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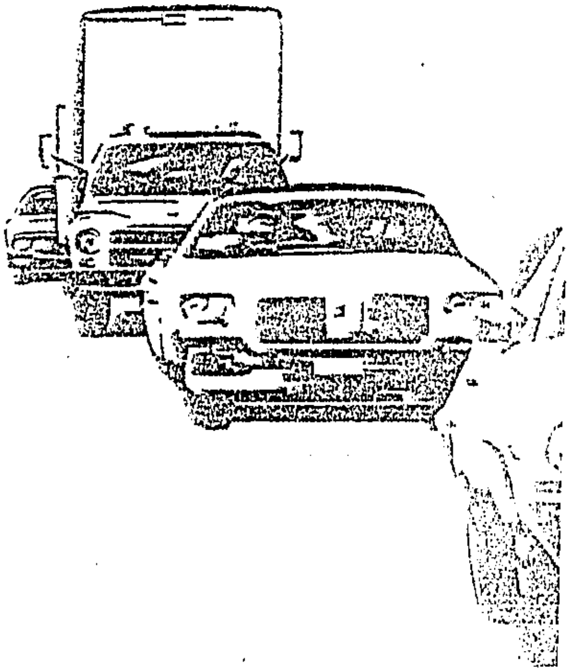
Bolt Beranek and Newman Inc.

Fundamentals and Abatement of Highway Traffic Noise

Textbook and Training Course
Prepared and Presented by
Bolt Beranek and Newman Inc.

For the Office of Environmental Policy
Federal Highway Administration
U.S. Department of Transportation



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This textbook has been prepared for the United States Department of Transportation by Bolt Beranek and Newman Inc. under Contract Number DOT-FH-11-7976.

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PREFACE

During recent years there has undoubtedly been an increase in environmental noise. In addition, everyone has become more aware of noise. Although the growth of noise may be a symbol of growth in technology, the increased awareness of the public toward noise has brought on a rapid response everywhere in trying to abate noise. Highway traffic noise is one of the identifiable problem areas; this has been caused by (1) increased vehicular size and quantity, (2) greater concentration of traffic on major highway routes, and (3) increased use of land near highways to fill the residential and commercial needs of a growing population.

In recognition of this problem, on 26 April 1972, the Federal Highway Administration ("FHWA") of the U. S. Department of Transportion issued an advance copy of its Policy and Procedure Memorandum ("PPM") 90-2 on "Interim Noise Standards and Procedures for Implementing Section 109 (i) of Title 23, United States Code." This was updated by the 8 February 1973 final version of PPM 90-2, entitled "Noise Standards and Procedures", a copy of which is included at the end of this textbook.

To assist in the understanding and implementing of PPM 90-2, the FHWA has made provision for conducting a one-week training course in the "Fundamentals and Abatement of Highway Traffic Noise." This course is being given in 1973 in each of the Field Regions of the FHWA and is available to qualified, selected personnel from the various State highway agencies and the FHWA field offices. The training course has been prepared and is being given by the staff of Bolt Beranek and Newman Inc., acoustical consultants. This manual serves as the textbook for the training course.

The training course and the textbook are directed toward two procedures that are in current use for prediction and abatement of highway noise: one procedure is based on the methodology given in Report 117 of the National Cooperative Highway Research Program ("NCHRP"), and the other is essentially a computer method devised by the Transportation Systems Center ("TSC"). Both these procedures have been approved by the FHWA.

Chapter 1 of this textbook and the first day of the five-day course are devoted to Fundamentals of Sound. This includes acoustic terminology, basic relationships of sound, outdoor sound transmission, and a brief review of certain aspects of human response to noise.

Chapters 2 and 3 are covered in the second day of the course. Chapter 2 presents noise data of automobiles and trucks as individual discrete sound sources, reviews briefly the principal components of truck noise, places autos and trucks into the context of moving sound sources, and introduces a statistical descriptor of highway noise, since highway noise is typically made up of various quantities and mixtures of autos and trucks, with each individual source emitting its own amount and type of noise.

Chapter 3 is concerned with instrumentation and techniques for making outdoor noise measurements, and contains suggestions on the selection of measurement times and locations in order to evaluate ambient noise levels of existing situations. Tape-recorded samples of noises will be measured in the classroom with the use of A-scale sound level meters.

Chapter 4 and the third day of the course are devoted to the basic features of highway noise prediction using the NCHRP Report 117 and TSC procedures. This chapter draws on the basic data of the earlier chapters and considers highway traffic noise as a system: a mixture of autos and trucks; a multi-lane roadway of varying lengths, or segments of roads of various length and directions; various distances from the highway to the neighboring areas of interest, and the acoustic influence of the intervening region between the highway and the neighboring areas.

Chapter 5 and the fourth day of the course include discussion of the noise abatement treatments that are available for noise control, both at the highway and off the highway. Principal concern is given to evaluation of the attenuation (noise reduction) that can be achieved with acoustic barriers alongside the road, since these treatments can fall within the design and jurisdiction of the highway engineer. Barrier designs are reviewed from the point-of-view of the NCHRP Report 117 and the TSC Computer procedures, and a new nomograph is presented and discussed as a quick, useful tool for evaluating acoustic barriers for a variety of applications.

The fifth day of the course is devoted to an interpretive discussion of PPM 90-2 by an FHWA representative from the Office of Environmental Policy, and to discussions of Special Urban Problems of highway noise and suggestions on the preparation and content of the Noise Report of an Environmental Impact Statement.

In reading the text, it may be helpful to realize that small graphs, tables, and examples used to illustrate specific details of the discussion are designated as "Sketches" and "Exhibits" and are contained within the Text material. Graphs, charts or compilations of data of documentary or reference value are designated as "Figures" and "Tables" and appear at the end of each chapter in which they are used.

The principal authors of the textbook and speakers at the course are Grant S. Anderson, Laymon N. Miller and Dr. John P. Shadley, all of Bolt Beranek and Newman Inc. ("BBN"). Technical assistance for some of the textbook material has been provided by B. Andrew Kugler, Carl J. Rosenberg, and Richard M. Schwartz. In addition, Mr. Kugler will assist with some of the lectures. Acknowledgment is gratefully given here for the BBN staff members who helped produce this textbook: our Secretaries, Technical Typists, Illustration and Printing Departments.

This project has been carried out under the supervision of Harter M. Rupert of the Office of Environmental Policy, Federal Highway Administration. Mr. Rupert or Jerry A. Reagan, also of the Office of Environmental Policy, will speak at the training course as the FHWA representative. The authors wish to express their sincere appreciation for the direction and assistance provided by Harter Rupert.

May, 1973

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Enclosure: Policy and Procedure Memorandum 90-2

CHAPTER 1

FUNDAMENTALS OF SOUND

In this opening chapter, it is intended to provide the reader with an elementary understanding of acoustics in sufficient detail that he may be conversant with the terminology and may understand and appreciate the basic factors involved with sound generation and propagation as applied to highway traffic noise. Time and space do not permit an elaborate academic development of much of the material; textbooks or reference books in acoustics may be studied by interested persons for a more detailed discussion and technical understanding of this subject.

1.1 DECIBELS

Just as "feet" are used to measure distance, and "degrees" are used to measure temperature, "decibels" are used to measure sound intensity. The ear is responsive to sounds having a tremendous spread in intensity variation: a "strong" sound, such as a diesel truck, may produce sound energy that is 1,000,000,000 times greater than that produced by a "weak" sound such as a cricket, for example. Because of this large spread in everyday signal strengths, and because the sensitivity of the ear is more nearly logarithmic than linear in its response, it was determined long ago to express sound levels on a logarithmic scale, since this can compress the large spread of intensities into a more practical numerical system. Thus, "decibels" are logarithmic units. The decibel is abbreviated to "dB". In its simplest form, a sound level in decibels is expressed by the term

$$10 \log (p_1/p_0)^2$$

where p_1 and p_0 are two sound *pressures*.

Just as there is, in concept, at least, a "standard foot" that serves as a reference length for distance measurements, there is a reference sound *pressure* upon which the decibel scale is based. This reference is 0.0002 microbar or 2×10^{-5} newton per square meter, abbreviated to "N/m^2." (Both of these units, 0.0002 microbar and 2×10^{-5} N/m^2, describe the same pressure; they are just different units in different measurement systems.) This reference pressure is the p_0 in the term: $10 \log (p_1/p_0)^2$. Actually, this reference base represents approximately the weakest sound that can be heard by the average young, alert, undamaged ear in the frequency region of maximum sensitivity. The "0 dB" level on the decibel scale represents this weakest sound having the reference sound pressure.

In acoustics, the word *level* is used whenever the quantity is expressed in decibels relative to the reference value. Thus, in the term $10 \log (p_1/p_0)^2$, p_1 and p_0 are *pressures*, and (p_1/p_0) represents a *pressure ratio* relative to the reference pressure p_0, but $10 \log (p_1/p_0)^2$ becomes a *pressure level* or *sound level* in decibels relative to the reference pressure. The squaring of the pressure ratio, as in $(p_1/p_0)^2$, maintains the proper relationship between *pressure*, *intensity*, and *power* in acoustic terminology, but this is incidental to the discussion and should not be a stumbling block here. A reader interested in more depth in the subject should refer to an acoustics textbook.

The faint rustling of the grass or of leaves in the trees or a weak whisper might produce a *sound level* of about 20 decibels, relative to the standard reference value of 0.0002 microbar or 2×10^{-5} N/m^2. Normal voice levels produce sound levels of about 60 to 70 decibels at close distance; an automobile might also produce sound levels of about 60 to 70 decibels, but at a distance of about 50 to 100 ft. A diesel truck might produce sound levels of 90 to 100 decibels near a roadway. These values are used here for illustration purposes only. More specific traffic noise level data will be presented later.

1.2 ADDITION OF DECIBELS

Since decibels are logarithmic units, sound levels cannot be added by ordinary arithmetic means. For example, if one truck produces a sound level of 90 dB when it passes, two trucks would not produce 180 dB. Actually, two similar trucks, each at 90 dB, would combine to produce 93 dB. This is almost obvious, when it is recalled from earlier exposures to mathematics that the logarithm of 2 is 0.301, or 10 times the log of 2 would be 3.01.

Suppose $(p_1/p_0)^2$ represents symbolically the sound pressure of a truck, relative to the reference pressure p_0. The sound pressure of two exactly similar trucks would be $2(p_1/p_0)^2$. The sound pressure *level* of one truck would be $10 \log (p_1/p_0)^2$, and the sound pressure *level* of two trucks would be $10 \log 2(p_1/p_0)^2$, each expressed in decibels. Now, in mathematics, the logarithm of the product of two quantities is equal to the sum of the logarithm of each of the two quantities. Thus, the sound pressure level of two similar trucks may be treated as follows:

$$10 \log 2(p_1/p_0)^2$$

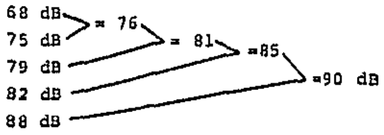
$$= 10 \log 2 + 10 \log (p_1/p_0)^2$$

$$= 3 + 10 \log (p_1/p_0)^2$$

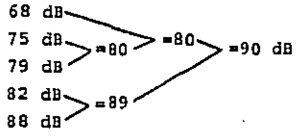
The second term is recognized as the sound pressure level of one truck. Thus, the sound level of two equal sources is 3 dB greater than the sound level of just one source.

Of course, all sound sources are not equal to one another, so a general method is required that permits addition of sound levels of any value. A chart for adding sound levels quite accurately by "decibel addition" is given in Figure 1.1. This chart can be used to an accuracy of 0.1 dB, but most real-life noise levels are not actually measured or known to this degree of accuracy. A more practical addition procedure for quickly estimating the sum of two or more decibel levels is given in the top of Table 1.1. The use of this table will yield a sum that has an accuracy within 1 dB. This table is simple enough that it can be memorized and used when any quick, rough estimate is required. Most real-life noise problems seldom justify accuracies of better than 1 dB, but when desired for computation purposes, an accuracy within 1/2 dB can be obtained by using the lower half of Table 1.1. Where high accuracy is required for special calculations or special assumptions (for example, to show small differences between situations or to emphasize incremental changes along a series of changing events), the sums may be computed quite precisely according to the chart of Figure 1.1, or with the use of the lower portion of Table 1.1, but it should be realized that in practical terms, noise levels are not really known to that accuracy. When computer programs, to be discussed later, produce noise levels to tenths of decibels, it is suggested that at the end of the computation the sound levels be rounded off to the nearest whole number.

