comparing Reactions to Transportation Noises from Different Surveys: A Railroad Noise vs Aircraft and Road Traffic Comparison," Third International Congress on Noise as a Public Health Problem, 25–29 September 1978, Frieburg, Germany.

14. James M. Fields, "Railway Noise and Vibration Annoyance in Residential Areas," Second Workshop on Railway and Tracked Transit System Noise, 19 October 1978, Paris.

15. Arline L. Bronzaft and Dennis P. McCarthy, "The Effect of Elevated Train Noise on Reading Ability," *Environment and Behavior*, 7 (4), December 1975; 517–527.

16. Neil D. Weinstein, "Effect of Noise on Intellectual Performance," *J. Appl. Psychol.*, 59 (5), 1974; 548–554.

17. Monique Vernet, "Effect of Train Noise on Sleep for People Living in Houses Bordering the Railway Line," Second Workshop on Railway and Tracked Transit System Noise, 19 October 1978, Paris.

the number of people affected can be *estimated* from average population densities; in the latter case, the noise levels should be *measured* and the occupants of the house should be *counted*. The complexity of the model should match the scope of the problem.

Note that an analysis for a "typical" case, based on estimates of average quantities, can be in serious disagreement with the results of analysis (or measurements) for some specific site, because of local peculiarities of terrain or building configuration.

The next section introduces a method of noise impact analysis that is adaptable to any desired degree of complexity. It is currently in widespread use by the U.S. Environmental Protection Agency.

3.2 Fractional Impact Method

Noise from a given source may have a certain impact because it affects a few people very greatly (this is the intensive aspect, dependent on the noise level) or because it affects a large number of people less greatly (the extensive aspect, dependent on the size of the population affected). The Fractional Impact Method evaluates noise as the product of the intensive and extensive aspects of the impact.

Sound levels produced by most noise sources generally vary with distance from the source, particularly over a large geographic area. As a consequence, people in different locations experience different sound levels. It is desirable to derive a single number which represents quantitatively the integrated effect (or "impact") of the noise on the total population experiencing the different sound levels. This single number quantification, defined below, is the Sound-Level-Weighted Population, LWP.

3.2.1 Sound-Level-Weighted Population

Sound-Level-Weighted Population is a single number representation of the severity of impact on a noise environment on the exposed population. Several assumptions are made in this method of analysis:

1. Intensity of human response is a function of the average sound level; the form of the function depends upon the response of interest (annoyance, speech interference, hearing loss), but the response generally increases (becomes more severe) as the noise level increases.

2. In order to introduce into the analysis the number of people affected by each level of environmental noise, we assume that a trade-off can be made between the *intensity* and the *extensity* of noise impacts; that is, the impact of high noise levels on a small number of people is equivalent to the impact of lower noise levels on a larger number of people* in an overall evaluation. Thus, the intensity (level of sound) and extensity (number of people affected by the sound) can be combined mathematically.

---

*That is, up to a point. For some purposes, such as protecting the abutters of a railroad right-of-way, it is wise to keep account explicitly of the population exposed to *very* high noise levels, in addition to calculating the total noise impact for the community. Since the Fractional Impact Method may hide the fact that a few people are exposed to very high levels, it is desirable to carry along in the impact analysis a supplementary criterion of impact based on an absolute maximum noise exposure, in order to avoid exposing *any* of the population to levels higher than the maximum acceptable level.

3. On the basis of these two assumptions, one can ascribe differing quantitative degrees of impact to different segments of the population, depending on the average sound level.

These concepts have been embodied in an analysis procedure called the Fractional Impact Method. In this method, the "fractional impact" is the product of a sound-level-weighting index and the increment of population exposed to the corresponding sound level. In other words, we define "partial noise impacts" for various sub-neighborhoods, each of which is exposed to a different noise level, L_i. Thus, out of the total neighborhood population, P, under consideration, we determine the actual numbers, P_i, of people who are exposed to various noise levels, L_i, and who, therefore, all suffer the same corresponding fractional impact. This fractional impact is represented in the weighting function $W(L_{dn})$, determined by the local value of day-night average sound level, L_i, in that neighborhood. Each local partial impact* is represented by the corresponding value of the product $W(L_{dn})_i \times P_i$.

The integral of W_iP_i over all the partially impacted subpopulations in the neighborhood gives the Sound-Level-Weighted Population, a measure of the impact on that neighborhood of the noise under study:

$$LWP = \int P(L_{dn}) \cdot W(L_{dn})\, d(L_{dn}) \quad , \tag{3.1}$$

*It is important NOT to think of the partial impact as a product of "people times decibels;" it is rather the product of "people times an index," which index describes the severity of their noise impact. The index is based on community response to various kinds of transportation noise, as measured in a number of social surveys on noise annoyance; see below, Sections 3.2.2 and 3.3.

where $P(L_{dn})$ is the population distribution function (i.e., $P(L_{dn})$ is the number of people exposed to community noise of level L_{dn}), $W(L_{dn})$ is the weighting function characterizing the severity of the impact, and $d(L_{dn})$ is the differential change in day-night average sound level. The integral extends over the range of L_{dn} existing in the community under study.

Equation 3.1 is appropriate if the population distribution is available as a function of day-night average sound level, L_{dn}. An alternative form of the equation is useful when one knows the values of day-night average sound level as a function of the distance, r (in feet), from the noise source, as in Section 3.6, below:

$$LWP = \int_{r_0}^{\infty} W(L_{dn})\ D\ dS \quad , \qquad (3.2)$$

where $W(L_{dn})$ is the weighting function (see next section); D is the local population density in people per square mile; dS is the incremental area in square miles (see below); and r_0 is the distance in feet from the source to the nearest inhabited dwelling.

For a point source, the incremental area is an annulus centered on the source, and

$$dS = 2\pi r\ dr \times 3.6 \times 10^{-8} \text{ square mile} \qquad (3.3)$$

(the final constant is needed to convert from square feet to square miles). For a line source, the incremental area consists of a pair of narrow strips parallel to, and on both sides of, the line source, and

$$dS = 2L\ dr \times 1.89 \times 10^{-4} \quad , \qquad (3.4)$$

where L is the length of the source (e.g., railroad tracks) in miles.

The integral need not actually be carried to infinity, as formally stated in Eq. (3.2), but only out to a distance where the day-night average sound level is so low that $W(L_{dn})$ is practically zero, i.e., L_{dn} less than 35 dB.

For a noise source at or near ground level, it is customary to use a value for population density that is some fraction of the actual local population density, to account for the fact that some people live on the side of the dwelling facing away from the source and are thus effectively shielded from the noise impact. For railroads and rapid transit lines, one typically counts only half the actual population density.

No such correction would apply for aircraft noise since all sides of the dwellings can be exposed.

The "neighborhood" in question may comprise a few city blocks, an entire city, or the whole United States. As stated in Section 3.1, the required amount of detail in the assessment would be less for the cases with broader scope.

It is not necessary to use the integral form to compute LWP; sufficient accuracy is usually obtained by taking average values of the weighting function between equal-decibel increments, up to 5 decibels in size, and replacing the integrals by summations of successive increments in average sound level. See the example given below (Section 3.4).

3.2.2 Sound level weighting function for impact analysis

In most cases, the primary concern is the effect of a noise on the residential population of the environment under consideration. The weighting function used for this analysis is based on the documented reaction of populations living in noise-impacted environments and is numerically derived from social survey data relating the fraction of the sampled population who express a high degree of annoyance for various values of day-night average sound level (see Figure 3.1).

Values of the function are listed in Table 3.1, and the function is plotted in Figure 3.2 (on the following pages.) The analytic expression for the function is:

$$W(L_{dn}) = \frac{\left[3.364 \times 10^{-6}\right]\left[10^{0.103L_{dn}}\right]}{\left[0.2\right]\left[10^{0.03L_{dn}}\right] + \left[1.43 \times 10^{-4}\right]\left[10^{0.08L_{dn}}\right]} \quad . \qquad (3.5)$$

3.3 Relation to Earlier Version of Fractional Impact Method

In a number of environmental noise assessments conducted by EPA, an early form of population weighting was used, where the significant range of day-night average sound levels was from 55 decibels to 80 or more decibels. This weighting function was described as "fractional impact," FI, and had the linear form:

$$FI = 0.05 \ (L_{dn} - 55) \quad . \qquad (3.6)$$

This function is shown as the dashed line on Figure 3.2.

Several features of Eq. (3.6) were unsatisfactory. Community response is probably not adequately described with a *linear* function of average noise level over a wide range of levels. Even though the data from individual social surveys are reasonably well fitted by linear regressions over the limited range of noise levels represented in the single surveys,

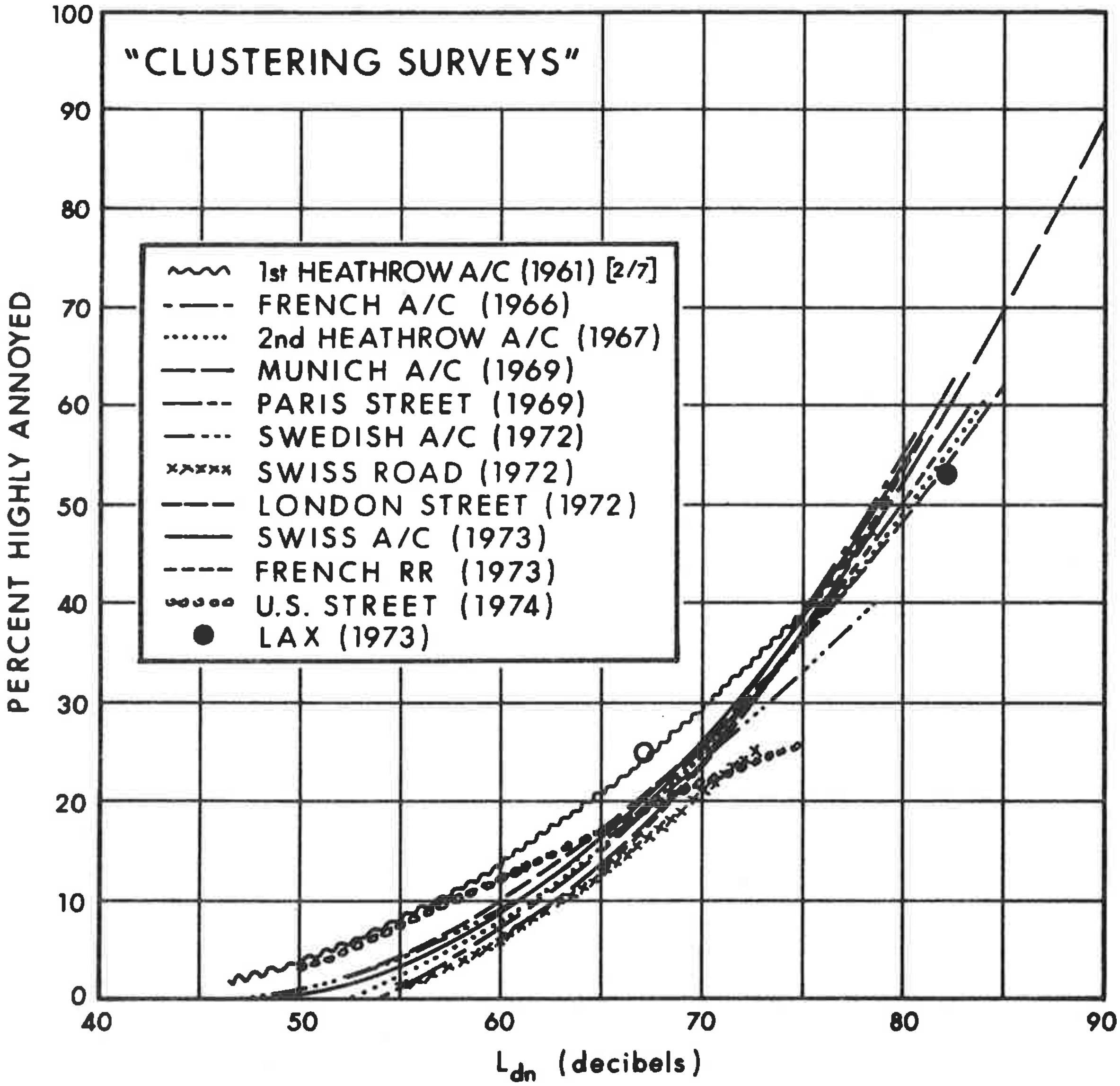


FIG. 3.1. SUMMARY OF ANNOYANCE DATA FROM ELEVEN SURVEYS. DATA SHOW CLOSE AGREEMENT (From Ref. 2).

TABLE 3.1 WEIGHTING FUNCTION $W(L_{dn})$

L_{dn}	$W(L_{dn})$	L_{dn}	$W(L_{dn})$	L_{dn}	$W(L_{dn})$
35.0	0.006	57.0	0.162	79.0	1.384
35.5	0.006	57.5	0.173	79.5	1.380
36.0	0.007	58.0	0.184	80.0	1.428
36.5	0.007	58.5	0.196	80.5	1.476
37.0	0.008	59.0	0.208	81.0	1.526
37.5	0.009	59.5	0.221	81.5	1.577
38.0	0.009	60.0	0.235	82.0	1.628
38.5	0.010	60.5	0.250	82.5	1.682
39.0	0.011	61.0	0.265	83.0	1.736
39.5	0.012	61.5	0.281	83.5	1.791
40.0	0.013	62.0	0.297	84.0	1.848
40.5	0.014	62.5	0.314	84.5	1.907
41.0	0.015	63.0	0.332	85.0	1.966
41.5	0.017	63.5	0.351	85.5	2.027
42.0	0.018	64.0	0.371	86.0	2.090
42.5	0.019	64.5	0.391	86.5	2.154
43.0	0.021	65.0	0.412	87.0	2.219
43.5	0.023	65.5	0.433	87.5	2.286
44.0	0.025	66.0	0.456	88.0	2.355
44.5	0.027	66.5	0.479	88.5	2.425
45.0	0.029	67.0	0.503	89.0	2.497
45.5	0.031	67.5	0.528	89.5	2.571
46.0	0.034	68.0	0.554	90.0	2.647
46.5	0.036	68.5	0.580	90.5	2.724
47.0	0.039	69.0	0.607	91.0	2.804
47.5	0.042	69.5	0.636	91.5	2.885
48.0	0.046	70.0	0.664	92.0	2.968
48.5	0.049	70.5	0.694	92.5	3.054
49.0	0.053	71.0	0.725	93.0	3.141
49.5	0.057	71.5	0.756	93.5	3.231
50.0	0.061	72.0	0.788	94.0	3.323
50.5	0.066	72.5	0.822	94.5	3.418
51.0	0.071	73.0	0.855	95.0	3.514
51.5	0.076	73.5	0.890	95.5	3.614
52.0	0.082	74.0	0.926	96.0	3.715
52.5	0.088	74.5	0.963	96.5	3.820
53.0	0.094	75.0	1.000	97.0	3.927
53.5	0.101	75.5	1.039	97.5	4.036
54.0	0.108	76.0	1.078	98.0	4.149
54.5	0.166	76.5	1.118	98.5	4.264
55.0	0.124	77.0	1.159	99.0	4.388
55.5	0.133	77.5	1.202	99.5	4.504
56.0	0.142	78.0	1.245	100.0	4.629
56.5	0.152	78.5	1.289	100.5	4.757

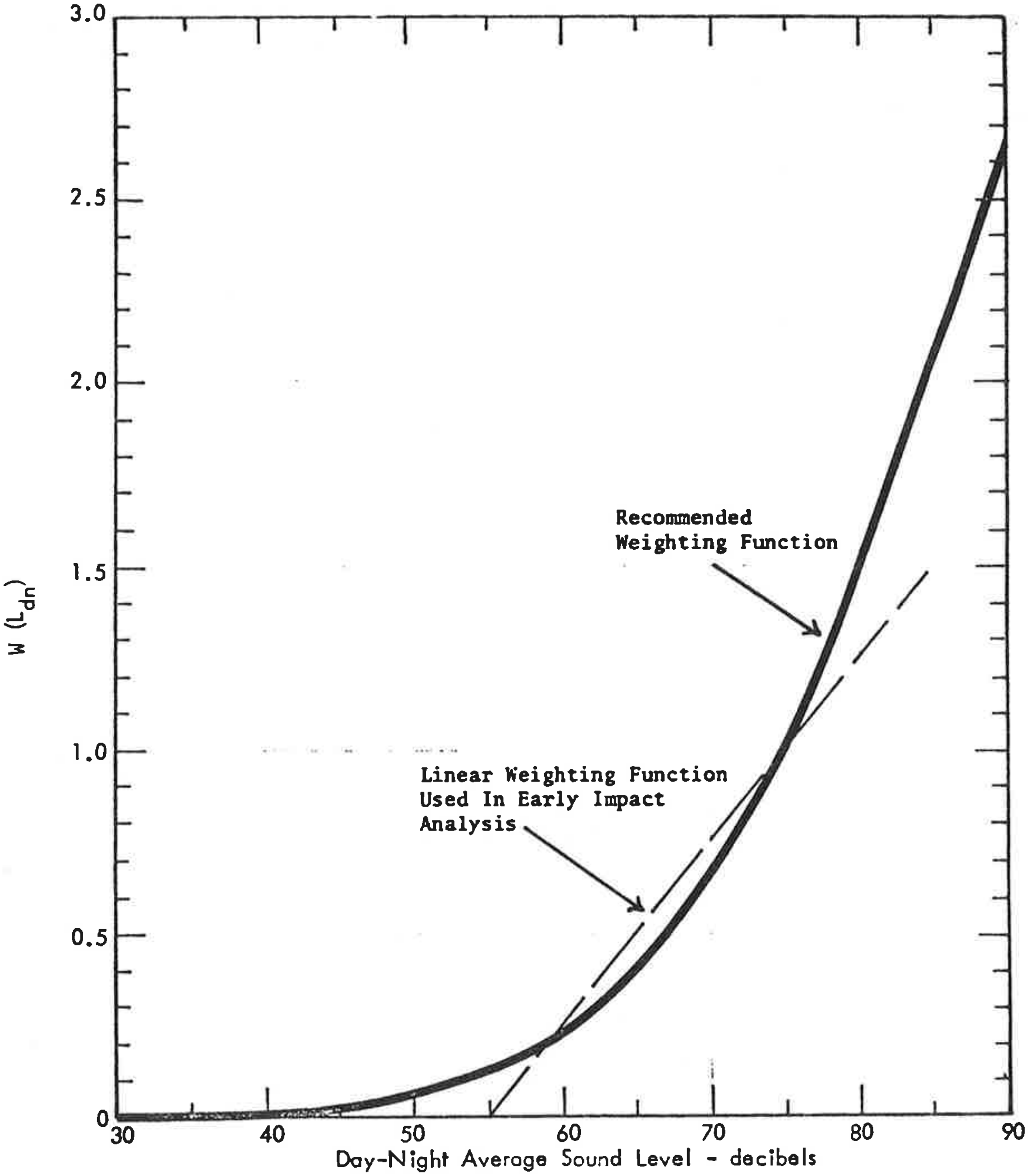


FIG. 3.2. SOUND LEVEL WEIGHTING FUNCTION FOR NOISE IMPACT ANALYSIS.

the collective survey results indicate that the rate of change of annoyance with sound level is greater at higher sound levels than at zero sound levels (see Ref. 8, Figure 6). Moreover, the choice of an arbitrary zero at L_{dn} = 55 dB is not easily justified. Finally, few data from noise sources other than aircraft were available at the time the original weighting functions were developed, and a weighting function derived only from aircraft-related social surveys may not be satisfactory for use in evaluating other sources of noise.

Fortunately, since the earlier analysis was made, data have become available from a number of social surveys associated with highway traffic noise, railway noise, urban traffic noise, as well as further aircraft studies. Based on these data, Schultz[2/] proposed a "universal" transportation noise response curve relating "percent highly annoyed," (%HA), to day-night average sound level:

$$\%HA = 0.8553\, L_{dn} - 0.0401\, L_{dn}^2 + 0.00047\, L_{dn}^3 \quad . \qquad (3.7)$$

This expression represents the least-squares fit of "percent of population highly annoyed" to "day-night average sound level" for the survey data. (Figure 3.1.)

For use as a weighting function for noise impact analysis, however, the cubic expression of Eq. (3.7) behaves awkwardly (e.g., goes negative) at sound levels below those used in the original regression analyses. The shape of the curve suggests that an alternate expression in the form of a power function would be equally suitable. Study shows that the entire range of the curve can be matched by combining two power functions, one controlling the lower range of sound levels, and the other the higher range.

The two power functions may be combined into a single expression, with an empirical choice of coefficients to achieve a best fit (less than one percent deviation) to Eq. (3.7). This expression is:

$$\%HA = \frac{\left[1.24 \times 10^{-4}\right]\left[10^{0.103L_{dn}}\right]}{\left[0.2\right]\left[10^{0.03L_{dn}}\right] + \left[1.43 \times 10^{-4}\right]\left[10^{0.08L_{dn}}\right]} . \qquad (3.8)$$

The weighting function given in Table 3.1 and Figure 3.2 is obtained by arbitrarily normalizing this expression to unity at L_{dn} = 75 dB, that is, by dividing Eq. (3.8) by 36.9, which is the value given by Eq. (3.8) for "percent highly annoyed" at L_{dn} = 75 dB.*

It can be shown that, for the range of day-night average sound level between 55 and 80 dB, the earlier linear weighting function leads to numerical values for Sound-Level-Weighted Population that differ by only about one percent from the values obtained with the newer and more general weighting function $W(L_{dn})$, in most applications. Thus, the adoption of the new weighting function as an index of noise impact will not change the conclusions of earlier noise impact assessments[1/].

3.4 An Example of the Computation of Level Weighted Population if the Population Distribution is Known

An estimate of the U.S. urban population exposed to various day-night sound levels of traffic noise in excess of 55 decibels

---

*This corresponds to EPA's judgment that a neighborhood is 100% impacted by noise (that is, it should not have to tolerate *greater* noise exposure) when as many as 37% of the population are actually highly annoyed and some are exposed to a finite risk of permanent hearing damage. At this noise level, $W(L_{dn})$ = 1.

is provided in Ref. 3, Table B.2. An example of the use of the day-night sound level weighting function applied to these data is shown in Table 3.2. The computation is performed by counting the population within successive 5-decibel increments of sound level, multiplying by the weighting function, then summing the weighted increments to obtain the sound level weighted population (LWP=33.04). One interpretation of this number is as follows: in the total population actually exposed to various traffic noise levels over 55 dB(A) (97.5 million), the overall noise impact on the community is the same as if about one-third of the population (33.04 million) were 100% impacted.

TABLE 3.2 EXAMPLE OF LEVEL WEIGHTED POPULATION COMPUTATION — URBAN TRAFFIC NOISE

L_{dn} (dB)	Cumulative Population (millions)	Incremental Population (millions)	Weighting Function	Level Weighted Population (millions)
		0.1	1.682	0.1682
80	0.1			
		1.2	1.202	1.442
75	1.3			
		5.6	0.822	4.603
70	6.9			
		17.4	0.528	9.187
65	24.3			
		35.3	0.314	11.084
60	59.6			
		37.9	0.173	6.557
55	97.5			

Total P = 97.5 LWP = 33.04

3.5 Model for Propagation of Noise from Elevated Rapid Transit Structures

Note that, in the example above, as in any noise impact analysis, the first requirement in the computation is to obtain the population distribution as a function of average sound level; in that example, the distribution was already given.

With respect to the noise of rapid transit systems, we must know how the noise is attenuated with increasing distance from the trains, in order to determine the distribution. That is, when we have determined the noise levels in different sub-neighborhoods at different distances from the noise source, we can count the number of people exposed to each of these noise levels, and thus determine the population distribution function vs L_{dn}.

Here, especially, it is important that the amount of detail in the analysis be chosen appropriately for the scope of the problem of interest. For example, if the immediate concern is to compare two types of elevated structure as to the general impact their noise would have on a surrounding community, one would deal with a "typical" neighborhood situation, based on estimates and averages, rather than calculating in careful detail the results for a specific neighborhood and group of buildings. The results of the analysis would apply to the "average case;" they might differ significantly from the results of analyzing a specific case or from actual noise measurements in a specific situation.