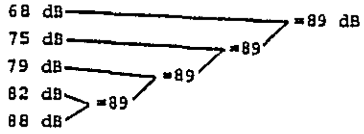
When there are several levels to be added, they should be added two at a time, starting with the lower valued levels and continuing the the addition procedure of two at a time until only one value remains. To illustrate, suppose it is desired to add the following five sound levels, using the summation procedure of the upper portion of Table 1.1:



Most of the time, the same five levels can be added in any sequence and the same sum will be obtained, as long as the lower valued levels are added early:



Since the upper part of Table 1.1 involves some rounding off to whole numbers, occasionally the addition sequence that is followed may make a difference of as much as 1 dB in the total. For example



In this last illustration, the sequence was selected such that all the lower valued levels were added last and they became negligible compared to the sum of the two highest values. To minimize errors, it is important to combine the lower values early in the sequence. Using Figure 1.1, for an accuracy of approximately 0.1 dB, the sum of the above additions becomes 89.6 dB, so either 89 or 90 would be an acceptable total.

When in doubt about the sum, combine levels using the more accurate procedures and then round off the final total to the nearest integer.

Later in the text some exceptions to this procedure will be made in the addition of certain kinds of noise levels.

When considering large quantities of essentially equal noise sources, it is useful to be able to add them faster than two at a time. Again, since decibels are logarithmic quantities, the decibel sum of a number of equal-valued sound levels is equal to the sound level of one source plus "10 log" times the total number of levels to be added. This approach is incorporated into the following table.

If there are several levels of the same value to be added together, add as follows:

No. of Equal Levels	Add to That Level
2	3 dB
3	5 dB
4	6 dB
5	7 dB
6-7	8 dB
8	9 dB
9-10	10 dB
N	10 log N dB

For example, if one sound source produces a level of 60 dB for a given set of conditions, then five similar sources under the same conditions, would produce a level of

$$60 + 10 \log 5$$

$$= 60 + 7$$

$$= 67 \text{ dB.}$$

A table of "10 log N" values is given in Table 1.2 for a useful range of values of N, including fractional values. This table has uses beyond the obvious one of simply adding a number of equal levels. Suppose, for example, that at a given position a sound level of 70 dB is produced by a traffic flow of 2000 automobiles per hour, and it is desired to know the approximate noise increase for a traffic flow of 6500 automobiles per hour. From Table 1.2, 10 log 6500 = 38 dB (approximately) and 10 log 2000 = 33 dB. Thus, one would expect about a 5 dB increase for the larger flow. This answer could be obtained another way:

$$\frac{6500}{2000} = 3.25$$

$$10 \log 3.25 = 5 \text{ dB}$$

Thus,

70 + 5 = 75 dB for the larger traffic flow.

As another example, suppose a particular quantity of traffic produces a noise level of 72 dB for a peak hour condition, and it is desired to know approximately the noise level reduction when the traffic is only 40% of peak hour volume. According to Table 1.2, a value of 0.40 (or 40%) yields a reduction of 4 dB. Thus, the lower traffic flow would produce approximately 72 - 4 = 68 dB. These samples are offered here merely to demonstrate the general applicability and versatility of the "10 log N" values; the noise levels selected are for illustration only.

1.3 SOUND PRESSURE LEVEL

The ear is sensitive to sound *pressure*. Sound waves represent tiny oscillations of pressure in the air just above and just below atmospheric pressure. These pressure oscillations impinge on the ear and "we hear the sound." The weakest audible sounds, mentioned earlier, having a pressure of 0.0002 microbar or 2×10^{-5} N/m^2, represent pressures of only two-ten thousandths of a millionth of atmospheric pressure ("microbar" = one millionth of barometric pressure).

A "sound level meter" is also sensitive to sound pressure. When a sound level meter is properly calibrated, it relates the sound pressure of an incident sound wave to the standard reference pressure, and it gives a reading in decibels relative to that reference pressure.

A simple but expressive definition of "noise" is that it is "unwanted sound"; so "noise level" is often used synonymously with sound pressure level. Sound pressure level is sometimes abbreviated to "SPL" or "Lp".

There is in acoustics another somewhat similar term, "sound *power* level." It is unnecessary to use sound *power* in the highway noise procedures, so this quantity is not defined here. The term is mentioned here only to draw a distinction between sound *pressure* level and sound *power* level. They are *not* the same quantity and must not be used interchangeably. It is beyond the scope of the present work to become involved in sound power data.

1.4 FREQUENCY, HZ AND CPS

With the recent trend in U.S. and international standards to recognize the early men of science, many new names for old units are being adopted. The traditional unit for frequency in the U.S. has been "cycles per second," abbreviated "cps". The new international unit for frequency, now adopted by U.S. standards groups, is "Hertz", abbreviated "Hz". Throughout this text the new unit "Hz" will be used; it has the same meaning as "cycles per second."

1.5 "OVERALL" FREQUENCY RANGE AND OCTAVE BANDS OF FREQUENCY

In order to represent properly the complete noise characteristics of a noise source, it is frequently necessary to break the total noise down into its frequency components: that is, to determine how much of the noise is low frequency, how much high frequency, and how much is in the middle frequency range. This is essential for any comprehensive study of a noise problem for three reasons: (1) people have different hearing sensitivity and different reactions to the various frequency ranges of noise, (2) different noise sources have differing amounts of noise across the full audio range of frequencies, and (3) engineering solutions for reducing or controlling noise are different for low and high frequency noise.

It is conventional practice in acoustics to determine the frequency distribution of a noise by passing that noise successively through several different filters that separate the noise into 8 or 9 "octaves" on a frequency scale. Just as with an "octave" on a piano keyboard, an "octave" in sound analysis represents the frequency interval between a given frequency (such as 350 Hz) and twice that frequency (700 Hz in this illustration). The normal frequency range of hearing for most people extends from a low frequency of about 20 Hz up to a high frequency of 10,000 to 15,000 Hz, or even higher for some people. Most current octave-band noise analyzing filters now cover the audio range of about

22 Hz to about 11,200 Hz in nine octave frequency bands. These filters are identified by their geometric mean frequencies; hence 1000 Hz is the label given to the octave frequency band of 700-1400 Hz. The nine standard octave bands are as follows (the numbers are frequently rounded off):

Octave Frequency Range (Hz)	Geometric Mean Frequency of Band (Hz)
22-44	31
44-88	63
88-175	125
175-350	250
350-700	500
700-1400	1000
1400-2800	2000
2800-5600	4000
5600-11,200	8000

The term "overall" designates the full frequency coverage of all the octave bands, hence 22-11,200 Hz, or in some cases, 44-11,200 Hz when the 31 Hz band is omitted.

When a sound pressure level includes all the audio range of frequency, the resulting value is called the "overall" level. When the level refers to the sound in just one specific octave frequency band, it is called an "octave band level" and the frequency band is either stated or clearly implied.

For some special situations, a noise spectrum may be studied in finer detail than is possible with octave frequency bands. In such cases one-third octave bands might be used. Even narrower filter bands might be used, for example to separate one particular frequency from another one if it is desired to separate the causes of a particular complex noise. The bandwidth and the identifying frequency of the band should always be specified. Such detailed analyses are not required for the purposes at hand, however.

1.6 WEIGHTING NETWORKS: A-, B-, AND C- SCALES

Sound level meters are usually equipped with "weighting circuits" that tend to represent the frequency characteristics of the average human ear for various sound intensities. Hence, readings are sometimes taken with "A-scale" or "B-scale" or "C-scale" settings on the meter. The "A-scale" setting of a sound level meter filters out as much as 20 to 40 dB of the sound below 100 Hz, while the "B-scale" setting filters out as much as 5 to 20 dB of the sound below 100 Hz. The "C-scale" setting is reasonably "flat" with frequency, i.e., it retains essentially all the sound signal over the full "overall" frequency range. It is very important, when reading A-, B-, or C-scale sound levels, to positively identify the scale setting used. The resulting values are called "sound levels" and are frequently identified as dBA, or dBB, or dBC readings. Note that these readings do not represent true "sound pressure levels" because some of the actual signal has been removed by the weighting filters.

For most acoustic applications the octave frequency band readings are the most useful. It is always possible to construct A-, B-, or C-scale readings from all the octave band readings, but it is never possible to exactly construct the octave band readings from the weighting scale readings.

1.7 A-SCALE SOUND LEVELS

A plot of the frequency response of the A-weighted network of a sound level meter is shown in Figure 1.2. This is taken from the American National Standards Institute ("ANSI") Standard S1.4-1971 and is required to be met by all sound level meters built under these standards. This is approximately the frequency response of the average young ear when listening to most ordinary, everyday sounds. In many past studies, it has been found that when people make relative judgments of the "loudness" or "annoyance" or "disturbance" of a noise, their judgments correlate quite well with the A-scale sound levels of those noises. Thus, a sound level of 65 dBA for one noise would typically be judged louder or more annoying than another noise of 60 dBA, when both are considered in a similar context. This is due to the fact that (1) high frequency noise (above about 500 Hz) is generally more annoying than low frequency noise (of the same sound pressure level), and (2) A-scale sound levels essentially emphasize the high frequency noise content, while rejecting some of the low frequency noise content (just as the ear does).

There are other weighting networks that have been used in these kinds of judgment tests; some give poor correlation with judgments, while others, specially devised, may give slightly better correlation with the judgments of loudness or annoyance or noisiness. The specially devised weighting networks were usually built around special problems or special applications and those weightings do not appear sufficiently superior in their test results to justify construction, validation, certification and use of sound meters having those special weightings for everyday use. The A-scale network has been in existance for over 30 years and has been incorporated in many U.S. sound level meters over that time. Thus, it is an available instrument, of relatively low cost; and it has been found to give reliable, reproducible correlation with many jury-type subjective judgments on the noisiness of many different types of noise.

A-scale sound levels are in current use in many community and city noise ordinances and in several state and city highway or traffic noise codes. Because of the relatively long and extensive use of A-scale sound levels in these kinds of applications, it has been decided that A-scale sound levels should be used in the procedures discussed in this text and advocated by the FHWA.

It is important to recognize and use A-scale sound levels, and not to confuse them with other types of sound levels. For example, a diesel truck might pass by an observation station and produce a peak noise level of 100 dB *overall*. The *overall* level includes all the noise over the full frequency range of the instrument (approximately 22-11,200 Hz or higher). Now, a diesel truck produces a large amount of its total noise in the low frequency octave bands of 63, 125, and 250 Hz. So, when the noise of that truck is observed on an A-scale meter, the A-scale filter removes about 26 dB of signal strength at 63 Hz, about 16 dB of signal strength at 125 Hz and about 9 dB of signal strength at 250 Hz. Thus, the A-scale sound level of that truck passage might be only about 85 dBA because of the rejection of much of the low frequency signal. In general, for most traffic noise (but not all), the A-scale sound level will be several decibels lower than the *overall* level, or the "all pass" level or the C-scale level. When reading about noise levels in non-technical writings, it is necessary to realize that the writer may have been unaware of some of these distinctions. Always express noise levels correctly as to their weighting scale, and be suspicious of all noise data for which proper definition of the weighting scale or the frequency characteristics of the filter are not explicitly stated.

1.8 CALCULATED A-SCALE READING

For this textbook, most original noise data were obtained in all the octave frequency bands and then converted to equivalent A-scale readings, so that the user could benefit from this simpler one-number system. Within the present scope of the text and the immediate applications envisaged by the FHWA, it is expected that only A-scale values will be required. However, for those users interested in exploring noise data in more detail, the method for converting octave band data to A-scale values is shown.

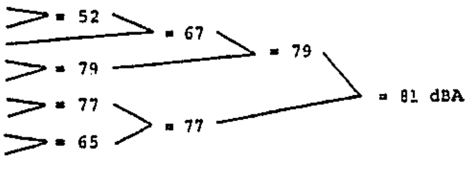
As mentioned in Section 1.7, ANSI Standard S1.4-1971 gives the frequency response of the A-scale filter; this is reproduced in the table immediately below.

Octave Frequency Band (Hz)	A-Scale Frequency Response (dB)
31	-39
63	-26
125	-16
250	-9
500	-3
1000	0
2000	+1
4000	+1
8000	-1

To calculate an A-scale value, apply the A-scale frequency response values to the known octave band levels, band by band. Then, add the resulting corrected band levels by "decibel addition" to obtain the final A-scale summation.

To illustrate, suppose it is desired to calculate the A-scale sound level for a noise made up of the octave band sound pressure level (SPL) readings shown in Column 2 below. The A-scale corrections are shown in Column 3, and the corrected octave band values are shown in Column 4. The Column 4 values are then added together by "decibel addition" (Section 1.2) to obtain the resulting 81 dBA sound level.

Column 1 Octave Frequency Band (Hz)	Column 2 SPL in Octave Band (dB)	Column 3 A-Scale Correction Term (dB)	Column 4 Corrected Band Value (dB)
31	75	-39	36
63	78	-26	52
125	83	-16	67
250	84	-9	75
500	80	-3	77
1000	75	0	75
2000	72	+1	73
4000	64	+1	65
8000	55	-1	54



1.9 SPEED AND WAVELENGTH OF SOUND IN AIR

The speed of sound in air is approximately 1100 ft per second for most normal conditions. Sound propagates as a pressure wave; sound is made up of vibrating air particles set into motion by a vibrating solid body or by an oscillating sound source; each air particle in the sound wave oscillates back and forth and strikes its neighboring air particles. Thus, the sound energy is transmitted by this successive transfer of vibration from one particle to the next. This "wave train" has a speed of 1100 ft per second; yet each particle in the wave train may only move back and forth a few millionths of an inch.