However, if the problem concerns the impact of the noise of a specific elevated structure on a specific site, then the local geometrical peculiarities must be taken into account in the analysis in as much detail as is possible. The latter case arises very seldom, and involves quite complex analysis procedures that are beyond the scope of this report.

For assessment of the impact of elevated structure noise on urban areas characterized by buildings immediately adjacent to one another (row housing, commercial, and office building, etc.), so that the side of the building away from the tracks is relatively well shielded from the train noise, no complicated calculation of "backyard shielding" (depending on the amount of space between houses) is needed. Here also, the great majority of the train noise impact will be felt by people living in dwellings abutting the track and on the side of the house facing the track; the residents on the backside may be omitted from the noise impact analysis without significant error.

Under these conditions, and for the short distances involved, a suitable noise propagation model is simple attenuation at the rate of 3 dB per doubling of distance (i.e., line source), with a correction for reverberant buildup due to the "city canyon" effect, if any. The correction depends on the street width, as shown in Table 3.3[4].

Note that the model for propagation of elevated structure noise and the method of counting the noise-exposed population presented here are tentative, and apply only for the urban configuration mentioned above. (They are presented here primarily in order to illustrate the Fractional Impact Method of assessing noise impact.) For other configurations, different propagation models or counting methods may need to be adopted; this can be accommodated in the noise assessment procedure without difficulty.

The next section describes how to measure the train passage noise at a standard reference distance and how to calculate the noise level that would exist at any other distance from the tracks.

TABLE 3.3 CORRECTION FOR CITY CANYON EFFECT ON RAPID TRANSIT NOISE

If the distance D in feet between the buildings is:	Then add this number ΔL_C to the predicted noise level:
70	5 dB
80	4 dB
90	3 dB
120	2 dB
200	1 dB
>200	0

3.6 Measurement Locations and Noise Levels at Nearest Dwellings

The noise of elevated structures should be measured with a microphone located at the height of the upper surface of the rails, at a distance of 7.5 m (25 ft) from the centerline of the nearest track. However, practical considerations may in some instances dictate the use of other microphone positions. From such measurements one may determine the noise levels at other locations by application of the appropriate extrapolation relations, as in Section 4 of Ref. 5. A procedure like that of Appendix E may be used to calculate L_{eq} and L_{dn} at any position from the maximum A-weighted level observed at the measurement location.

For multi-car trains one may estimate the noise level L(r) obtained at a distance of r ft from the track centerline from the level L(25') measured at the 25 ft distance by use of the relation

$$L(r) = L(25') - 10 \log r + 14 + \Delta L_C \text{ [dB(A)]}. \qquad (3.9)$$

Here L_c is a correction that accounts for the city canyon effect and may be taken from Table 3.3. This correction is zero unless there are buildings on both sides of the track.

If it is believed that the noise radiated from the structure may be directional or if there is interest in the noise below the structure, a second measurement may be made at a position directly underneath the first microphone position, at a height of 1.5 m (5 ft) above the ground. This measurement would not ordinarily be used in assessing the noise impact on the surrounding community.

3.7 Two Examples of Rapid Transit Noise Impact Computation

The first example is that of a rapid transit line on elevated structure passing through a suburban community consisting of single-story houses. This situation is not very realistic, but it is useful in illustrating the steps in the noise impact calculation procedure.

Let us choose to work with values of L_{dn} at 5 dB increments, and assume that a value of L_{dn} = 66 dB(A) was found at the reference distance of 25 ft in an open area, for typical daily operation of the system. Assume also that the nearest dwelling is at a distance of 55 ft from the elevated structure, the length of the line in this neighborhood is 18 miles, and the population density is 4700 people/sq mi.

Using $L_{(25\ ft)}$ = 66 dB(A), Eq. (3.9) allows us to calculate the distance from the elevated structure at which we would find various values of L_{dn}, in five-decibel increments:

L_{dn}	Distance (ft)
62.5	55 (nearest dwelling)
60	100
55	316
50	1000
45	3160
40	10000
35	31600

We begin by counting the number of people exposed to each of these values of L_{dn}. Assume that all the population in the 18-mile-long strip defined by the two distances from the track, 100 ft and 316 ft, corresponding to values of L_{dn} = 60 and 55 dB (see table above) are exposed to a day-night average sound level of 57.5 dB(A) (the average of the L_{dn} values at the boundaries of the strip). The area in the pair of 57.5 dB strips (one on each side of the track) is [see Eq. (3.4)]:

$$dS = 2L\ dr$$

$$= 2 \times 18 \text{ mi} \times (316-100) \text{ ft} \times 1.89 \times 10^{-4} \text{ ft/mi}$$

$$= 1.47 \text{ sq mi} \quad . \qquad (3.10)$$

The population exposed to 57.5 dB(A) is found by multiplying this incremental area by the local population density and dividing by 2, to account for the assumption that only that half of the people that faces the tracks is significantly impacted.

$$dP = \frac{D\ dS}{2} = \frac{4700 \times 1.47}{2} = 3454 \text{ people} \quad .$$

The weighting function (i.e., noise impact index) corresponding to 57.5 dB(A) (see Table 3.1) is 0.173. The partial noise impact in this pair of strips is 0.173 × 3454 = 598.

A similar procedure is followed for the other strips defined by values of L_{dn} in 5-dB increments, as shown in Table 3.4, and the values of WdP are finally summed to yield LWP = 8398.

This example is unrealistic, not only because it supposes a rather improbable elevated rapid transit in a community of one-story houses, but also because it uses, out to a distance of almost six miles, a noise propagation model [Eq. (3.9)] that is valid only for fairly short distances, where the noise propagates in essentially free space without encountering any obstacles. The calculation leads to the implausible conclusion that the number of people that suffer noise impact increases with increasing distance from the trains!

This propagation model is not valid for the large distances in the example, because sound at great distances propagates at near-grazing incidence to the ground, subject to ground attenuation effects and shielding by various obstacles. The example is included here only to illustrate the steps in the procedure.

TABLE 3.4 EXAMPLE NO. 1

L_{dn}	Average	Distance (ft)	Area, dS (sq mi)	dP/2	Weighting, W	WdP
62.6		55				
	61.3		0.306	719	0.275	198
60		100				
	57.5		1.469	3454	0.173	598
55		316				
	52.5		4.654	10937	0.088	962
50		1000				
	47.5		14.710	34569	0.042	1452
45		3162				
	42.5		46.526	109336	0.019	2077
40		10000				
	37.5		147.102	345691	0.009	3111
35		31620				
					Total LWP =	8398

The second example concerns a city canyon with tall, continuous buildings on both sides of an elevated structure. As a result, there will be a correction for the canyon effect; the only exposed population is in the rooms on the side of the buildings facing the tracks.

We assume a distance from the elevated track to the building facade, on both sides of the line, of 35 ft, and a population density of 16,650 people/sq mi, corresponding to urban center office/residential high-rise[3/]. The noise level measured at the reference distance of 25 ft in an open area is assumed to be L_{dn} = 77 dB(A); the length of the line is 27 miles.

According to Eq. (3.9), the level at the facade would be 75.5 dB(A), if the line were in the open; but the canyon effect increases that value. Assuming that the elevated structure is 30 ft wide, the distance between buildings on opposite sides of the line is about 100 ft, corresponding to a correction (see Table 3.3) of 2.5 dB to be added. Thus, the noise level at the facade would be 78 dB(A) and the weighting function (see Table 3.1) is 1.245.

Assuming the "strip" of noise-exposed area to extend 20 ft into the building, the incremental area is approximately [see Eq. (3.4)]:

$$dS = 2 \times 27 \times 20 \times 1.89 \times 10^{-4} = 0.204 \text{ sq mi}$$

and the impacted population is

$$dP = 0.204 \times 16,650 = 3397.$$

Since we count the exposed strip as extending only 20 ft into the building, we automatically account only for people on the noise-exposed face of the building, so it is not necessary to divide the population by 2 in this case. The noise impact would be

$$LWP = 3397 \times 1.245 = 4229.$$

In this case, only one "strip" need be counted on each side of the track; the remainder of the population in more distant strips is assumed to be so well shielded from the noise that they suffer essentially no noise impact.

Some judgment will be required to determine in each case the best way to count the exposed population.

3.8 Effect of a Proposed New Noise Source in Terms of Change in Community Noise Impact, Δ

When a new noise source is being considered for a community, it is always desirable (and may be required by law) to predict how the noise of the new project will impact the community. The best way of expressing this impact is to calculate the Level Weighted Population (LWP_1) for the community, based on all existing sources of noise *before* the intended project is started; and then calculate the LWP_2 for the same population *after* the new project is fully operational. The difference

$$\Delta = LWP_2 - LWP_1 \tag{3.11}$$

represents the increase in Level Weighted Population due to the introduction of the new project.

If there are several different ways in which the project could be implemented, then the value of Δ corresponding to each way should be calculated, and that way should be chosen which minimizes Δ, that is, which causes the smallest increase in LWP.*

*Note that it is preferable to minimize Δ, not LWP_2, because the latter will usually incur greater cost (see Section 3.9).

In some cases, the value of LWP may even decrease (i.e., negative value for Δ); this could happen, for example, if the introduction of a highway corridor through a heavily populated area displaces so many people to quieter areas that it more than balances the added noise of the highway for the remaining people.

As an obvious extension, values of Δ can be plotted against the dollar costs of the various ways of implementing the project, in order to determine the most cost-effective way of proceeding with the project.

3.9 Background Noise and the Method of Identifying the Noise Impacted Population

It will be noted that the basic LWP computation procedure, described in Sections 3.2 to 3.7, takes no account of the background noise in the community, that is, the noise from all sources other than the one under consideration. This marks a departure from traditional procedures of evaluating noise impact, which have always considered the noise under study in relation to the local background noise. The traditional approach assumes that a given noisy intrusion will cause less disturbance in a noisy urban neighborhood than in a quiet rural area. The approach is not only reasonable and has a long, respectable and successful history, but it also has enormous economic implications. If a product or a system must be designed so that its noise is acceptable in the *quietest* neighborhood that it will affect, then the cost of noise control will be much greater than if the different parts of the system can be tailored to the local background noise for acceptability in each neighborhood that the system impacts.

For comparing the noise of one type of elevated rapid transit structure against another, the background noise is irrelevant and can be ignored. But when it comes to the design of a transit system that must pass through neighborhoods with widely different background noise levels, it would be uneconomical indeed if we could not take advantage of using less costly (noisier) structures in the noisy neighborhoods, reserving the costlier noise control measures for the quiet neighborhoods, where the impact would otherwise be unacceptable.

This discussion has led us in a roundabout way to a problem that was finessed in the discussion of Δ, the change in LWP, in Section 3.8; namely, how are we to choose the population that will be used to compute LWP_1, the noise impact due to the community background noise before the project of interest is finished? Obviously, some way must be found to limit the computation to those parts of the communtiy that will be significantly impacted by the finished project; otherwise, the value of LWP_1 could be made as large (and Δ as small) as desired simply by extending indefinitely the size of the computation neighborhood: the only limitation would be the size of the entire community.

A practical means of coping with this problem is to calculate the noise levels that will exist in the vicinity of the completed project (say, the rapid transit right-of-way), and then compare these levels, area by area, with the preexisting background noise levels. Then one defines the "impacted population" as those people in areas where the new project will increase the value of L_{dn} by one decibel above the local background noise level. This is equivalent to a project noise level five decibels *lower* than the existing background noise level in each neighborhood. This traditionally corresponds to the desirable condition of "no community reaction," assuming that there are no unfavorable attitudinal factors involved.

In each neighborhood, the design of the system should incorporate such noise control measures that the resulting system noise is reduced to acceptable levels in relation to the local background noise level, as determined by computations of LWP and Δ.

Note that designing in terms of LWP will NOT protect the community from the possibility of a few people being impacted by extremely high noise levels. Therefore, in addition to the "sliding criterion" based on differing background noises in the community, it is also necessary to establish a "maximum permissible" noise exposure. For rapid transit systems, this maximum permissible criterion noise level should be given in terms of the A-weighted noise level during train passages, not by L_{dn}; the reason is that L_{dn} involves averaging over time, and compliance with a "maximum permissible L_{dn}" could still permit brief noisy events of much higher noise level.

3.10 Uses for the LWP Computation

The LWP computation can be performed for all kinds of noise that impact the community, including aircraft, highway, road or street traffic, railroads, rapid transit systems, construction noise, and even the noise to which operators and passengers of noisy vehicles are exposed.

The LWP computation can be used for:

- calculating the number of people exposed to various levels of L_{dn} in the United States due to various noise sources, or to all of them together;
- establishing the total U.S. noise impact (LWP) for various types of noise source, or the aggregate;

- relating the total noise impact to the total noise *energy* output of various types of source, or the aggregate;
- establishing priority for regulating or abating different noise sources;
- determining the year-to-year effect of a proposed regulation or abatement method in reducing noise energy and noise impact;
- comparing the effectiveness of one regulation or abatement method against another;
- comparing the effectiveness of *sets* of regulations, abatement methods, or strategies, in reducing noise impact;
- evaluating the effect of shifting population in relation to noise sources;
- evaluating the effect of specific local noise reduction measures (depressed roadways, noise protection barriers, improved housing construction, airport curfews);
- assessing the potential effect of noise technology in product design;
- evaluating the degradation of the environment caused by gradual deterioration of noise abatement capability of products in use;
- calculating the effect of different timing sequences for regulatory and noise abatement program actions, including labeling, with special consideration of discounted value of results that are realized only in the distant future;
- studying the implications of measurement uncertainties in enforcement procedures and their effect on the noise environment;

- providing necessary input to cost/benefit evaluations;
- evaluating the relative importance of the same population of noise sources in different geographical locations (tropics vs. northern climate, for example);
- guiding the plans for carrying out noise annoyance surveys.

The analysis procedure used with all of the above-mentioned uses can be summarized as follows:

1. The current noise impact in the United States is calculated for each type of noise in terms of Level Weighted Population (LWP).
2. The Fractional Impact steps in the LWP calculation are used to determine the number of people in the U.S. exposed to various levels of L_{dn} due to the type of noise under consideration.
3. The total noise energy currently generated in the U.S. by that type of noise is calculated, and is associated with the current LWP for that type of noise. These two quantities represent the baseline for the analysis: that is, 100% of the current noise impact corresponding to the total current generated noise energy for the type.
4. A general relationship between "percent reduction in current noise energy" and the resulting "remaining LWP in the United States," for the type of noise are determined as follows. Across-the-board decrements of total noise energy are calculated corresponding to overall noise attenuation

arbitrarily increasing in 2½ dB steps, and, by a recalculation of the Fractional Impact analysis for each step of attenuation, the corresponding values of LWP are determined.

5. The successive noise level attenuations, called for by the year-to-year enforcement of a given assumed regulation (or by progressive application of a noise control measure to the population of noise sources under consideration), are translated into total noise energy reductions, and these decrements are subtracted from the total *current* noise energy for the type. This determines a curve of remaining noise energy vs. time after promulgation of the regulation or noise control measure.

6. By the use of the general relationship of Step 4, the corresponding decrease in LWP vs time is plotted, to trace the trend of improvement in the noise impact achieved by the regulation or noise control measure in question.

The reason for dealing in noise energy, rather than decibels, is that it is easy to add and subtract changes in energy but difficult to combine noise reductions in decibels due to the various actions.

Following the analysis described in the six steps above, for each of the intended noise control methods, the individual trends of decrease in energy vs. time for all the noise control methods can be summed to determine the trend of *total* noise energy decrease with time; and similarly, the trend of total noise impact in LWP can be found.

References - Chapter 3

1. "Guidelines for Preparing Environmental Impact Statements on Noise," Report of Working Group 69 on Evaluation of Environmental Impact of Noise, Henning von Gierke, Chairman; Committee on Hearing, Bioacoustics, and Biomechanics; Assembly of Behavioral and Social Sciences; National Research Council; National Academy of Sciences; Washington, D.C., 1977.

2. Theodore J. Schultz, "Synthesis of Social Surveys on Noise Annoyance," *J. Acoust. Soc. Am.*, 63 (8), August 1978.

3. "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," Report No. 550/9-74-004, March 1974, U.S. Environmental Protection Agency, Washington, D.C., 20460.

4. Ben H. Sharp, Bruce A. Day and Kenneth J. Plotkin, "The Assessment of Noise at Community Development Sites," Draft Research Report No. WR75-6, April 1976, page 42, Wyle Research, El Segundo, California.

5. Leonard G. Kurzweil and Robert Lotz, "Prediction and Control of Noise and Vibration in Rail Transit Systems," Report No. UMTA-MA-06-0025-78-8, September 1978, U.S. Department of Transportation, Transportation Systems Center, Cambridge, MA.

APPENDIX A: CONSIDERATIONS RELATED TO AVERAGE SOUND LEVEL

A.1 Need for a Simple and Practical Rating Scheme

All efforts to alleviate noise pollution must finally rest on the means for describing the magnitude of the noise problem as it affects human beings. To assess the present noise exposure, to establish criteria for an acceptable noise environment, to limit the noise output of especially prominent sources of disturbance — all these goals demand the adoption of a rating scheme, such that a numerical evaluation of the noise (preferably in terms of a single number) will bear a meaningful relation to the amount of public disturbance caused by the noise. Thus, we look for ways to measure the physical properties of the community noise exposure that are closely connected with people's subjective judgment. We measure, with acoustical test equipment, certain aspects of the noise that, either alone or in combination, can be used to predict accurately how people will respond to the noise.

The question of what and how much to measure is important in choosing a measure to characterize community noise, largely because of the economic implications of the cost of making measurements. It is more expensive to make "complicated" measurements than "simple" ones. Thus, for a given measurement budget, one can, for example, mount a more extensive survey, covering a greater area of the community, if the data to be taken are relatively simple. Of course, recent technological advances in logic circuitry have made it possible to make certain relatively complex measurements routinely and simply. It is a question of choosing between the ultimate refinement in measurement techniques and a practical measurement approach that is no more complicated than is needed to predict the impact of noise on the people, and that can be extensively applied at a reasonable cost.

A.2 People's Response to Noise

The evidence of research on human response to sound indicates clearly that the magnitude of sound as a function of frequency and time is the basic indicator of human response to sound.

A.2.1 Magnitude

Sound is a pressure flucturation in the air; the magnitude of the sound describes the physical sound in the air; loudness, on the other hand, describes how people judge the sound when they hear it. Magnitude is stated in terms of the amplitude of the pressure fluctuation. The range of magnitude between the faintest audible sound and the loudest sound the ear can stand is so enormous (a ratio of about 1,000,000 to 1) that it would be very awkward to express sound pressure fluctuations directly in pressure units. Instead, this range is "compressed" by expressing the sound pressure on a logarithmic scale. Thus, sound is described in terms of the sound pressure level (SPL), which is ten times the common logarithm of the ratio of the square of the sound pressure in question to the square of a (stated or understood) reference sound pressure, almost always 20 micropascals. The unit of sound pressure level is the decibel, abbreviated dB.

In mathematical terms, sound pressure level L, expressed in decibels, is:

$$L = 10 \log \left(\frac{p^2}{p_0^2} \right) \qquad (A.1)$$

where p is the sound pressure and p_0 is the reference pressure, 20 μPa.

A.2.2 Frequency analysis of the noise and the A-weighted sound level

One of the most useful ways to characterize a noise is by a frequency analysis, because people not only distinguish the high-frequency components in a composite noise, but they find high-frequency noises much more annoying than low-frequency noises of the same level. Therefore, to evaluate how disturbing each noise will be we should know how much of the sound energy in that noise is contained in each band of frequency. This means keeping track of an entire set of frequency band sound levels for each noise: as many as nine different numbers for octave-band data, or twenty-five different numbers for 1/3-octave band data, to cover the important frequency range from 31 to 8000 Hz.

Fortunately, much of this complication can be avoided by the use of a special electrical weighting network in the measurement system that simulates the response of the average human ear to sounds of different frequency: each frequency of the noise then contributes to the total reading an amount approximately proportional to the subjective response associated with that frequency. Measurement of the overall noise with a sound level meter incorporating such a weighting network yields a single number, such as the A-weighted sound level, or simply sound level, in decibels.

For zoning and monitoring purposes, this choice marks an enormous simplification and a significant economy. For this reason, A-weighted sound level has been adopted without exception in large-scale surveys of city noise coming from a variety of sources. It is universally accepted as an adequate way to deal with the ear's differing sensitivity to sounds of different frequency. The magnitude aspect of a noise can then be handled in terms of greater or smaller sound levels.

A.2.3 Noise abatement and simple ratings

The dominant characteristic of environmental noise is that it is not steady — at any particular location the noise usually fluctuates considerably, from quiet at one instant to loud the next. Thus, we cannot simply say that the noise level at that location is "so-many decibels." To describe the noise environment completely requires a statistical approach. Consequently, we could speak of the whole time-varying pattern of sound levels at a location. Such a noise environment can be described by giving the complete curve depicting the cumulative distribution of sound levels, showing exactly what percent of the whole observation period each level was exceeded.

A complete description of the noise environment would distinguish between daytime, evening, and nighttime, and between weekday and weekend noise level distributions; it would also give distributions to show the difference between winter and summer, fair weather and foul.

The practical difficulty with the statistical methodology is that it yields a large number of statistical parameters for each measuring location; and, even if these were averaged over more or less homogeneous neighborhoods, it still would require several numbers to characterize the noise environment in that neighborhood. It is literally impossible for any such array of numbers to be effectively used either in an enforcement context, for the purpose of noise abatement, or to map out existing noise environment base lines.

It is essential, therefore, to look further for a suitable single-number evaluation of community neighborhood noise. Note that the ultimate goal in noise abatement is to characterize with reasonable accuracy the noise environments of neighborhoods (within which there may actually exist a fairly wide range of noise levels) so as to prevent extremes of noise at any given time, and to detect unfavorable trends in the future noise climate. For these purposes, pinpoint accuracy and masses of data for each location are not required, and may even be a hindrance, since one could fail to see the forest for the trees.

A noise measure must be found that collapses the array of statistical parameters described above into a single usable figure for describing the noise environment of a neighborhood, even if that simiplification entails some compromise with the current standard of highest attainable accuracy.

A.3 Average Sound Level

The average sound level, sometimes called the equivalent continuous noise level (both having the symbol L_{eq}) is the continuous sound level that is equivalent, in terms of noise energy content, to the actual fluctuating noise existing at the location over the observation period.* The Equivalent Continuous Noise Level was developed in Germany over a period of years and was introduced in 1965 as a rating specifically to evaluate the impact of aircraft noise upon the neighbors of airports A.1/.** It was almost immediately recognized in Austria as appropriate for evaluating the impact of street

---

*L_{eq} is read "L-equivalent."

**References are listed at the end of this Appendix.

traffic noise in dwellings[A.2/], and in schoolrooms[A.3/]. It has been embodied in the National Test Standards of both East Germany[A.4/] and West Germany[A.5/] for rating the subjective effects of fluctuating noises of all kinds, such as from street and road traffic, rail traffic, canal and river ship traffic, aircraft, industrial operations (including the noise from individual machines), sports stadiums, playgrounds, etc. It is the rating used in both the East German[A.6/] and West German[A.7/] standard guidelines for city planning. It was the rating that turned out to correlate best with subjective response in the large Swedish traffic noise survey of 1966-67. It has come into such general use in Sweden for rating noise exposure that commercial instrumentation is currently available for measuring L_{eq} directly; the lightweight unit is small enough to be held in one hand and can be operated either from batteries or an electrical outlet[A.8/]. Other devices are now available in the United States.

During the period when the L_{eq} rating was coming into wide acceptance in Europe, there was little familiarity with it in this country, because the relevant literature was not available in English. One exception was the use of the concept of equivalent level in the 1957 original Air Force Planning Guide for noise from aircraft operations[A.9/]. A more recent application is the development of the CNEL (Community Noise Equivalent Level) measure for describing the noise environment of airports. This measure, contained in the Noise Standards, Title 4, Subchapter 6, of the California Administrative Code (1970) is based upon a summation of L_{eq} over a 24-hour period with weightings for exposure during evening and night periods.