Assume, for illustrative purposes, that an advancing sound wave can be simulated by a very long "Slinky" spring. A quick jerk on one end of the spring will start a pressure wave moving along the spring; a brief instant later another jerk will start another pressure wave, and so on. If these jerks can be repeated uniformly and periodically, a continuing advancing wave train can be observed on the Slinky spring even though each coil of the spring only oscillates back and forth a relatively short distance. The periodic rates of producing the jerks on the spring might be considered as the "frequency", and the distance between successive pulses advancing along the spring might be considered as the "wavelength". If the frequency of the jerks is low, the distance between advancing pulses on the spring is quite large. If the frequency of the jerks is quite high, the distance between advancing pulses on the spring ("wavelength") is quite short.

The same basic mechanism exists in a sound wave, where the frequency that excites the wave and the resulting wavelength between advancing pressure pulses are related through the velocity of sound in air. Hence,

$$c = f\lambda \quad \text{or} \quad \lambda = c/f$$

where c is the velocity of sound in air (approximately 1100 ft/sec), f is the frequency of the sound, and λ is the resulting wavelength of that frequency in air. As examples, the following frequencies produce the following wavelengths in air.

Frequency (Hz)	Wavelength (ft)
20	55
31	35
63	17.5
125	9
250	4.5
500	2.2
1000	1.1
2000	.55
4000	.27
8000	.14 (=1.7 in.)
14000	.08 (=0.95 in.)

Thus, within the range of audio frequencies, wavelengths can range from about 50 ft to about 1 in. This is a very large spread and it accounts for many unusual effects in acoustics. For example, a sound source 1 ft in diameter is so small in terms of a 55 ft wavelength at 20 Hz that it cannot radiate energy well at that frequency, and the energy that it does radiate would have no directivity (somewhat as a bare light bulb radiates light in all directions). On the other hand, a sound source 1 ft in diameter is quite large for 14000 Hz sound; it is equal to 12 wavelengths in diameter and this is large enough to radiate energy efficiently and to produce a somewhat directional beam (somewhat as a searchlight beam).

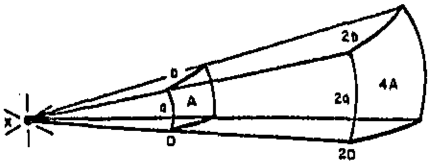
As another example, 1 in. thick acoustic tile is so thin in terms of low frequency wavelengths of sound that it has little absorptive effect for sounds having wavelengths of 10-50 ft. But, when the wavelength begins to approach the dimensions of the acoustic tile, the material becomes quite effective. Acoustic tile may absorb as much as 50-90% of the incident sound energy for frequencies of 500-5000 Hz, whose wavelengths range from about 2 ft to 2 in.

As another example (and this is the one we are really leading up to), we may place a barrier in front of a noise source, expecting to provide a quiet "shadow zone" behind the barrier. In the low frequency region, a normal size barrier appears quite small compared to wavelengths of 10-50 ft, so the barrier does not provide very much sound shielding (it does not cast a very strong "acoustic shadow"). However, for high frequency sound, the barrier appears large in terms of 1 ft to 1 in. wavelengths and produces relatively good shielding.

Whenever considering various acoustic properties of sources, materials or sound control treatments, always think of the device in terms of wavelength dimensions. Usually, most acoustical products will perform well when they are generally large or comparable to wavelength dimensions and they will perform relatively poorly when they are quite small in terms of wavelength dimensions.

1.10 SOUND LEVEL REDUCTION WITH DISTANCE

As a general rule, sound from an essentially localized source spreads out uniformly as it travels away from the source, and the sound level drops off at the rate of 6 dB for each doubling of distance. This is referred to in acoustics as the "inverse square law". This effect is due to spreading only, and this is an effect common to all types of energy originating from an essentially point source and free of any special focussing or beam-controlling devices. This is illustrated in concept in Sketch 1.1 below. Suppose X represents a "point source" of noise. Suppose the noise radiates uniformly in all directions, but for this illustration suppose we confine our interest to the sound energy that is contained within the solid angle bounded by the four radiating lines shown. At the distance D from the source, the area of the segment within the radiating lines is a x b or A. If we now move out to a distance 2D from the noise source, for the same solid angle of sound propagation, each side of the new surface is doubled, i.e. a has increased to 2a and b has increased to 2b. The new surface area at 2D is thus 4 times the original area at D, or 4A. Since the same amount of sound energy passes through both area A and area 4A, we see that the "energy per unit area" at distance 2D is one-fourth what it is at distance D. "Energy per unit area" is defined as "intensity" of a sound signal and "intensity" is related to sound pressure. A reduction of a factor of 4 in intensity is the equivalent, then, of a 6 dB reduction in sound level. (Recall that two equal amounts of energy produce a 3 dB change, thus four equal amounts will produce two 3 dB changes, or 6 dB).



SKETCH 1.1

Sketch 1.1 illustrates "spherical spreading" of sound from a point source. In reality, the small areas A and 4A are actually only small segments of large spherical (or hemispherical) shells that in concept radiate out from the point source in three dimensions somewhat as ripples radiate out in two dimensions from a pebble dropped on the surface of a calm pond of water.

Since a microphone, or a person's ear, only samples a small area of sound level or sound intensity, that microphone or ear will then receive a 6 dB lower signal for each doubling of distance from the source. This is the essence of the "inverse square law", which says that the sound pressure or intensity varies inversely as the square of the distance; i.e., at twice the distance, the intensity decreases by a factor of 4 (or -6 dB according to Table 1.2); at three times the distance, the intensity decreases by a factor of 9 (or -9.5 dB); at four times the distance, intensity decreases by a factor of 16 (or -12 dB), etc.

The "inverse square law" is reduced to tabular form in Table 1.3. The "starting distance" in Table 1.3 is 50 ft, since this is a distance that has been used widely in vehicular noise studies as a reference distance. This table applies to A-scale sound level drop-off from a "point source", and it takes into account that air absorbs a certain amount of high frequency energy due to "molecular absorption" over relatively long distances (greater than a few hundred feet). Since A-scale sound levels emphasize high frequency noise components, this "molecular absorption" increases the rate of drop-off with distance slightly greater than the "inverse square law" would provide alone. The A-scale reduction with distance also takes into account the approximate frequency spectrum shape of typical vehicular traffic noise. The loss due to this effect has been calculated for a few representative distances, and it averages approximately 1 dBA per 1000 ft, starting beyond the first 2000 ft distance. There is also a small amount of acoustic energy loss due to sound transmission in the presence of a variety of small but typical atmospheric effects (discussed briefly in Section 1.11). These are here assigned the fairly reasonable value of 1 dBA per 1000 ft, starting beyond the first 1000 ft distance.

These two extraordinary effects associated with the A-scale rate of sound level reduction are most noticeable at large distances (say over 2000 ft) and are negligible at short distances (say under 1000 ft). Since most serious highway noise problems usually arise due to close distances to the roadway, the departure of A-scale levels from true inverse square law that occurs at the larger distances is not of major concern. Nevertheless, these effects are included in Table 1.3 (and also in Tables 1.4 and 1.5 which are presented later). The mathematical construction of Table 1.3 is described approximately by the following formula:

$$\text{dBA Reduction} = 20 \log \frac{D}{50} + \underbrace{\left|\frac{D-1000}{1000}\right|}_{\text{for } D>1000} + \underbrace{\left|\frac{D-2000}{1000}\right|}_{\text{for } D>2000}$$

where D is distance in feet.

Although Table 1.3 represents fairly accurately the average rate of drop-off of A-scale sound levels with distance from a single vehicle, this drop-off rate is not realized for most high-traffic-density roads because an observer seldom hears just a single vehicle. Rather, an observer near a well-travelled road usually is within hearing range of several vehicles. In the limiting case, a long continuous line of vehicles along a roadway becomes a "line source" (as opposed to a "point source"), and the rate of sound level drop-off with distance approaches "cylindrical spreading" which produces a 3 dB drop-off rate for each doubling of distance.*

A series of charts (Figures 1.3-1.9) is used to illustrate a gradual change-over from a point source to a line source. For each chart, suppose that each sound source produces a sound level of 80 dBA at a reference distance of 50 ft. It is desired to show in each chart the total sound level at observer points A, B, C, D, and E at distances of 50, 100, 200, 400, and 800 ft respectively, due to the sound sources positioned along a line perpendicular to the line of observer points.

In the first chart, Figure 1.3, only a single sound source is used, and its sound reduction follows the inverse square law drop-off of Table 1.3, producing the expected 6 dBA reduction for each doubling of distance from the source to the observer points A, B, C, D, and E.

Figure 1.4 shows three sound sources spaced at 400 ft distances along the 800-ft source line perpendicular to the observer points. Each individual source radiates hemispherically as a point source, but the three sources combine to produce the levels shown at points A, B, C, D, and E. Notice that the drop-off rate (shown in the Difference column) starts at 5.7 dBA for the first distance doubling, then drops to 5.0 and 4.5, and then begins to rise again to 4.9 dBA per double distance ("DD") for the outer distance doubling. Notice also that at point A, the presence of the nearby source 1 produces 80 dBA, while the more remote sources 2 and 3 increase the total to only 80.2 dBA. Yet, at point E, remote from all sources, source 1 produces a level of 56 dBA while sources 2 and 3 combine to produce 58 dBA, to give a total of 60.1 dBA. (Accuracies of 0.1 dB are used in these charts to indicate small differences.)

Five sources are placed at 200 ft separation along the 800-ft source line in Figure 1.5. Now, the drop-off rate with distance starts at 4.8 dBA/DD, drops to 4.1 and 4.2 and then rises to 5.1 dBA/DD. Notice that sources 2-5 still produce only a small change (0.6 dB) on the original level produced by source 1 at the closest observer point A. At point E, however, the 5 sources produce 6.4 dB higher level than that produced by source 1 alone (from Figure 1.3). [Question: if all 5 sources had been located at source 1, what would be the sound level at Point E? At point A?].

In Figure 1.6, nine sources at 100 ft spacing are distributed along the 800-ft source line; and in Figure 1.7, seventeen sources at 50 ft spacing are distributed along the line. Between points A and B, the drop-off rate is down to 3.8 dBA/DD in Figure 1.6 and down to 3.3 dBA/DD in Figure 1.7. This shows that at relatively close distances to the line of sources, many nearby sources are required to approach the 3 dBA/DD value. Between the more remote points C, D and E, the drop-off rate rises into the region of 4 to 5 dBA/DD in both Figures 1.6 and 1.7.

Figure 1.8 is similar to Figure 1.6, except that the source line has been lengthened.

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* Empirically-derived and analytically-derived models demonstrating this rate of drop-off for relatively high traffic flow conditions are described in the National Cooperative Highway Research Program ("NCHRP") Report 78, entitled "Highway Noise -- Measurement, Simulation, and Mixed Reactions", 1969, and NCHRP Report 117, entitled "Highway Noise -- A Design Guide for Highway Engineers", 1971.

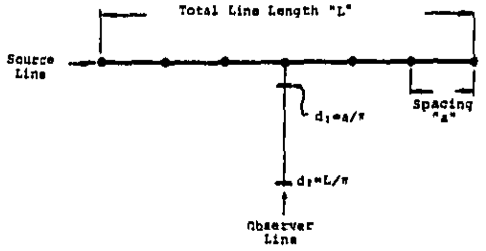
In Figure 1.8, twenty-one sound sources are uniformly distributed (at 100 ft distances) over a longer line, here 2000 ft long. Now, the drop-off rate falls in the range of 3.4-3.6 dBA/DD for distances out to 400 ft, but increases to 4.4 dBA/DD for the 800 ft distance.

The final chart in this sequence is Figure 1.9, which doubles the length of the source line of Figure 1.8. For this 4000 ft line of point sources at 100 ft spacing, it is seen that the drop-off rate starts at 3.5 dBA/DD for the close observer points, then drops to 3.1 and then increases to 3.5 and 3.8 dBA/DD for the outer observer points. The contributions of various groups of these sources may also be seen in the levels tabulated in Figure 1.9. The central 9 sources, for example, strongly control the total sound level at Points A and B, while the more remote sources gradually add more noticeably to the sound levels at the more remote observer points. At Point E, all sources beyond the central 9 sources actually produce a slightly larger total contribution than do the 9 central sources.