A.4 Related Applications of the Energy Equivalence Concept

The concept of representing a fluctuating noise level in terms of a steady noise having the same energy content is widespread in recent research. There is solid experimental evidence that it accurately describes the onset and progress of permanent noise-induced hearing loss[A.10/], and considerable evidence to show that it applies to annoyance in various circumstances[A.11/]. The concept is approximately borne out by Pearson's experiments[A.12/] on the trade-off of level and duration of a noisy event, and by numerous investigations of the trade-off between number of events and noise level in aircraft flyovers[A.13/]. Indeed, the Noise Exposure Forecast currently in use by the FAA[A.13/] is a formulation of L_{eq}, modified by corrections for day vs night operations, etc. The concept is embodied in several recommendations of the International Standards Organization, for assessing the noise from aircraft[A.14/], industrial noise as it affects residences[A.15/], and hearing conservation in factories[A.16/].

A.5 Extension to Day-Night Average Sound Level L_{dn}

The sole difference between the average noise level discussed above and the day-night average sound level is the application of a penalty to noises occurring in the nighttime period between 2200 and 0700. The rationale for this correction is discussed at length in Appendix B of this report.

The day-night average sound level has been found to be a very stable noise descriptor. In a recent survey of 48 Canadian sites[A.17/], repeated noise measurements at the same site on consecutive weekdays yielded the result that over 60% of the values of day-night average sound level repeated within one decibel.

A.6 How L_{eq} Deals With Different Noise Situations

It is interesting now to observe how L_{eq} changes for different kinds of statistical distributions of noise level, having different amounts of fluctuation.

For distributions with increasing amounts of fluctuation, L_{eq} gives more and more weight to the peak levels. For example, for noise exposures that have "normal" or Gaussian distribution, the following table shows how both the "noise climate" $(L_{10} - L_{90})$, and L_{eq} change with increasing standard deviation, σ (the measure of fluctuation).

TABLE A-1: CHANGE OF L_{eq} WITH INCREASING FLUCTUATION OF NOISE LEVEL

If σ =	$L_{10} - L_{90}$ =	L_{eq}
0	0	All percentile levels are equal
1	2.6	L_{43}
2	5.2	L_{36}
3	7.8	L_{33}
4	10.4	L_{31}
5	13.0	L_{28}
6	15.6	L_{24}
7	18.2	L_{20}
8	20.8	L_{17}
9	23.4	L_{14}
10	26.0	L_{12}
11	28.6	L_{10}
12	31.2	L_{8}
13	33.8	L_{6}

For road traffic noise, the standard deviation σ is typically 4 or 5 dB; thus L_{eq} would correspond to a level somewhere around L_{30}. For greater fluctuation, L_{eq} approaches L_{10}. This is a reasonable way to account for the subjective effect of such noise: the greater the fluctuation, the more the peaks of noise will intrude and become annoying, and, consequently, the more important it becomes to weight the noise rating toward the peaks.

References — Appendix A

A.1 Bürck, W., M. Grutzmacher, F.J. Meister, E.A. Müller, and K. Matschat, "Fluglärm, Gutachten erstattet im Auftrag des Bundesministers für Gesundheitswesen" (Aircraft Noise: Expert Recommendations Submitted under Commission from the German Federal Ministry for Public Health), Göttingen, 1965.

A.2 Bruckmayer, F. and J. Lang, "Störung der Bevölkerung durch Verkehrslärm" (Disturbance of the Population by Traffic Noise), Österreiche Ingenieur-Zeitschrift, Jg. 1967, H. 8, 302-206; H.9, 338-344; and H. 10, 376-385.

A.3 Bruckmayer, F., and J. Lang, "Störung durch Verkehrslärm in Unterrichsträumen (Disturbance Due to Traffic Noise in Schoolrooms), Österreichische Ingenieur-Zeitschrift, 11 (3): 73-77 (1968).

A.4 "Schallschutz: Begriffe" (Noise Control: Definitions), TGL 10 687, Blatt 1 (Draft), November 1970, Deutsche Bauinformation, East Berlin.

A.5 "Mittelung zeitlich schwankender Schallpegel (Äquivalenter Dauerschallpegel)" (Evaluation of Fluctuating Sound Levels (The Equivalent Continuous Sound Level), DIN 54 641, (Draft) April 1971, Duetsche Normen, Beuth-Vertrieb GmbH, Berlin 30.

A.6 "Schallschutz: Territoriale und Städtebauliche Planung" (Noise Control: Land Use and City Planning), TGL 10 687, Blatt 6, (Draft) November 1970, Deutsche Bauinformation, East Berlin.

A.7 "Schallschutz in Städtebau" (Noise Control in City Planning), DIN 18 005, (Draft) August 1968, Deutsche Normen, Beuth-Vertrieb GmbH, Berlin 30.

A.8 Benjegård, Sven-Olaf, "Bullerdosimetern" (The Noise Dose Meter), Report 51/69, Statens Institut fur Byggnadsforskning, Stockholm, 1969.

A.9 Stevens, K.N. and Pietrasanta, A.C., and Staff of Bolt Beranek and Newman Inc., "Procedures for Estimating Noise Exposure and Resulting Community Reactions from Air Base Operations," WADC TN-57-10, Wright-Patterson Air Force Base, Ohio: Wright Air Development Center, 1975.

A.10 Robinson, D.W. and Miss J.P. Cook, NPL Aero Report No. Ac 31, June 1968, National Physical Laboratory, England.

A.11 Meister, F.J., "Der Einfluss der Einwirkdauer bei der Beschallung des Ohres" (The Influence of the Effective Duration in Acoustic Excitation of the Ear), Lärmbekämpfung 10(3/4), June/August 1966.

A.12 Pearsons, K.S. "The Effects of Duration and Background Noise Level on Perceived Noisiness," FAA ADS-78, April 1966.

A.13 Galloway, W.J., and Dwight E. Bishop, "Noise Exposure Forecasts: Evolution, Evaluation, Extensions and Land Use Interpretations" Bolt Beranek and Newman Inc., Report No. 1862, August 1970; also FAA-No-70-9.

A.14 "Procedure for Describing Noise Around an Airport," R-507. International Standards Organization, Geneva, 1970.

A.15 "Noise Assessment with Respect to Community Noise" R-1996, International Standards Organization, Geneva, 1970.

A.16 "Assessment of Noise-Exposure during Work for Hearing Conservation," R-1999, International Standards Organization, Geneva, 1970.

A.17 Bradley, J.S. "A Second Generation Noise Survey," Proceedings of Inter-Noise'76, Washington, D.C., 5-7 April 1976, pp. 377-380.

APPENDIX B: NIGHTTIME ADJUSTMENT IN THE RATING OF COMMUNITY NOISE EXPOSURE

A number of the noise ratings used in the assessment of community noise apply an adjustment for noisy events occurring during the nighttime (that is, these events are treated as if they were noisier than they actually are), in order to account for their greater presumed potential for creating disturbance than if they occurred during the daytime[B.1/]. The rationale for such an adjustment is discussed in this appendix.

B.1 Nighttime Adjustments in Various Noise Ratings

When the nighttime adjustment was first introduced[B.2/], it was with this explanation: "Time of Day. Most residents agree that intruding noise is more tolerable in the daytime than during the evening. During the night, the background noise levels from traffic and other sources are usually lower than the corresponding daytime levels and hence an intruding noise is subject to less masking. Therefore, the noise is more noticeable. We estimate that a correction number of -1 should be applied to the level rank if the intruding noise occurs only in the daytime. No correction is applied for round-the-clock operation or for operation after, say, ten o'clock at night." The correction of -1 in level rank is equivalent to permitting "daytime only" noises to be 5 dB louder than round-the-clock or nighttime noises.

The nighttime adjustment of 10 dB used in the current CNR and civil NEF methods of rating aircraft noise is quantitatively based on overt community response evaluations, as follows. It was estimated in the 1961 London social survey[B.3/] that a reduction of 17 NNI units was required to achieve the same acceptability for nighttime aircraft operations as for day operations. (For a fixed noise level, this is equivalent to 11 units in CNR or NEF.)

Both CNR and NEF assess nighttime *exposure*, on an energy basis, to be 10 dB more disturbing than daytime. It is of interest to see how this compares with other ratings.

The French system has a complex adjustment applied to a three-period day, in which daytime (0600-2200), early nighttime (2200-0200), and late nighttime (0200-0600) are weighted according to the expression:

$$10 \log_{10} N_D + 6 \log_{10} [(3N_1+N_2) - 1] \quad , \qquad \text{(B.1)}$$

where N_D, N_1, and N_2 are the numbers of operations in the three time periods [B.4].

The ICAO index, WECPNL, permits either two-period or three-period days. Using the two-period day, 0700-2200 and 2200-0700, the nighttime noise *levels* are adjusted by 10 dB.

The International Standards Organization also allows either a two-period or a three-period division of the day in assessing noise with respect to community response[B.5]. The corrections to the criterion level, against which the noise in question is to be compared, are zero for daytime, -5 dB for evening, and -10 to -15 dB for nighttime; for the two-period, the corrections would be zero and -10 to -15 dB. The international standard does not specify the hours defining the various periods, but leaves it up to the individual country to set its own limits in accordance with its particular life style.

The CNEL measure adopted for rating airport noise environments in California adopts the ICAO specification for three periods in the day, 0700-1900, 1900-2200, 2200-0700. The evening and nighttime periods, respectively, are given 5 dB and 10 dB adjustments on noise *level*, not noise *exposure*.

Day-night average sound level uses the same two-period day and 10 dB adjustment as in the WECPNL measure.

B.2 Some Anomalous Results and the Explanations

It may be asked, however, whether there is really a need for the nighttime adjustment at all. Although there is a general consensus in the surveys (and in the resulting noise ratings) that nighttime noise deserves a stricter evaluation than daytime noise, a few anomalous results have appeared that at first glance appear to contradict the general view. Let us consider these now, to see whether an explanation can be found for the anomaly in each case.

For example, a substantial effort was made in the second London survey[B.6/] to resolve this problem. They even constructed a separate annoyance scale for nighttime operations for use in comparing night and day operations. No clear results were obtained. Under closer scrutiny, this negative conclusion is explained by the fact that nighttime noise exposure is substantially reduced in London by nighttime limits on both the number of flights permitted and use of noisier aircraft. The daytime noise exposure substantially outweighs the nighttime exposure and thus governs the subjective response.

A similar circumstance explains the otherwise astonishing fact that, following a complete cessation of nighttime over-flights for neighbors of Los Angeles International Airport (LAX), where aircraft noise has been a hotly disputed issue, fewer than 20% of the interviewed residents had noticed the change[B.7/]. The explanation is that the number of daytime operations at the airport is so great (687) that complete elimination of the 50 nighttime flights lowered the day-night average sound level by less than 3 dB, so no substantial change in community response occurred.

A large-scale social survey has been conducted by Tracor, Inc. under NASA sponsorship; seven U.S. cities were surveyed[B.8]. In a preliminary report of the Tracor work, Hazard[B.9] indicated that average annoyance scores were more than doubled if aircraft were heard between midnight and 6 a.m. However, in the final Tracor report[B.8] nothing is said on the subject, and no explanation was given for the omission.

Turning now to the effects of automotive traffic, in a recent survey dealing with street traffic noise in Paris[B.10], there was found to be almost complete independence between annoyance in nighttime activities and the noise exposure; the highest correlation coefficient was 0.05. This result is surprising because, in a pilot survey, the people interviewed had frequently mentioned nighttime noise as being the most annoying. Upon closer study, however, it was determined that, in responding to questions about sleep disturbance, the subjects actually gave reasons other than the noise for the interruption of their sleep. Once awakened- they felt annoyed by the noise, but it wasn't the noise that had awakened them.

Similar anomalous evidence comes from a recent French survey of response to railroad noise[B.11]. Very weak dependence was found between the noise exposure and its effects on sleep. There was, however, significant correlation (r = 0.15 to 0.21) between poor quality of sleep and age. Considering the correlation between quality of sleep and nighttime noise exposure *for different age categories*, one finds a distinct threshold. The correlation between train noise and sleep disturbance, which is almost null for the population under 40 years (r = 0.16, N = 153), becomes significant at the 5% level (r = 0.27) for the population over 50 (N = 68). This threshold of biophysiological evolution of individuals is well known to medical doctors. The noise under study was only in exceptional cases the primary cause of sleep disturbance for people under forty. (Since annoyance amounts to a subjective evaluation of a disturbance by the individual, it is necessary that he be conscious of this disturbance in order to judge it!) But among the more aged, however, poor quality of sleep, *due to age*, allowed the subject to hear nighttime noise more frequently, and thus to be annoyed and to mention the noise as disturbing his sleep.

One can conclude from the available evidence that there may, indeed, exist situations in which justification for a nighttime penalty is difficult to find; for example, in the aircraft studies cited above, in which the entire response is swamped by the daytime noise, or in cases where the nighttime noise is not sufficient to awaken most of the residents.

B.3 Basis for Using a Nighttime Adjustment

At high and low extremes of noise exposure, nighttime noise is not significantly more disturbing than daytime noise, and no adjustment in the noise rating appears to be needed.

Near the threshold of noise acceptability, however, it is important to take the increased potential for nighttime disturbance into account, as indicated by the following results.

In a study[B.12/] of 55 cases of all kinds of community noise, the failure to include a nighttime adjustment in rating the noise increased the standard deviation from 3.3 to 4.6 dB in the correlation between noise exposure and community response; this would extend the boundaries of the data-point envelope from ±5 dB to ±7 dB. Although this may not seem a very dramatic change, it proves that a significant number of people do rate nighttime noise as significantly more disturbing than daytime noise.

In a survey of response to traffic noise in Vienna[B.13], in order to find neighborhoods with the same percentage of people highly disturbed at nighttime as in other neighborhoods in the daytime, the average sound level over 24 hours in the neighborhood had to be about 10 dB lower, as indicated in Figure B.1.

Also, the majority of sleep studies show at least some adverse effects of nighttime noise exposure[B.14]. For example, a recent study[B.7] of sleep, by means of electrophysiological measurements in the home, concluded that "statistically significant differences in sleep behavior between similar groups of middle-aged people may be attributed to exposure to intense aircraft noise." Figure B.2 shows the noise levels and Figure B.3 shows the corresponding differences in the amount of time spent in various levels of sleep.

The assessments of community noise impact should be most accurate when dealing with situations near the threshold of acceptability because the transition from little annoyance to high annoyance occurs rapidly in this range. For sites with noise exposure near the basic standard, therefore, it is important to account for the increased potential for annoyance by nighttime noise, by the inclusion of a nighttime adjustment in the noise rating.

Criticism can be directed at the amount of the adjustment, the time periods chosen, and the "quantum" jumps taken as the clock passes the hour. But there is no strong evidence for adjustments other than 10 dB on night exposure, and the two-period day seems reasonable for typical living habits in this country.

Also, it may be recalled that HUD's present noise policy embodies nighttime adjustments, both for aircraft and nonaircraft noise exposure. The adjustment is explicit in both the CNR and NEF ratings used in assessing aircraft noise, as described above; the amount of the adjustment is 10 dB.

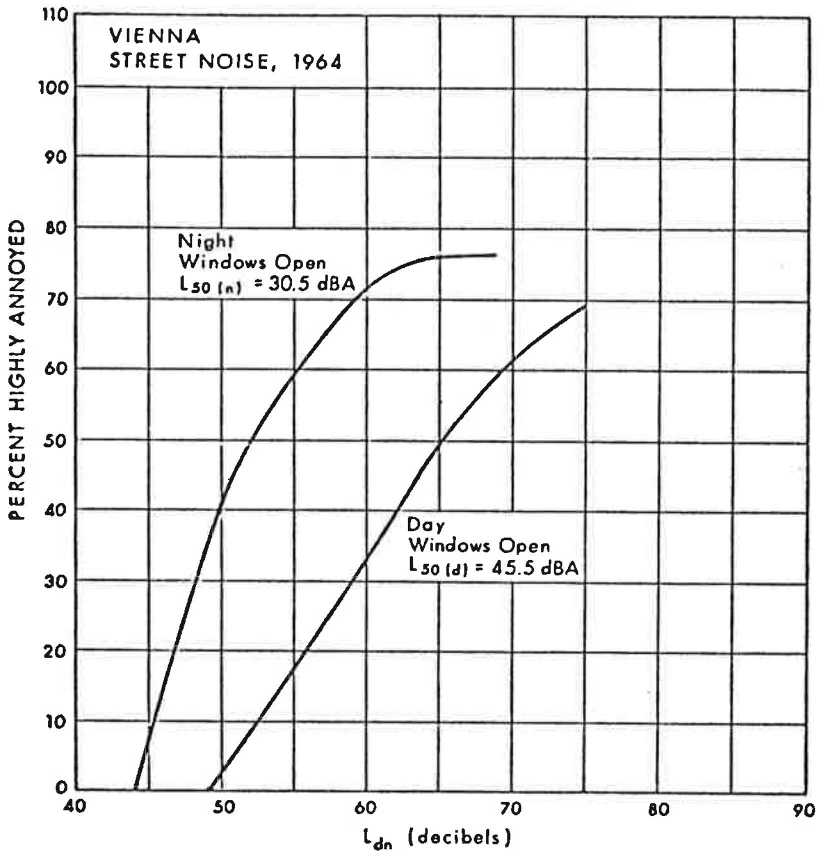


FIG. B.1. ANNOYANCE DUE TO STREET TRAFFIC NOISE IN VIENNA 1964. ON AVERAGE, THE SAME AMOUNT OF ANNOYANCE IS CAUSED AT NIGHT BY NOISE LEVELS 10 dB LOWER THAN DAYTIME. (From page D-8 of Ref. B.15).

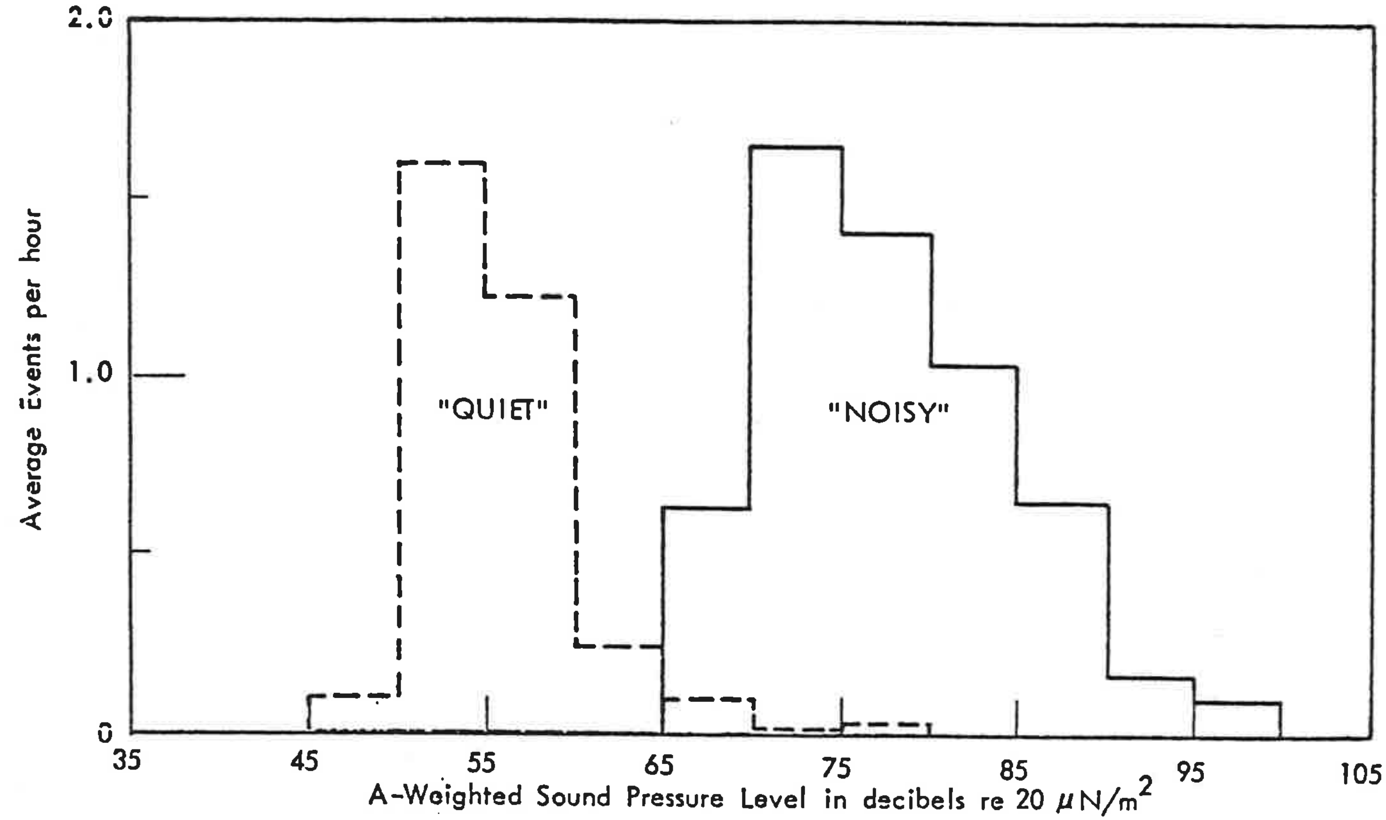


FIG. B.2. MAXIMUM NOISE LEVELS INSIDE HOMES DURING THE HOURS 12:00AM – 5:00AM (From Ref. B.15)

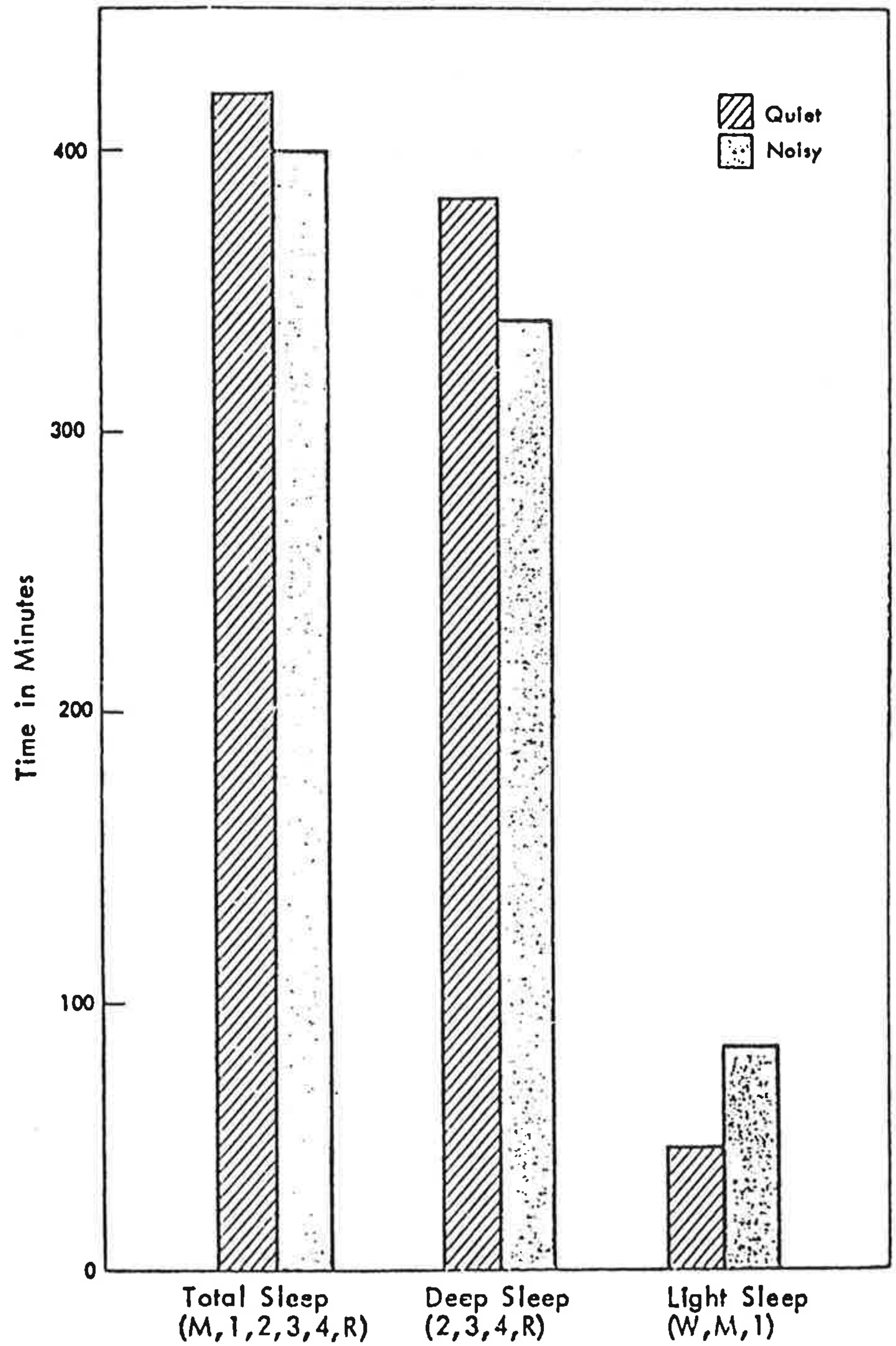


FIG. B.3. AVERAGE AMOUNT OF SLEEPING TIME IN "QUIET" AND "NOISY" AREAS (From Ref. B.15)

For nonaircraft noise, a nighttime adjustment of about the same amount is implicit in the interim standards for indoor noise exposure. The interior noise level, in order to be acceptable, must not exceed 45 dB for more than eight hours in a 24-hour day, of which only 30 minutes may occur in the nighttime period from 11 p.m. to 7 a.m.