The significance of this point will be emphasized later as we discuss noise control in highway design. However, it becomes obvious at this point, perhaps, that if we should hope to achieve extensive noise reduction for a group of residences 800 ft from a long, straight, flat highway, we cannot simply limit our concern to the nearest 800 ft length of traffic (contained within the central 9 sources of Figure 1.9), because other sources all along the source line combine to produce just as much noise as the relatively few nearest sources.

It is probably apparent that additional filling of the line with sound sources would continue to bring the drop-off rate down to the ultimate 3 dBA per double distance. The significance of this lengthy development is that when we later consider actual highway layouts and nearby residential neighbors, we shall select some reasonable value of drop-off rate to assist in the estimation of noise levels along the highway right-of-way. We can surmise from Figures 1.3-1.9, that quantity of traffic flow and distance from the roadway are factors that influence the noise drop-off either side of the highway. All discussion up to this point assumes clear line-of-sight between noise sources and observation points and no interference with sound transmission; this also assumes that the sound sources are omni-directional, that is, each source radiates sound uniformly in all directions.

The Difference column (the drop-off rate) in Figures 1.4-1.9 shows a variation that typically starts with a given value at close distance, which then decreases for the medium distances, and then increases for the greater distances. The variation is not random, it actually follows a predictable pattern. Assume in Sketch 1.2 an array of point sources and observer locations, somewhat similar to the arrays of Figures 1.4-1.9.



SKETCH 1.2

It has been shown* that for observer distances d_1 (to the line source) less than a/π, the drop-off rate approaches 6 dB per double distance; at observer distances between d_1 and d_2 (i.e. between a/π and L/π), the drop-off rate approaches 3dB per double distance; and at observer distances d_2 beyond L/π, the drop-off rate approaches 6 dB per double distance. The geometry for this condition requires equal spacing "a" of the point sources, a limited line length "L", and at least 3 sources in the array. The derivation gives justification for the variations shown in Figures 1.4-1.9 even though the values never quite reach the limiting values of 3 and 6 dB. In effect, this approximation tells us that at very close distances, we see (or hear) essentially only one source at a time, and at very large distances the limited length of the line of sources begins to resemble a point source.

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* "Noise and Vibration Control," edited by Leo L. Beranek (McGraw-Hill Book Company, 1971) pages 166-168.

For the intermediate observer distances, the array of sources behaves approximately as a line source, depending on the density of sources. Actually, in Figure 1.4, the closest observer points A and B are within the distance a/π ($= 400/\pi = 127$ ft), and we see that the 5.7 dB/DD drop-off rate does approximate the estimated 6 dB rate. In Figure 1.7, observer points A, B, and C are greater than a/π (16 ft) and less than L/π (254 ft), and we see that the 3.3 and 3.9 dBA/DD drop-off rates approach the estimated 3 dB rate. In Figure 1.7, observer points D and E are beyond L/π (254 ft), and we see that the 5.3 dBA/DD drop-off rate approaches the estimated 6 dB rate. In summary, all the configurations of Figures 1.4-1.9 generally tend to agree with this estimation procedure: in the close-in region (less than a/π) only Figure 1.4 provides data (rate 5.7 dB/DD); in the intermediate region, drop-off rates range between 3.1 and 4.1 in Figures 1.5-1.9; and for the remote region (greater than L/π), drop-off rates range between 4.8 and 5.3 in Figures 1.4-1.7. All of this might be simply summarized as follows, when applied to high-density highway situations. For a line of sources of length L, the drop-off rate will approximate 3 - 4.5 dB/DD for observer distances less than L/3 and it will approximate 4.5 - 6 dB/DD for observer distances greater than L/3. For most highway situations, the very close-in condition (inside a/π in Sketch 1.2) will not be appropriate, because vehicles do not maintain fixed spacing and because housing areas or other occupant uses would not take place at such close distances to highways.

In this discussion of the sound level drop-off with distance, the concept of spherical (actually "hemispherical") spreading at 6 dB per double distance and cylindrical (actually "semi-cylindrical") spreading at 3 dB per double distance has been discussed. In actual use this is an awkward method for describing the various rates of drop-off that can exist between the two limiting conditions of 3 dB and 6 dB per double distance. So, there is need for a simpler method for describing a drop-off rate mathematically. In Sketch 1.1 on page 1-7, only a small segment of a hemispherical shell was shown at distance D from the sound source*. The area of the complete hemispherical shell would be $2\pi D^2$. Since we place so much data into terms that are easily converted to decibels, and since decibels are logarithmic units, the quantity $2\pi D^2$ can be expressed in logarithmic terms as $10 \log 2\pi D^2$. Recall from earlier exposures to mathematics that

$$10 \log D^2 = 20 \log D.$$

The term $20 \log D$ provides a means for simply describing the 6 dB drop-off rate for each doubling of distance. For example, let $D_1 = 100$ ft and $D_2 = 200$ ft. From the logarithmic functions in Table 1.2, we see that

$$10 \log 100 = 20 \text{ dB}$$

$$10 \log 200 = 23 \text{ dB}$$

Then,

$$20 \log 100 = 40 \text{ dB}$$

$$20 \log 200 = 46 \text{ dB}$$

Thus, the difference between the sound levels at 100 and 200 ft is 46-40 = 6 dB, in accordance with the "inverse square law" for point source radiation.

Now, for cylindrical spreading from a line source, the function $10 \log D$ is sufficient to produce the 3 dB per double distance drop-off rate. From above,

$$10 \log 100 = 20 \text{ dB}$$

$$10 \log 200 = 23 \text{ dB}.$$

This gives a 3 dB change for the distance change from 100 to 200 ft.

In highway practice, there is seldom an infinitely long line of an infinite number of vehicular sound sources, so the idealized line source and its ultimate 3 dB drop-off rate ("10 log D" function) is never quite realized. Also, with busy highways there is seldom such low traffic densities that only single sources ("20 log D" function) control the design. We now have, however, the ability to select any number between 10 and 20 to apply to the "log D" function to express any desired drop-off rate. In NCHRP Report 78, considerable evidence is given in support of $15 \log D$ as the function for relating sound levels to distance. Checking the example at 100 and 200 ft distances,

$$15 \log 100 = 1.5 \times 20 = 30 \text{ dB}$$

$$15 \log 200 = 1.5 \times 23 = 34.5 \text{ dB}.$$

This term gives a 4.5 dB per double distance drop-off rate. This rate would apply approximately to the situation charted in Figure 1.5 where five sound sources are spaced at 200 ft intervals.

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* "Hemispherical" because the sound source is assumed to be located on the earth's surface, such as a vehicle on a highway, and sound radiates into the air around the source but not into the earth below.

A function "12 log D" would provide a drop-off rate of 3.6 dB per double distance which would approximately describe the conditions of Figure 1.9 with 41 sound sources at 100 ft intervals.

In general, any desired drop-off rate can be obtained as follows: multiply the 10 log D function by a multiplier which is one-third the desired drop-off rate, i.e.,

$$\frac{\text{Desired Rate}}{3} \times (10 \log D).$$

The following table indicates the method for obtaining a few of these drop-off rates, including the samples used in the above illustrations.

Desired Rate (dBA per DD)	Multiplier	Log Function
6.0	6.0/3 = 2.0	20 log D
4.5	4.5/3 = 1.5	15 log D
4.0	4.0/3 = 1.333	13.3 log D
3.6	3.6/3 = 1.2	12 log D
3.0	3.0/3 = 1.0	10 log D

This procedure will hold for A-scale sound levels over short distances (say out to 1000 ft). For longer distances, as mentioned earlier, the molecular absorption of high frequency sound and various atmospheric effects tend to reduce A-scale levels slightly faster than these fixed rates would suggest.

Two of these drop-off rates are in current use in highway noise evaluation procedures. The 3 dBA/DD rate is used in the Traffic Noise Prediction Computer Program of the Transportation Systems Center (hereinafter referred to as the "TSC Computer Program"*). The 4.5 dBA/DD rate is used in NCHRP Report 117. The enclosed Tables 1.4 and 1.5 provide sound level reductions as a function of distance for these two drop-off rates, using 50 ft as the starting distance. Table 1.4 is constructed around the 3 dBA/DD drop-off rate, and it also includes the influence of molecular absorption on the higher frequency portion of A-scale levels and the additional small loss due to atmospheric effects. The formula for constructing Table 1.4 is approximately:

$$\text{dBA Reduction} = 10 \log \frac{D}{50} + \underset{\text{for } D>1000}{\left|\frac{D-1000}{1000}\right|} + \underset{\text{for } D>2000}{\left|\frac{D-2000}{1000}\right|}$$

where D is distance expressed in ft.

Table 1.5 is constructed around a 4.5 dBA/DD drop-off rate and also includes the extra losses mentioned earlier. The formula for constructing this table is approximately:

$$\text{dBA Reduction} = 15 \log \frac{D}{50} + \underset{\text{for } D>1000}{\left|\frac{D-1000}{1000}\right|} + \underset{\text{for } D>2000}{\left|\frac{D-2000}{1000}\right|}$$

One concluding remark should be made here regarding the drop-off rate. In typical high-density highway traffic, including both automobiles and large trucks, there are usually such a large number of automobiles that the highway becomes a line source for automobiles and the noise drops off at a rate approaching 3 dBA/DD. However, typically, the large trucks are fewer in number, but noisier than automobiles, and the highway truck noise may appear as an array of randomly-distributed point sources that do not have enough continuity to achieve full line-source status. Thus, the noise of these stronger sources may propagate with a variable drop-off rate somewhere between 6 dBA/DD and 3 dBA/DD depending on the quantity of trucks. The total effect of the highway, then, is that of a line source attributable to automobiles and a mixed source (points and short line segments) attributable to trucks. This must be handled as a statistical mix of sources with a resulting compromise drop-off rate that attempts to represent reasonably correctly the real-life highway noise problem.

1.11 EFFECT OF ATMOSPHERICS

Precipitation, wind fluctuations, wind gradients (with altitude), temperature, temperature gradients (with altitude), and relative humidity are possible atmospheric factors in sound transmission.**

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* Traffic Noise Prediction Model MOD 2 referenced and described in "Manual for Highway Noise Prediction" (in three volumes), Reports No. DOT-TSC-FHWA-72-1 and 2, of the Transportation Systems Center, 55 Broadway, Cambridge, Mass. 02142.

**For a more detailed summary of atmospheric effects on sound propagation, the reader may refer to "Noise and Vibration Control," edited by Leo L. Beranek, McGraw-Hill Book Company (1971), pp. 169-174.

Rain, mist, fog, hail, sleet and snow are the various forms of precipitation to consider. These have not been studied extensively in their natural state so there are no representative values of excess sound attenuation to be assigned to them. Generally, various forms of precipitation may cause a speed reduction in traffic flow and this may tend to reduce the noise slightly. Wet road surfaces, on the other hand, will increase the high frequency content of tire noise. Rain, hail and sleet may change the background noise levels in residences along a roadway and thus provide some masking of the traffic noise. A thick blanket of snow provides an absorbent ground cover for sound traveling at grazing incidence near the ground. In practice, of course, these various forms of precipitation are intermittent, temporary and of relatively short total duration, and they can not be counted on for steady-state sound control, even if they should offer noticeable attenuation. Also, since windows are usually closed during precipitation, any change in source noise or in background noise due to precipitation is generally of secondary importance.

A steady, smooth flow of wind, equal at all altitudes, would have no noticeable effect on sound transmission. In practice, however, wind speeds are slightly higher above the ground than at the ground, and the resulting wind speed gradients tend to "bend" sound waves over large distances. Sound traveling with the wind is bent down to earth, while sound traveling against the wind is bent upward above the ground. There is little or no increase in sound levels due to the sound waves being bent down; in fact, there is additional loss at the higher frequencies and at the greater distances. There can be noticeable reduction of sound levels (sometimes up to 20-30 dBA) at relatively long distances (beyond a few hundred yards) when the sound waves are bent upward, for sound traveling against the wind (for 10-20 mph wind speeds).

Irregular, turbulent or gusty wind provides fluctuations in sound transmission over large distances. The net effect of these fluctuations may be an average reduction of a few decibels (say up to 4-6 dBA) per 100 yd for gusty wind with speeds of 15-30 mph, but the short-term instantaneous fluctuations may be even greater than these average losses.* However, gusty wind or mixed wind direction cannot be counted on for noise control over the lifetime of a highway.

Constant temperature with altitude produces no effect on sound transmission, but temperature gradients can produce bending in much the same way as wind gradients do. Air temperature above the ground is normally cooler than at the ground, and the denser air above tends to bend sound waves upward. For normal temperature distributions there is little or no increase, but there may be a significant decrease in transmitted sound levels at large distances (highly variable, but up to 10-20 dBA over a 1000-2000 ft distance). With "temperature inversions" the warm air above the surface bends the sound waves down to earth. These effects are negligible at short distances but they can produce some increase in sound levels at ground elevation at large distances (over a half-mile) for some geometries and thermal structures. Generally, temperature gradients will not consistently increase or decrease noise levels from highways at the close distances where sensitive neighbors may live.