The use of day-night average sound level conveniently incorporates the 10-decibel nighttime adjustment uniformly for all noise sources.

References — Appendix B

B.1 Theodore J. Schultz, "Noise Assessment Guidelines/Technical Background," Report No. TE/NA 172, U.S. Department of Housing and Urban Development, 1971.

B.2 Walter A. Rosenblith, Kenneth N. Stevens, and BBN staff, "Handbook of Acoustic Noise Control: Volume II. Noise and Man," WADC Technical Report 52-204, Wright Air Development Center, June 1953.

B.3 "Noise — Final Report," Cmnd. 2056, H.M.S.O. London, July 1963.

B.4 W.J. Galloway, "Community Noise Exposure Resulting From Aircraft Operations: Technical Review," Report No. AMRL-TR-73-10g, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, July 1974.

B.5 Reference B.1, Table 2. ISO R1996-1971: Acoustics — Assessment of Noise with Respect to Community Response.

B.6 "Second Survey of Aircraft Noise Annoyance Around London (Heathrow) Airport," H.M.S.O., London, 1971.

B.7 Sanford Fidell and G. Jones, "Effects of Cessation of Late-Night Flights on an Airport Community," *J. Sound Vib.* 42 (4), 411-427, 1975.

B.8 "Community Reaction to Airport Noise — Vol. 1," prepared by Tracor Inc. NASA CR-1761, July 1971.

B.9 W.R. Hazard, "Community Reactions to Aircraft Noise — Public Reactions," Paper 41 of Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, October 1976.

B.10 D. Aubrée, S. Auzou, and J.-M. Rapin, "Étude de la gêne due au Trafic Automobile Urbain" (Study of Annoyance Due to Urban Automotive Traffic), no report number, June 1971, "Annexe 4: Catalogue des caracteristiques du Bruit aux Divers Points de Mesure," (Catalog of Noise Characteristics at Various Measurement Locations), Centre Scientifique et Technique du Batiment, Paris.

B.11 D. Aubrée, "La gêne due au bruit des trains," (Annoyance Caused by the Noise of Trains), no report number, January 1975, Centre Scientifique et Technique du Batiment, Nantes, France; pp. 31-32.

B.12 K.M. Eldred, "Community Noise," Report No. NTID 300.3, December 31, 1971, U.S. Environmental Protection Agency, Table 15.

B.13 Reference B.1, Table IX, p. 97.

B.14 Reference B.1, pp. 82-85, 87.

B.15 T.J. Schultz, W.J. Galloway, and P.W. Hirtle, "Noise Assessment Guidelines – Technical Background (revised)", Bolt Beranek and Newman Inc. Report No. 3415, February 1977. Prepared for Department of Housing and Urban Development, Office of Policy Development and Research, under contract H-2234R. To be published as HUD technical report.

APPENDIX C: USE OF AVERAGE SOUND LEVEL BY VARIOUS AGENCIES

The first use of day-night average sound level as a measure for environmental noise was its adoption by EPA in response to the requirement of the Noise Control Act of 1972[C.1/] that EPA develop methods for describing cumulative noise exposure resulting from environmental noise. After careful consideration of the various factors that enter into the selection of a noise measure suitable for use with all sources of community noise in June, 1974, EPA specified average (equivalent) level, and its variant, day-night average sound level (L_{dn}), as the selected measure for environmental noise[C.2/]. The legislative history behind this requirement, the rationale for choice of average sound level, and relationships between L_{dn} and other noise measures are described in Ref. C.2.

Subsequent to the publishing of Ref. C.2, EPA, in July 1974, sent letters[C.3/] to all federal agencies advising them that, in all environmental impact assessments which EPA would review, it proposed that L_{dn} should be used as the descriptor for environmental noise, and requested comment on the EPA position. Further, in all subsequent noise regulatory actions within EPA's own mandate, the health and welfare benefits of the regulation have been evaluated using L_{dn} as the environmental noise descriptor.

The first federal agency to respond to EPA was the DOD. The primary impact on DOD related to the evaluation of aircraft noise around military airfields. Performance of airbase analyses in terms of L_{dn} merely required the use of sound exposure level descriptions of individual aircraft noise, instead of perceived noise level descriptions as used in the NEF and CNR methodologies. The possibility of such a requirement had been anticipated by the USAF in its development of the NOISEMAP computer program system and the noise data files for individual aircraft that were acquired in the program for both USAF and USN aircraft. It was a simple matter to convert from NEF to L_{dn}, and all analyses since January 1975 have routinely been produced in L_{dn}. Computer programs and data files for this purpose are operational at the USAF Tyndall AFB and at the USN Aircraft Environmental Support Office at North Island NAS, as well as at outside contractor facilities.

It is also worth observing that, in support of the EPA effort to develop an airport noise regulation for civil airports, EPA has developed a complete civil aircraft noise data file in order to perform airport noise analyses in terms of L_{dn}. This data file, and the adoption of the USAF developed NOISEMAP analysis system, form the basis for current airport analyses by EPA. The EPA civil aircraft data file and NOISEMAP program are operational at NASA-Langley in the Aircraft Noise Program Office and at outside contractor facilities. The program and data file are also available to anyone who has access to the Control Data Cybernet system, available nationwide. The state of Maryland has already acquired access to the package for its own purposes.

In the civil aircraft field, FAA has been evaluating, for several years, how it wishes to describe airport noise problems in environmental impact assessments. In the past, FAA has used CNR, then NEF, and finally its internally generated ASDS descriptor. The ASDS method has been less than successful, however, and is being gradually phased out. Recently FAA has issued proposed procedures for considering environmental impacts[C.4/]. In this proposal it specified either NEF, CNR, or L_{dn} as "aggregated noise measures."

The most active state law requiring substantive noise analyses around civil airports is that of California. The noise measure used here, CNEL, differs from L_{dn} only in having separate weighting penalties for evening and night operations. For almost all cases, the numerical difference between CNEL and L_{dn} is in tenths of decibels. California accepts L_{dn} analyses in lieu of CNEL as a matter of course.

Another major form of noise analysis is that done by the individual state highway departments in conjunction with grants from the Federal Highway Administration, FHWA. Analyses performed for this purpose must be in accord with procedures specified by FHWA. These requirements specified L_{10} as the measure of environmental noise until 1975. Two computer programs were approved for these analyses, one developed by the Transportation System Center of DOT (TSC)[C.5/] and another by the Highway Research Board (HRB)[C.6/], now the Transportation Research Board (TRB). In a study to refine and improve the prediction of highway noise, a new program was developed by TRB, combining the best features of both older programs with substantial new additions and data[C.7/]. In this program, it was found essential to compute noise levels in terms of *average* sound level because of the need to add the contributions of many sources to the noise level at a given location. The new program then makes an empirical correction to the average sound level to obtain L_{10}. Recommendations were made that FHWA specify average sound level as more appropriate for environmental noise, since the ability to predict L_{10} at lower traffic flows is poor, while the ability to predict average level accurately is not affected by low traffic flows. With the increasing use of the new TRB program by a number of states, FHWA now specifies either L_{10} or average sound level in its procedures, with appropriate changes in numerical values for acceptable limits.

References — Appendix C

C.1 Noise Control Act of 1972.

C.2 EPA Document 550/9-74-004, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," March 1974.

C.3 Letters from Russell Train, EPA Administrator to Federal Agencies, July 1974.

C.4 "Policies and Procedures for Considering Environmental Impact," Proposed FAA Order 1050.1B, 41 FR 34222, August 12, 1976.

C.5 J.E. Wesler, "Manual for Highway Noise Prediction," DOT TSC-FHWA, 72-1, March 1972.

C.6 C.G. Gordon, W.J. Galloway, B.A. Kugler, D.L. Nelson, "Highway Noise — A Design Guide for Highway Engineers," NCHRP Report 117, 1971.

C.7 B.A. Kugler, D.E. Commins, W.J. Galloway, "Design Guide for Highway Noise Prediction and Control," Final Report NCHRP 3-7/3, November 1974.

APPENDIX D. THE RELIABILITY OF ESTIMATES OF ANNOYANCE

A notable feature of surveys dealing with community annoyance caused by noise is the wide dispersion of individual scores at all noise levels. Thus, although the correlation coefficients tabulated in Section 2.4.1, Table 2.1, may seem very low, a correlation coefficient of 0.33 actually represents rather good correlation, as survey results go that relate subjective response to noise *alone*. Considerably improved correlations have usually been found when the individual's attitudinal variables were also taken into account, or when a large group of subjects was employed. That is, the prediction of community response based on group data is quite accurate, but prediction of individual response remains poor.

Efforts to remedy this state of affairs have concentrated on improving noise measures or annoyance scales, or on trying to take account of factors other than noise.

As against this approach, the British Building Research Establishment (BRE) has recently begun examining the reasons for score dispersion, looking first at *score reliability*[D.1/]. By means of repeated studies, it has been found that the individual scores themselves are only moderately reliable; in *fact, nearly two thirds of the variance is unreliable*. By averaging the scores of individuals over repeated occasions, allowing for differences in noise levels, the dispersion is markedly reduced and *the variance accounted for by the noise measures is therefore significantly increased.*

If the reliable variance alone is considered, it seems that *existing noise measures do, in fact, account for a large proportion of the score variance.* In addition, *almost all of the remainder can be accounted for by permanent, inherent individual differences in noise tolerance,* and by differences in environmental circumstances *such as the actual degree of noise exposure offered by different residences,* and the judged quality of the general environment, *without recourse to further, more elaborate noise indices.*

There is further reason to be skeptical of the great importance placed in the past on nonacoustical variables in accounting for variance in individual subjective response data. Not that nonacoustical variables are entirely unimportant, but the acoustical variables themselves have often been poorly handled, with the result that the effect of the nonacoustical variables has been inflated. Of particular importance in this connection is the measurement of the noise to which the interviewed subjects were assumed to have been exposed.

Clearly, the outdoor noise stimulus can vary widely from subject to subject in the neighborhood, depending on his distance from the measuring location, the house orientation, shielding by other buildings, the terrain, etc. But even more important, anyone who has simultaneously measured the noise just outside and inside a house knows that the exterior and interior noise exposures bear little or no relation to one another, as shown in Figure D-1, which presents the difference between the outdoor noise and the indoor noise as a function of the the time of day, in terms of L_1, L_{10}, L_{50}, L_{90}, and L_{eq}.

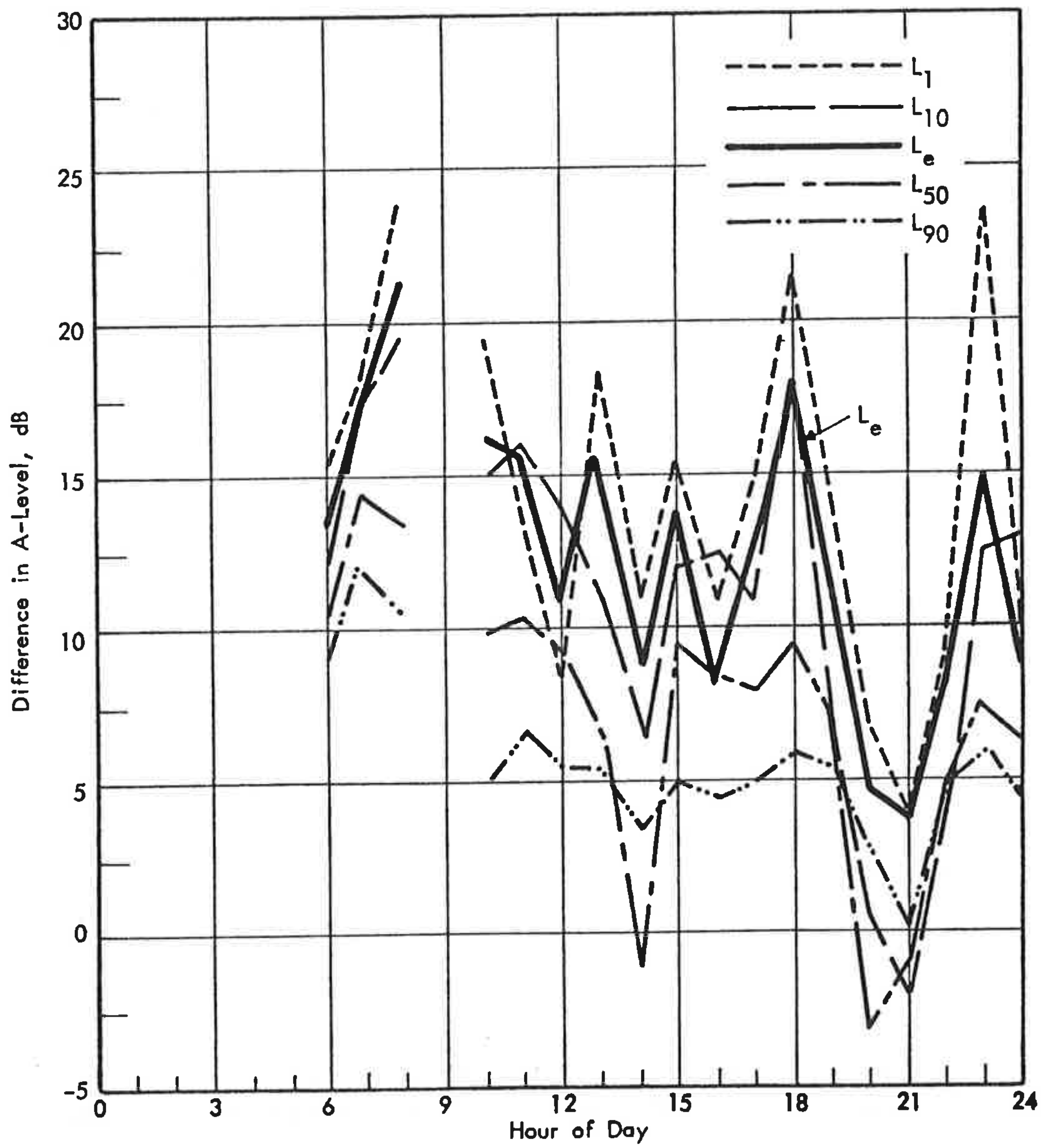


FIG. D.1. DIFFERENCE BETWEEN OUTSIDE AND INSIDE HOURLY NOISE LEVELS — SUBURBAN RESIDENTIAL SITE (GRANADA HILLS, CA).

Now, if there were nothing going on inside the house, the difference between outdoor noise and indoor noise would be directly related to the sound attenuation of the windows, and, therefore, it would be constant for all times of day. Instead, it fluctuates widely, covering a range of 20 to 30 dB.

Thus, instead of each member of the survey test sample being exposed to the same noise as was measured at the survey microphone, the official outdoor noise stimulus may have little or nothing to do with the noise heard indoors by the various subjects, because of noisy indoor activity.

For example, in a recent survey of community response to noise in Antwerp and Brussels, the correlation between the measured noise and the subjective response, in terms of disturbance of reading, listening to television and radio, etc., was 0.87 with the windows open, as shown in Figure D.2. Given the small scatter of data one would have little hesitation in drawing a curve through those points. With the windows closed, however, the correlation dropped to 0.4!

It is at least possible that, with respect to past surveys, the half of the sample population who responded below the median annoyance simply have not heard the noise measured in the survey. For these subjects, the survey's measured noise is a random variable, and it is no wonder that we must look for nonacoustical variables to help account for much of the variance.

This situation could be significantly improved if we agreed to measure, in addition to, say, the average sound level or the day-night average level, the occurrences (levels and numbers) of maximum (i.e., short-term rms) noise levels outdoors. These

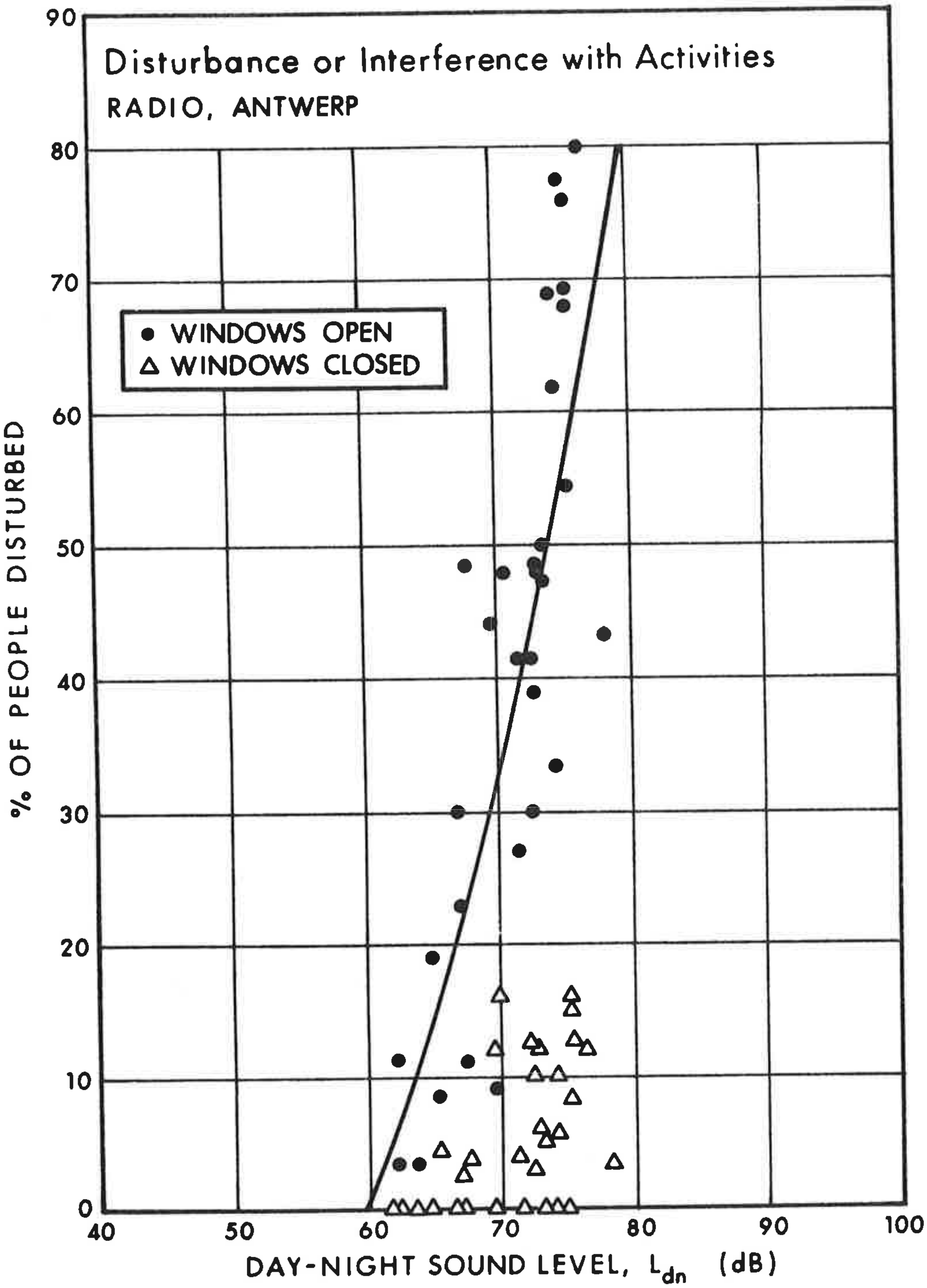


FIG. D.2. INTERFERENCE BY ROAD TRAFFIC NOISE WITH RADIO LISTENING. NOTE THE DIFFERENCE IN CORRELATION BETWEEN NOISE AND INTERFERENCE, DEPENDING ON WHETHER WINDOWS WERE OPEN OR CLOSED.

might be associated with identifiable events, such as a fire truck siren, an aircraft flyover, or a train or heavy truck passage. These noisy events are the *only* candidates likely to intrude indoors with sufficient intensity to attract the subject's attention and thus generate annoyance. Not even L_1 identifies such events with useful accuracy, so such a procedure would mean a drastic change in current noise measurement practice; but it is likely that more deliberate and careful attention to the population of *maximum* outdoor noise levels will lead to better correlation between outdoor noise and annoyance, and (perhaps) less need to rely on nonacoustical variables.

References — Appendix D

D.1 F.J. Langdon, "The Reliability of Estimates of Annoyance with Road Traffic Noise," Third International Congress on Noise as a Public Health Problem, 25-29 September 1978, Freiburg, Germany.

APPENDIX E: CALCULATION OF DAY-NIGHT AVERAGE SOUND LEVEL (L_{dn}) FROM MAXIMUM PASSBY NOISE LEVEL AT REFERENCE MEASUREMENT DISTANCE OF 25 FT

For the passage of a *single* rapid transit vehicle during the observation period T (sec) traveling with velocity v (ft/sec) at a perpendicular distance d (ft) from the observation point, the value of the average sound level is:E.1/

$$L_{eq} = 10 \log \left\{ \frac{1}{T} \int_{-T/2}^{+T/2} 10^{L_m(25')/10} \left[\frac{(25)^2}{d^2 + (vt)^2} \right] dt \right\} \quad \text{(E.1)}$$

where $L_m(25')$ is the maximum A-weighted sound level measured at the reference distance of 25 ft from the track during a passby, and t is the time in seconds. The value of t is zero when the vehicle is opposite the observation point, at distance d.

Carrying out the integration (see Chemical Rubber Handbook, Integral No. 58) leads to:

$$L_{eq} = L_m(25') + 10 \log \left[\frac{2\ (25)^2}{Tvd} \tan^{-1} \frac{Tv}{2d} \right] . \quad \text{(E.2)}$$

For an observation period T much longer than the vehicle passage time, the $\tan^{-1}$ term goes to $\pi/2$, and therefore

$$L_{eq} = L_m(25') + 10 \log \left[\frac{1.963 \times 10^3}{Tvd} \right] . \quad \text{(E.3)}$$

If the observation period is one 24-hour day, then T = 86,400 sec and

$$L_{eq(24)} = L_m(25') - 10 \log vd - 16.43 \tag{E.4}$$

for a single vehicle passage per day.

If N vehicles pass by in 24 hours, then

$$L_{eq(24)} = L_m(25') - 10 \log vd + 10 \log N - 16.43 \tag{E.5}$$

Finally, the day-night average sound level is given by:

$$L_{dn} = L_m(25') - 10 \log vd + 10 \log (N_d + 10N_n) - 16.43, \tag{E.6}$$

where N_d is the number of vehicles between 0700 and 2200, and N_n is the number of vehicles between 2200 and 0700.

References — Appendix E

E.1 Wittig, Larry E., "North Jersey Coast Line: Noise and Vibration Environment Analysis," Report No. 3667, Bolt Beranek and Newman Inc., July 1978, Appendix A.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1979--601-463--69

APPENDIX F: REPORT OF INVENTIONS

This report pertains to criteria for rating the audible noise produced by elevated structures used in rail rapid transit systems. Diligent review of the work leading to this report has indicated that in the course of this work there were made no new inventions, discoveries or improvements of inventions.