Since wind speeds and temperature variations for a height of up to 50 ft above the earth's surface are not known and are not readily measured, this is considered outside the field of interest of the highway engineer while making highway noise evaluations. Thus, rather than attempt to obtain detailed micro-meteorological data and attempt to correlate it with possible effects on sound transmission, it is cautioned that atmospheric variations can influence short-term sound transmission even though they cannot be relied upon for long-term noise reduction. Thus, when ambient noise readings are being taken for various noise sources located more than a few hundred feet from the measurement position, these atmospheric effects may produce artificially low noise levels at any particular time.

"Molecular absorption" is a mechanism involved in the physics of sound in air that can actually absorb some sound energy for relatively long distance sound transmission. This effect is most noticeable at high frequency and it is dependent on temperature and relative humidity of the air. The table below gives the approximate sound absorption as a function of frequency for the conditions of 60°-70° F. and 60-70% relative humidity.

Octave Frequency Band (Hz)	Absorption Rate ** (dB per 1000 ft)
31-250	0
500	0.7
1000	1.4
2000	3.0
4000	7.7
8000	14.4

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*"On the Effect of Atmospheric Turbulence on Sound Propagated over Ground," Uno Ingard and George C. Maling, *J. Acoust. Soc. of America*, vol. 35, pp. 1056-1057, (July 1963).

**"Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity for use in Evaluating Aircraft Flyover Noise," ARP 866, August 31, 1964, Society of Automotive Engineers, 485 Lexington Avenue, New York 10017.

A-scale sound levels for typical truck spectra have been calculated for several distances out to 4000 ft making use of these average absorption rates. Out to 2000 ft, the dominant low- and mid-frequency of the truck noise controls the A-scale reading sufficiently, that the influence of absorption on the higher frequency noise is negligible. Beyond 2000 ft, and out to 4000 ft, the absorption begins to influence the rate of drop-off slightly, about 1 dBA per 1000 ft. Thus, Tables 1.3, 1.4, and 1.5 have been constructed to include an additional 1 dBA loss per 1000 ft, starting at 2000 ft, attributable to the molecular absorption effect on truck noise. The same rate is taken as applicable to the noise spectra of automobiles, although this is not exactly correct. The slight error in applying this same rate to auto noise is probably no greater than 1 dBA at 1000-2000 ft, and at these distances truck noise is generally the controlling noise in most highway situations. Inside 1000 ft distance, the influence of molecular absorption is negligible for all highway traffic for most reasonable values of temperature and relative humidity.

Very low values of relative humidity produce unusual effects. In the temperature range of 60°-100° F., relative humidity in the range of 10-20% increases dramatically the effect of molecular absorption. These low values of relative humidity are not found in most inhabited areas, but when they do occur in arid regions they can decrease noticeably the very high frequency content of noise, particularly in the 4000 and 8000 Hz octave bands, for sound transmission over long distances (greater than 1000 ft). This still does not significantly affect the A-scale level of traffic noise, because much of the noise energy of concern falls in the 250-1000 Hz frequency region. An interesting, but not particularly useful, effect of molecular absorption is that at low relative humidity (10-20%) and very low temperatures (below about 20°F), the molecular absorption at high frequency almost vanishes. During these conditions, high frequency sounds are heard much better than under more normal temperature conditions. For example, on dry, low-temperature days (near 0°F), the high frequency sounds of aircraft flyover noise are dramatically enhanced. This is an interesting acoustic phenomenon, but of little practical value in most highway noise analyses.

In summary, there are atmospheric effects which would seldom increase but could significantly decrease sound levels at large distances from a source. These decreases are usually of an intermittent, short-time duration and they are usually beneficial to the receiver (in giving temporary noise reduction) when they occur, but it is best not to rely on them for long-time benefits in terms of noise control design. Because some amount of wind and thermal gradients are almost always present, a small token amount of attenuation of sound is suggested for long distance sound transmission. This is assigned a value of 1 dBA per 1000 ft starting after the first 1000 ft. This amount is contained in the data of Tables 1.3, 1.4, and 1.5, and approximately this amount of attenuation is included in the TSC Computer Program.

A final reminder is given relative to the influence of atmospheric effects on sound propagation. Just as wind and thermal gradients can reduce noise transmission from highways under certain conditions (greater than the 1 dB per 1000 ft just mentioned), these gradients can also reduce ambient or background noise levels arising from certain sources, such as remote street traffic, city noise, or industrial noise. This can result in temporarily and artificially lower background noise (sometimes by as much as 20-30 dBA) and this can lead to an unrealistic picture of the ambient noise conditions at a measurement site. For this reason it is good practice, when making community background noise measurements, to make a few repeat measurements at a few locations at one or two later time periods (a few days or weeks later, if possible). This at least offers the opportunity for a different set of atmospheric conditions to prevail. The effect of non-typical ambient readings will be mentioned in Chapter 3 on noise measurements.

Another weather-related influence on background measurements is the high frequency sound of crickets, peepers, katydids or other chirping wild-life, and the sound of leaves rustling in even a slight breeze. These high frequency sounds strongly influence A-scale background readings in rural and suburban areas and can produce falsely high values. Alternative time periods or measurement positions should be selected when these noise sources prevail in an area.

1.12 EFFECT OF PLANTINGS, WOODS, AND VEGETATION

Heavy dense growths of woods provide a small but useful amount of attenuation. NCHRP Report 117 suggests the use of 5 dBA attenuation for a 100 ft depth of woods of sufficient density that no visual path exists through this 100 ft depth. The woods should extend at least 15 ft above any line-of-sight between highway traffic sources and all portions of the neighboring buildings to be protected. For an additional depth of woods of 100 ft or more, an additional 5 dBA attenuation can be assumed, but the total attenuation claimed for all such plantings should not exceed 10 dBA in any configuration. To be effective in both winter and summer, there should be a reasonable mixture of both deciduous and evergreen trees. Also, the underbrush or ground cover should be sufficiently dense and tall to provide attenuation of sound passing under the tree growth.

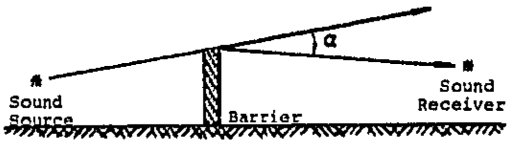
For low-density growth, a token amount of attenuation, such as 2 or 3 dBA per 100 ft depth, might be permissible, but this is left to the judgement of the user. Again, the total attenuation for such plantings should not exceed 10 dBA. The reason for imposing the 10 dBA limitation on any type of natural growth is that some sound paths are passing over the top of the trees and are frequently scattered or bent back down to earth beyond the tree growth by various mixtures of wind and temperature gradients or wind turbulence. These paths of sound ("sky waves") will limit the total sound reduction that can be achieved by trees or other tall, dense natural growth at the earth's surface.

Occasional trees and hedges have aesthetic and psychological value as partial visual barriers of highway activity, but they provide negligible attenuation of sound. Do not destroy them, but do not expect them to have significant acoustic value.

Extensive fields of tall crops, such as corn, cane and wheat, and tall grass, weeds or other ground cover, and even freshly plowed fields can provide sound absorption for sound paths at "grazing incidence" (parallel to the earth's surface, passing just along the top of these absorptive surfaces). However, this is not entirely reliable as a permanent attenuator for the same reason as given above for trees: sound passing above the grazing incidence paths and returning to earth or arriving at the receiver by scattered or bent sound waves does not receive the full attenuation effects of the absorptive surface. During calm, stable atmospheric conditions, absorption effects of ground surface and vegetation can be experienced and measured and found to be significant*; but during the lifetime of a highway, such ideal conditions are a rarity, and more often the flanking paths of the "sky waves" of sound will control. Thus, no acoustic credit should be given for this type of plant growth. We recommend that the attenuation value for tall grass and shrubbery contained in the TSC Computer Program not be used. It greatly overestimates the benefit derived. In addition, for this type of attenuation to be at all applicable, the ground cover would have to extend over large distances in order to offer absorption over all the paths from a long exposed length of highway to a receiver area.

1.13 EFFECT OF BARRIERS**

A wall, a building, an earth berm, a hill or some other type of solid structure, if large enough, can serve as a partial barrier to sound and can provide a moderate amount of sound reduction to an area located within the "shadow zone" provided by the barrier. Sound barriers do not cast as sharply defined shadows as light barriers do, because wavelengths of sound are usually somewhat comparable to the dimensions of the barrier, whereas with light, the dimensions of a barrier are many, many times larger than the wavelength of light. Sketch 1.3 below helps explain the mechanism of a sound barrier.



SKETCH 1.3

Suppose that sound radiates uniformly in all directions from the sound source, which we will consider here to be a point source. Among the many paths of sound radiating from the source, we are primarily interested in the sound path that follows the line drawn to the top of the wall. The sound in this path would continue in the straight line if sound wavelengths were as small as light wavelengths. Since they are not, some of the sound "bends" over the top of the wall (this is called "diffraction"). In the sketch, one portion of the diffracted sound is shown following the line drawn to the "receiver" of the sound. This particular sound beam has been deflected by an angle α from the original path direction. Thus, even though the receiver appears to be located in the shadow zone of the wall, and even though the receiver cannot see the sound source, some sound may be heard in this shadow zone. It is a fundamental fact of acoustics, however, that the larger the angle α, the less sound will be heard at the receiver location. Thus, if we want to design an effective sound barrier, it is essential to provide a large height or a large area for the barrier so the deflection angle α is as large as possible.

Now, let us consider the same idea of a barrier wall, but let us modify the sketch in order to add some dimensions that are involved in estimating the effectiveness of the wall as a sound barrier.

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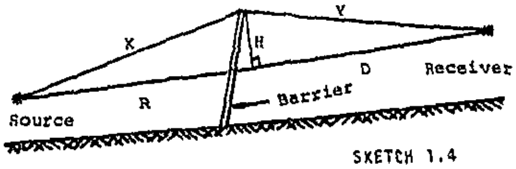
*"Noise Reduction by Vegetation and Ground," Donaly Aylor, *J. Acoust. Soc. of America*, vol. 51, pp. 197-205 (Jan. 1972); also, "Sound Transmission Through Vegetation in Relation to Leaf Area Density, Leaf Width, and Breadth of Canopy," Donald Aylor, *J. Acoust. Soc. of America*, vol. 51, pp. 411-414 (Jan. 1972).

**See P. 14 of NCHRP Report 117 for a brief discussion and list of a few references on barriers. See also "Sound and Vibration Control," L. L. Beranek, pp. 174-180.



SKETCH 1.4

In Sketch 1.4, first draw a straight line (the "line-of-sight") from the source to the receiver. Next, draw a perpendicular line from the "line-of-sight" to the topmost point of the barrier. The length of this line is labeled H in the sketch. This is the "effective height" of the barrier. A barrier must interrupt the line-of-sight to be effective, and the larger the value H beyond the line-of-sight, the better the barrier. The line-of-sight can now be divided into its two segments R and D. Next, draw lines from the top of the barrier to the sound source and to the sound receiver. These are labeled X and Y in the sketch. It is obvious, according to the Pythagorus theorem for right triangles, that $R^2 + H^2 = X^2$ and $D^2 + H^2 = Y^2$, from which

$$X = \sqrt{R^2 + H^2} \quad \text{and} \quad Y = \sqrt{D^2 + H^2}.$$

It has been found that a simple way to express the effectiveness of a barrier is in terms of the difference between the line-of-sight distance from the source to the receiver (R + D in Sketch 1.4) and the total sound path distance caused by placing the wall in the path (i.e., X + Y in the sketch). In conjunction with the first Sketch 1.3 of a barrier wall, it was stated that large values of the angle α yield large values of barrier attenuation. In Sketch 1.4, it follows then that large values of the path length difference

$$(X + Y) - (R + D)$$

may be related to large values of α, which in turn may produce large values of barrier attenuation. These path length differences lend themselves to simple sketches and calculations. When the path length difference, identified by the notation δ ("delta"), is determined, the barrier attenuation can be read from a curve. Since the path length differences frequently are very small distances, it is important that all distances be estimated closely and that the sketch of the layout really represent the correct layout. If a slant distance is involved, estimate the true slant distance, do not use an approximate horizontal or projected distance instead. Also, slide rule accuracy may not be good enough in the calculation of square roots.

The procedure given here is similar to and consistent with the procedure given in NCHRP Report 117, but the form is different. The procedure is summarized in Figure 1.10. This procedure is applicable to only a single source or a short portion of a line source. A later procedure will take into account long line sources and multiple receiver positions. Also, the dimensions involved in this procedure are constructed around A-scale spectra of vehicle noise. Thus, without adjustment, the Figure 1.10 material should not be applied to just any type of sound source.

Using the procedure outlined in Figure 1.10, the attenuation of a sample barrier is now calculated. Suppose a barrier wall is built to intrude beyond the line-of-sight by 15 ft (i.e., H = 15 ft). Suppose the wall is located 60 ft from the sound source (R = 60 ft) and 300 ft from the receiver (D = 300 ft). Although these dimensions readily permit calculation of the hypotenuse of the two right triangles using the Pythagorus theorem, let us follow the procedure of Step 3 in Figure 1.10.

$$H/R = 15/60 = .25$$

$$H/D = 15/300 = .05$$

For this small value of H/D, δ_D can be calculated from

$$\delta_D = 1/2\ H^2/D = 1/2 \times 225/300 = .38 \text{ ft}$$

For the larger value of H/R, δ_R can be determined by using Chart A:

for $H/R = .25$, $M = .03$

Then, $\delta_R = MR = .03 \times 60 = 1.8$ ft

The total path length difference

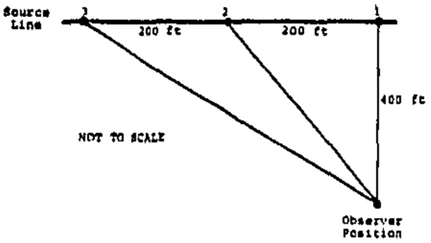
$$\delta = \delta_R + \delta_D = 1.8 + .38 = 2.2 \text{ ft}$$

Then, from Chart B, for $\delta = 2.2$, the barrier attenuation is approximately 17 dBA.

Under ideal conditions, for the dimensions indicated and for a fairly localized sound source and receiver, this barrier could achieve an attenuation of approximately 17 dBA (for noise having a spectrum shape similar to that of highway traffic). For actual highway applications, of course, the source might be a long line of traffic, the barrier would be of extended length to cover the line of traffic, and the receiver might represent a number of houses in a residential area. For these real-life conditions, the attenuation might not achieve the full 17 dBA value. Later in the course, barriers will be considered for extended sources. Some of the factors that must be considered in actual barrier designs and uses are mentioned here in preparation for the later detailed treatment.

In Section 1.10 it was pointed out that the distant ends of long lines of vehicular noise sources influence the sound levels received at areas somewhat remote from a highway. This is illustrated in Figure 1.9 where it may be seen that noise sources 1000-2000 ft from the central cluster of sources produce noise levels that are within 5-7 dB of those produced by the central sources when heard 800 ft away from the roadway. In connection with that discussion, it was stressed that complete noise control of a highway must therefore include consideration of long lengths of the highway, even though the remote ends of the highway would appear far enough away to be of no concern.

Let us illustrate this point with an example. In Sketch 1.5 assume a simple array of three noise sources along the source line, and suppose we are concerned with the noise levels received at the indicated observer position 400 ft from the source line.



SKETCH 1.5

The sound levels at this observer position were calculated in Figures 1.3, 1.4, and 1.5, if we will assume that these sound sources produce 80 dBA at 50 ft distance. Thus, the sound level contributions to the observer are as follows, in dBA:

Source 1	Source 2	Source 3	Total
62.0	61.0	59.0	65.6

Now suppose that a 200 ft length of barrier wall is built near the road to shield the observer from Source 1, but that nothing is done to reduce the levels of Sources 2 and 3. Suppose that the barrier achieves 15 dBA reduction for Source 1. The resulting sound level contributions to the observer are as follows, in dBA:

Source 1	Source 2	Source 3	Total
47.0	61.0	59.0	63.2

Thus, the 200 ft wall only achieved a reduction of 2.4 dBA for the observer.

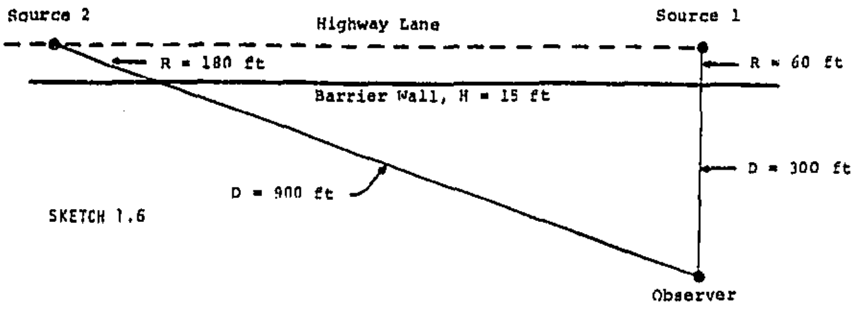
Next, suppose the wall is lengthened to 300 ft to shield Sources 1 and 2, and assume the barrier reduces Source 2 noise by 15 dBA also.

Source 1	Source 2	Source 3	Total
47.0	46.0	59.0	59.4

Thus, the additional length of wall reduced the noise an additional 3.8 dBA for a total reduction of 6.2 dBA.

To be completely effective, the wall should be extended again to shield the noise from Source 3. Thus, for this limited segment of roadway, it is seen that a barrier wall along the full length of exposed road would be required to achieve the order of 15 dBA noise reduction. For longer lengths of exposed roadway, longer lengths of barrier walls would be required to achieve substantial noise reduction for the neighbors.

Next, consider the attenuation of a long barrier wall beside a long section of highway. Consider the layout in plan shown in Sketch 1.6. Let the dotted line represent a highway lane, and let the heavy solid line represent a barrier wall having H = 15 ft. Consider Sources 1 and 2 and their paths that transmit sound to the observer. For sound Source 1, R = 60 ft and D = 300 ft. Actually, this example is the one first used on page 1-15 to



SKETCH 1.6

illustrate use of Figure 1.10. The barrier produces an estimated attenuation of 17 dBA for Source 1 as heard at the observer position. Now, the same barrier extends several hundred feet down the road and provides shielding to the observer for noise from Source 2.

For Source 2:

$H/R = 15/180 = .083$

$H/D = 15/900 = .017$

$\delta_R = 1/2\ H^2/R = 1/2 \quad 225/180 = .63$ ft

$\delta_D = 1/2\ H^2/D = 1/2 \quad 225/900 = .125$ ft

$\delta = .63 + .12 = .75$ ft

Attenuation = 13 dBA

Because of the new combination of dimensions, the path length difference for Source 2 is smaller than it was for Source 1 and the attenuation is less, even though the effective barrier height remains 15 ft for the entire length.

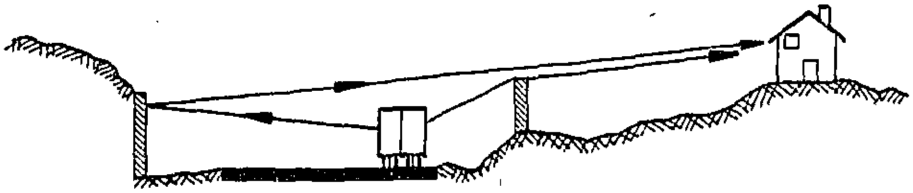
The purpose of the last two illustrations is to emphasize that long lines of barriers may be required to achieve substantial noise reduction from a highway, and that the barrier attenuation changes for various portions of the roadway because of the various distances involved. Actually, barrier designs can be optimized such that for certain specific layouts the barrier attenuation can be made to increase or decrease in accordance with other needs of the problem.

A real-life factor that does not show up in the calculations is that for large values of R and D there is more opportunity for wind and thermal gradients to introduce additional bending of the sound waves diffracted over the top of a barrier and this tends to produce lower attenuation than that calculated.

Another limitation on the effectiveness of barriers is illustrated in Sketch 1.7. Suppose a barrier wall is built on the right side of the roadway to protect neighbors on the right side. For some other reason, suppose a wall or reflecting surface is located on the left side of the road. For some geometries, the left side wall could actually reflect traffic noise over the top of the right side barrier and reduce its effectiveness.

It is because of these various limitations and the sometimes hard-to-predict or hard-to-control geometrical considerations that highway barriers may not achieve the attenuation values calculated for them. Of course, in a complete analysis of barrier effectiveness, both automobiles and trucks must be considered. Because of the higher elevation of the truck noise source above the roadway, a barrier will be less effective for truck noise than for automobile noise.

A unified design approach for barriers is given later; it will take into account some of the weaknesses or limitations mentioned in this introductory discussion. Although walls have been used chiefly in the above illustrations of barriers, other forms such as earth berms, hills, cuts, embankments or any other types of natural or constructed solid structure may serve as barriers. The barrier must have adequate mass and solidity to prevent appreciable sound transmission through the barrier itself. A surface weight of not less than approximately 4 lb/sq ft will be sufficient for most barrier walls. (This low weight should not be used in indoor situations where sound isolation from one area to another is required.) For berms or stepped side walls or thick structures, the "top" of the barrier, for calculation purposes, should be the point that provides the greatest path length difference. For long-length highway barriers, this will have to be checked for many positions along the highway. When only short-length barriers are used to protect localized noise sources or receivers, the length of the barrier should be sufficient to extend horizontally beyond the line-of-sight from all parts of the noise source to all parts of the receiver by a distance 2H at each end of the barrier. It is also imperative in any barrier design to consider the top-most part of the noise sources (such as the assumed average 8 ft height of the exhaust stack of diesel trucks) and the top-most part of the receiver (such as the second-floor bedroom windows for two-floor residences along the highway) in setting up the H value for the wall. Some acceptable barrier wall structures will be discussed during the course.



SKETCH 1.7

1.14 BARRIER EFFECT OF BUILDINGS

In built-up residential or commercial areas, the first row of buildings along a highway may provide some reduction of highway noise to areas beyond that row of buildings. In turn, additional rows of buildings may give additional noise reduction to areas still farther beyond.

First, considering just the ratio of open area to closed area of a row of buildings acting as barriers, it is possible to estimate approximately the reduction of highway noise penetration through that row of buildings. When the projected area of the first row of buildings represents approximately 50% of the area along the roadway, there is justification for expecting approximately a 3 dB reduction of noise to the next row of buildings (from the earlier discussion of decibel addition, recall that one-half the noise represents a 3 dB reduction). If the projected area of the buildings represents approximately 80-90% of the area along the roadway, one might expect a noise reduction of about 7-10 dB, based on area considerations alone (from Table 1.2, an opening of only 10% area would represent -10 dB and an opening of 20% area would represent -7 dB). Of course, if a long continuous solid building occupies 100% of the area, that building could be treated as a barrier and its effectiveness estimated according to Section 1.13. When buildings in the first row along the roadway occupy only about 10-20% of the area paralleling the roadway, each individual building might product a small localized barrier effect, but the combined effect of such sparsely located buildings is negligible in producing noise reduction to the second or third row of buildings.

Several studies have been carried out on noise penetration into a community bordering a noise source, and the findings are not very precise nor consistent, possibly due to variations in geometry, house sizes, lot sizes, house spacing, etc. It appears reasonable, however, to follow the suggestion offered in NCHRP Report 117, where 5 dBA is used as the reduction provided by the first row of buildings and 10 dBA is used as the maximum reduction provided by multiple rows of buildings. These values assume rather dense "packing" of the houses (possibly 60-80% house area and 20-40% open area) such as to form an effective visual barrier between the roadway and the interior houses. For noticeably less dense packing of the houses, it can be left to the discretion of the user to apply a slightly lower attenuation rate, if desired.

It is to be understood, of course, that the average height of the first row of houses must equal or exceed the average height of the second row of houses for the noise reduction to be realized. Strictly speaking, the height of the protective row of houses must produce essentially a positive value of H (see Sketch 1.4) for the following row of houses. For flat, level ground, a row of one-floor buildings will provide little protection to the second floor of a row of two-floor buildings.

1.15 OUTDOOR-TO-INDOOR NOISE REDUCTION PROVIDED BY A BUILDING FACADE

Noise coming from an outdoor noise source or by an outdoor noise path may be heard by a person who is either indoors in his own building or outdoors on his property. If he is outdoors he may judge the noise against the background noise due to other sources in the area. If he is indoors, he may tend to judge the noise by whether it is audible or identifiable or intrusive into his surroundings.

When outdoor noise enters into a building it suffers some noise reduction, even if the building has open windows. The actual amount of noise reduction depends on building construction, orientation, wall area, window area, open window area, interior acoustic absorption, etc. For practical purposes, however, the approximate noise reduction values provided by a few typical building constructions are given on page B-1 of PPM 90-2. These are repeated in the accompanying Table 1.6. Since the open-window condition provides the lowest value of noise reduction, and since many buildings are characterized by open windows much of the year, it should be noted that the 10 dBA value assigned by PPM 90-2 represents an average of many conditions and the user might wish to apply his own value for certain situations. For example, for a school room with a large exterior wall area facing the highway, with a relatively large open-window area, and with relatively little sound absorptive material inside the room, the noise reduction may be as low as 6-8 dBA. On the other hand, for a bedroom having only one or two windows open 3-6 in. wide, and having a moderate amount of acoustic absorptive material (bed, drapes, carpet, clothes, upholstered furniture, etc.), the noise reduction may be as high as 15 dBA. So, it is seen that the relative amount of open window area and the interior absorption determines the actual noise reduction value for a building.

When the outdoor noise is known, in A-scale sound levels, the noise inside the building can be estimated by merely subtracting the "noise reduction" value of the structure from the outdoor level, where all levels are expressed in dBA. Actually, the "noise reduction" of a structure usually varies with frequency and the values given in PPM 90-2 and Table 1.6 reflect the frequency distribution of traffic noise and the frequency characteristics of typical building structures.

If critical situations dictate, specific details of a building may be required in order to calculate more precisely the noise reduction provided by the building. Typically, noise is excluded by solid surfaces having high surface weight. Thus, an open window is a poor structure for excluding noise, while a building of massive wall construction and well-sealed heavy windows is a good structure for excluding noise.

Prevailing weather conditions and the general practices of the highway neighbors should determine the selection of the window condition (from Table 1.6) to be used in a noise evaluation. Where a range of noise reduction values appear applicable in a given study, the lower end of the range should be used for conservative design.

To illustrate the use of Table 1.6, suppose that a group of residences have an outdoor noise level of 64 dBA due to nearby traffic activity. In the winter time, the houses which are predominantly of frame construction are equipped with storm windows; and in the summer time most of the houses are not air-conditioned and have their windows open. The inside noise levels due to highway traffic would then be:

in the winter time – 39 dBA

in the summer time – 54 dBA.

1.16 HUMAN RESPONSE TO NOISE

If people were not bothered by noise, there would be no highway noise problem and this course would be unnecessary. Since people are bothered by noise, it is helpful to know (a) some of the ways that people judge noise, (b) some of the known quantitative relationships between noise levels and noise interference, and (c) the design goals for noise control set forth by the FHWA.

The degree of disturbance or annoyance of an unwanted noise depends essentially on three things: (1) the amount and nature of the intruding noise, (2) the amount of background noise present before the intruding noise, and (3) the nature of the working or living activity of the people occupying the area where the noise is heard.

Each of these items deserves a brief explanation. Regarding the first item, the nature of the noise, three attributes of noise are significant factors:

frequency distribution of the noise,
intensity of the noise (noise level), and
time pattern of the noise.

Concerning the first of these three attributes, humans have better hearing sensitivity in the high frequency region than in the low frequency region, so it follows that high frequency noise will seem more pronounced than low frequency noise to human listeners. This is borne out by many reliable tests on large numbers of people listening to many types of noise. As mentioned earlier (Section 1.7), the A-scale frequency weighting network emphasizes the high frequency content of noise, and A-scale sound levels correlate well with human judgements of annoyance or disturbance of noise. The second attribute mentioned above (intensity, or noise level) is probably obvious. Higher noise levels are more intensive and more overpowering; they may make it difficult or impossible to hear things we want to hear. If they are truly unwanted, and if there is no relief from them, we may become aroused to indignation or anger if the noise persists, especially if we can pin-point the cause and find justification for blaming the noise on someone else. The time pattern of the noise, the third attribute mentioned above, can be related both to the time characteristics of the noise source and the time at which the noise is heard. In terms of the time characteristics of the noise, a smooth continuous flow of noise (such as from a fan) is more comfortable or acceptable than impulsive noise (such as from a jack-hammer) or intermittent noise (such as from a passing truck), even though all of these noises might be judged as unwanted. There is evidence that noise levels that change markedly with time are more identifiable than noise levels that remain constant, and noises that are more identifiable tend to be more annoying. Related to traffic noise, this suggests that a steady flow of traffic and a steady-state continuous noise level are less objectionable to neighbors than intermittent flow with time-varying noise levels. Still pursuing the "time pattern" of the noise, obviously, the time at which the unwanted noise occurs is a factor: an automobile horn in your neighbor's driveway, that wakens you at 2:00 a.m. is more annoying than the same sound 12 hours later.

The second factor regarding disturbance or annoyance of noise is associated with the background noise. People tend to compare an intruding noise with the background noise that was present before the new noise came into existence. If the new noise has distinctive sounds that make it readily identifiable or if its noise levels are considerably higher than the background or "ambient" levels, it will be noticeable to the residents and it might be considered objectionable. On the other hand, if the new noise has a rather unidentifiable, unobtrusive sound and its noise levels blend into the ambient levels, it will hardly be noticed by the neighbors and it probably will not be considered objectionable.

The third factor involved in annoyance of noise concerns the nature of the working or living activity of the people where the noise is heard. People trying to sleep in quiet suburban homes do not want very much intruding noise; while office workers in a busy mid-city office could have greater amounts of noise without even noticing it; and factory workers in a continuously noisy manufacturing space might not even hear a noisy nearby highway.

Of course, most of these factors are "relative", and it would be helpful to have some specific quantitative relationships between noise levels and interference or disturbance of noise. There are a few relationships that can be identified and mentioned.

a) Interference With Speech

NCHRP Report 117 summarizes considerable effort on the study of interference of speech communication by intruding noise. Tables 7 and 8 on page 27 of NCHRP Report 117 are reproduced here as Table 1.7. The upper half of Table 1.7 indicates the maximum "L_{50} A-scale noise level" that will permit reasonably acceptable speech communication for the voice levels and listener distances shown. The lower half of Table 1.7 indicates a limiting condition that almost precludes reliable speech communication; it gives the maximum "L_{10} A-scale noise levels" for barely acceptable speech communication. This material is based on automobile noise, essentially steady-state flow for the upper half of the table and discrete events for the lower half of the table. The L_{50} and L_{10} A-scale noise levels represent a way of describing a fluctuating noise level. This concept is used extensively in highway noise evaluations; more discussion will be offered later. For the present, L_{50} is simply defined as the noise level that is exceeded 50% of the time, and L_{10} is the noise level that is exceeded 10% of the time. To illustrate the use of Table 1.7, suppose two men are standing 5 ft apart, facing each other, using a familiar vocabulary and speaking at normal voice levels. They could just carry on a reasonably reliable conversation if the interfering noise does not exceed 52 dBA for more than 50% of the time or 58 dBA for more than 10% of the time. Conversely, when the L_{50} and L_{10} noise levels are known for a given traffic condition, the speech communication conditions can be estimated from Table 1.7. Although the data were derived for the frequency distribution of auto noise, the findings are reasonably applicable to truck noise spectra also. Of course, trucks will typically make more noise and make conversation more difficult, as the table shows.

The quality of telephone usage can also be approximated in terms of essentially steady-state interfering noise. This is summarized briefly in Table 1.8.

b) Interference With Sleep

Although some very interesting work on noise interference with sleep has been undertaken, it indicates mostly the need for continued work to understand better the sleep mechanism in people. The work of Thiessen and Olson* of the National Research Council in Ottawa, Canada reveals that a tape recorded truck passage wakened more than 50% of the test subjects when the peak noise reached 50 dBA, while some subjects did not waken when the peak reached 75 dBA. Earlier work of other experimenters showed that more than 50% of the subjects were wakened by a steady noise at 45 dB and that a range of 35 dB in noise levels was required to waken all subjects.

These are not definitive tests upon which we can base reliable criteria for highway noise intrusion, although the noise levels used and the results noted seem fairly reasonable.

c) Sound Level Differences

Under controlled laboratory conditions, listening to a steady unwavering pure tone sound that can be changed to slightly different sound levels, a person can just barely detect a sound level change of approximately one-half decibel for sounds in the mid-frequency region. When real-life sounds or noises are heard, it is possible to just detect level changes of 2-3 dB. A 5 dB change is readily noticeable. A 10 dB change is judged by most people as a doubling or a halving of the loudness of the sound. (Some of these sound level differences will be presented in the classroom with tape recorded events.) A 20 dB change is a dramatic change. A 40 dB change represents the difference between a faintly audible sound and a very loud sound. Each 10 dB step still carries the connotation of a doubling or a halving of loudness regardless of the levels at which the comparative sounds are presented.

In terms of noise control, this means that a 2-3 dB reduction in noise from a highway will hardly be noticed. A 10 dB reduction in highway noise may be achieved at considerable expense, yet the neighbors can still hear the remaining noise as though it were only half as loud as before. Yet, Table 1.2 shows that 50% of the noise energy must be removed to obtain a hardly perceptible 3 dB reduction, 90% of the noise energy must be removed to obtain a 10 dB reduction, and, extrapolating beyond the table limits, 99% of the noise energy must be removed to achieve a 20 dB noise reduction. This emphasizes the immensity of the problem; yet, subjectively a 20 dB quieter sound seems to be only one-fourth the loudness of the original sound, as heard by the listeners.

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*Community Noise -- Surface Transportation" by G.J. Thiessen and N. Olson, Sound and Vibration magazine, April 1968. Highlights of this work are summarized on page 27 of NCHRP Report 117.

d) Recommended Noise Criteria and PPM 90-2 Design Noise Levels

In summary of the above factors and of many other comprehensive studies on background noises in communities and intruding noises in communities, a table of recommended design criteria is given in NCHRP Report 117. Table 11 on page 30 of NCHRP Report 117 is reproduced here as Table 1.9. The inside and outside noise levels listed in Table 1.9 are intended as desirable goals for noise control, but the achievement of these goals may be technically difficult and economically unfeasible in some situations.

The design noise levels advanced in PPM 90-2 are reproduced here in Table 1.10. In support of these design noise levels, Paragraph 5.a.(7) of PPM 90-2 states:

> "Incorporation of Noise Abatement Measures in Plans and Specifications.
>
> For those projects to which the standards apply, the plans and specifications for the highway section shall incorporate noise abatement measures to attain the design noise levels in the standards, except where an exception has been granted." [Procedures for requesting exceptions are listed in the Standard and its Appendix.]

Although it represents a digression from the discussion of human response to noise, the following excerpt is added to illustrate the extent to which the FHWA intends to pursue noise control in order to try to satisfy highway neighbor needs. Paragraph 5.b. of PPM 90-2 outlines the types of noise abatement treatments that are considered to fall within the scope of this Standard:

> "(1) Shifts in alignment and grade are design measures which can be used to reduce noise impacts. The following noise abatement measures may also be incorporated in a project to reduce highway-generated noise impacts. The costs of such measures may be included in project costs.
>
> (a) The acquisition of property rights (either in fee or a lesser interest) for providing buffer zones or for installation or construction of noise abatement barriers or devices.
>
> (b) The installation or construction of noise barriers or devices, whether within the highway right-of-way or on an easement obtained for that purpose.
>
> (2) In some specific cases there may be compelling reasons to consider measures to "sound-proof" structures. Situations of this kind may be considered on a case by case basis when they involve such public or non-profit institutional structures as schools, churches, libraries, hospitals, and auditoriums. Proposals of this type, together with the State's recommendation for approval, shall be submitted to FHWA for consideration."

Some of the introductory material earlier in this chapter and much of the analysis detail to follow in later chapters are aimed at helping the highway engineer design and evaluate some of these noise abatement treatments.

e) Noise-Induced Hearing Damage

The Walsh-Healey Public Contracts Act of 1969 and the Occupational Safety and Health Act of 1970 ("OSHA") establish the following maximum permissible noise exposures for persons working in noise environments:

Duration per day, hours	Sound level dBA
8	90
6	92
4	95
3	97
2	100
1-1/2	102
1	105
1/2	110
1/4 or less	115

Uninformed people sometimes interpret this to mean that any noise level above 90 dBA will cause loss of hearing, regardless of exposure time. It is essential that people or groups concerned with noise and noise control understand the full implication of this table. The table is intended to apply to industrial areas and workers and it is intended to protect the hearing of people exposed on a daily basis for these noise levels and durations over a life-time of employment. To experience continuous 90 dBA noise levels from highway traffic, one would have to stand approximately 10-20 ft from a highway lane carrying approximately 1000 trucks per hour. To approach the OSHA exposure limits, one should then remain there beside the highway for 8 hrs per day on a daily basis for many years. This is a rather unrealistic situation. There is a strong possibility that the OSHA table of values will be reduced by 5 dBA in future legislation in order to provide greater hearing protection for people exposed to noise. Even with this reduction it is unlikely that residents near a highway are receiving hearing damage due to traffic noise.

1.17 DESCRIPTORS OF NOISE

Several procedures have been devised by various acousticians to rate noises. "Sones" and "phons" are units used for expressing loudness and loudness level of sounds. "Perceived noise levels", expressed in PNdB and using "noys" as units of relative noisiness, were first developed as a rating scheme for comparison of the subjective noisiness of jet aircraft and propeller aircraft. "NC" curves (Noise Criteria curves) represent a family of curves that can be used to describe the relative levels and frequency distribution of noise in buildings that is considered acceptable for various functional uses of the buildings. These various descriptors of noise have specific applications, and they probably could be adapted to use as indicators of traffic noise. As stated earlier, however, A-scale noise levels and subjective judgements of noise have been tested many times and found to give adequate correlation.

Because traffic noise contains fluctuations in noise levels and therefore the levels must be studied on a somewhat statistical basis, several attempts have been made to interrelate various percentile collections of noise levels to arrive at a reliable indicator of the disturbance or annoyance of noise. Noise levels, such as L_{99}*, L_{90}, L_{50}, $L_{\text{energy mean}}$, L_{10} and L_1 have been tried in various combinations. TNI (Traffic Noise Index) represents one approach and NPL (Noise Pollution Level) represents another method of combining these statistical levels. NPL is of special interest because it suggests that annoyance of noise is related to both the energy mean of the noise and some measure of the fluctuations of noise.

After considering all of these noise evaluation procedures, it was finally determined by the FHWA and interested associated groups that the L_{10} and L_{50} noise levels would be used as the principal noise descriptors for highway design. The L_{10} values provide an indication of the noisiest portion of highway traffic and they represent an approximate indicator of noise level fluctuations as a factor in annoyance. The L_{50} values are used in the procedure for arriving at the L_{10} values.

In the next chapter, Chapter 2, information will be summarized on the noise characteristics of automobiles and trucks, leading to the use of L_{10} values as an indicator of highway noise. In Chapter 3, noise measurements will be discussed and a procedure will be given for obtaining a simple manually-read determination of L_{10} levels for traffic and community background noise.

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*L_{99} = noise level exceeded 99% of the time. Other levels L_{90}, L_{50}, etc. have similar meanings in terms of percentage distribution of the noise levels, usually expressed in dBA or some other applicable unit.

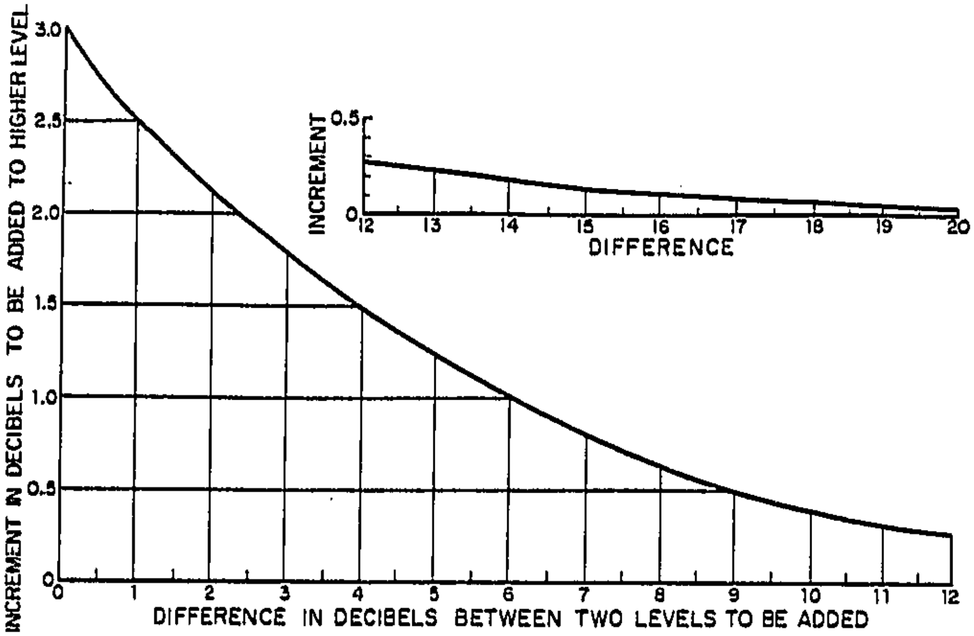


FIGURE 1.1 CHART FOR COMBINING SOUND LEVELS BY "DECIBEL ADDITION"

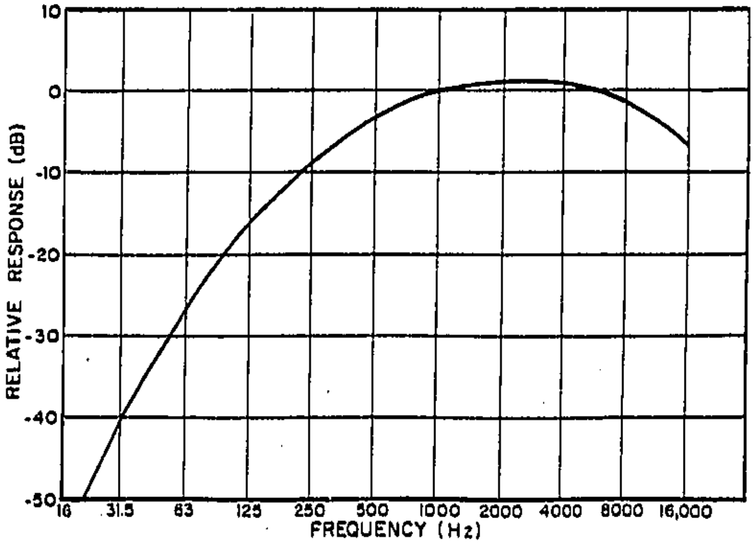
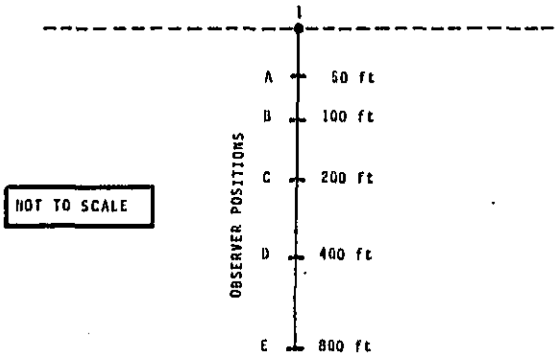


FIGURE 1.2 ELECTRICAL FREQUENCY RESPONSE SPECIFIED FOR THE A-SCALE FILTER OF SOUND LEVEL METERS (ANSI S1.4-1971)

FIGURE 1.3

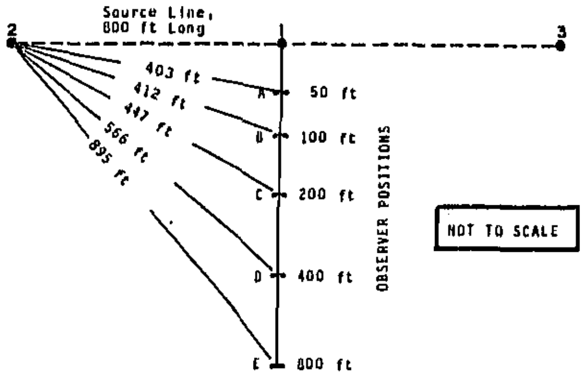
CALCULATED A-SCALE SOUND LEVELS AT OBSERVER POINTS A, B, C, D, AND E FOR SOUND SOURCE AT POINT 1. SOURCE PRODUCES SOUND LEVEL OF 80 dBA AT 50 FT DISTANCE.



Point	Total Sound Level (dBA)	Difference, Drop-off Rate (dBA/DD)
A	80	
		6.0
B	74	
		6.0
C	68	
		6.0
D	62	
		6.0
E	56	

FIGURE 1.4

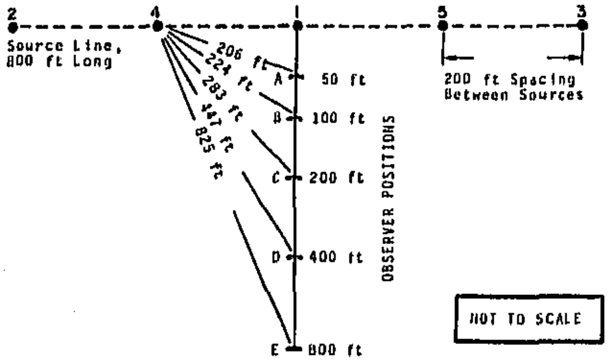
CALCULATED A-SCALE SOUND LEVELS AT OBSERVER POINTS A, B, C, D, AND E FOR 3 SOUND SOURCES EQUALLY SPACED AT 400 FT INTERVALS ALONG AN 800 FT SOURCE LINE. EACH SOURCE PRODUCES SOUND LEVEL OF 80 dBA AT 50 FT DISTANCE



	Sound Level Contributions				
Point	Source 1 (From Fig. 1.3)	Source 2 (dBA)	Source 3 (dBA)	Total Sound Level (dBA)	Difference, Drop-Off Rate (dBA/DD)
A	80.0	61.9	61.9	80.2	
					5.7
B	74.0	61.7	61.7	74.5	
					5.0
C	68.0	61.0	61.0	69.5	
					4.5
D	62.0	59.0	59.0	65.0	
					4.9
E	56.0	55.0	55.0	60.1	

FIGURE 1.5

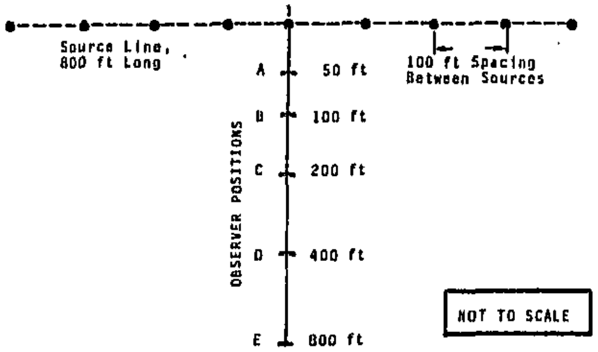
CALCULATED A-SCALE SOUND LEVELS AT OBSERVER POINTS A, B, C, D, AND E FOR 5 SOUND SOURCES EQUALLY SPACED AT 200 FT INTERVALS ALONG AN 800 FT SOURCE LINE. EACH SOURCE PRODUCES SOUND LEVEL OF 80 dBA AT 50 FT DISTANCE



Point	Sound Level Contributions Sources 1-3 (From Fig. 1.4)	 Source 4 (dBA)	 Source 5 (dBA)	Total Sound Level (dBA)	Difference, Drop-Off Rate (dBA/DD)
A	80.2	67.7	67.7	80.6	4.8
B	74.5	67.0	67.0	75.8	4.1
C	69.5	65.0	65.0	71.7	4.2
D	65.0	61.0	61.0	67.5	5.1
E	60.1	55.7	55.7	62.4	

FIGURE 1.6

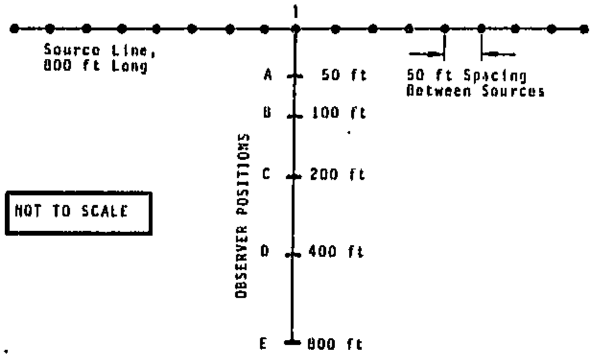
CALCULATED A-SCALE SOUND LEVELS AT OBSERVER POINTS A, B, C, D, AND E FOR 9 SOUND SOURCES EQUALLY SPACED AT 100 FT INTERVALS ALONG AN 800 FT SOURCE LINE. EACH SOURCE PRODUCES SOUND LEVEL OF 80 dBA AT 50 FT DISTANCE.



Point	Total Sound Level (dBA)	Difference, Drop-off Rate (dBA/DD)
A	82.1	3.8
B	78.3	3.7
C	74.6	4.4
D	70.2	4.8
E	65.0	

FIGURE 1.7

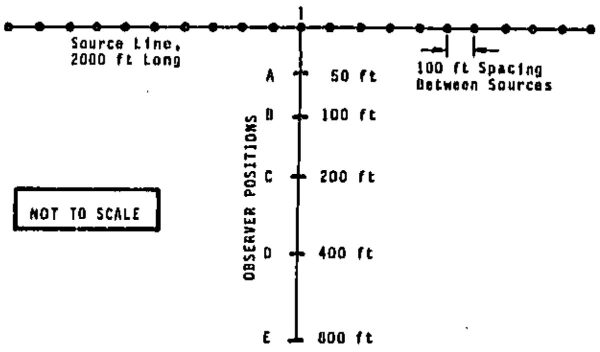
CALCULATED A-SCALE SOUND LEVELS AT OBSERVER POINTS A, B, C, D, AND E FOR 17 SOUND SOURCES EQUALLY SPACED AT 50 FT INTERVALS ALONG AN 800 FT SOURCE LINE. EACH SOURCE PRODUCES SOUND LEVEL OF 80 dBA AT 50 FT DISTANCE.



Point	Total Sound Level (dBA)	Difference, Drop-off Rate (dBA/DD)
A	84.6	
		3.3
B	81.3	
		3.9
C	77.4	
		4.4
D	73.0	
		5.3
E	67.7	

FIGURE 1.8

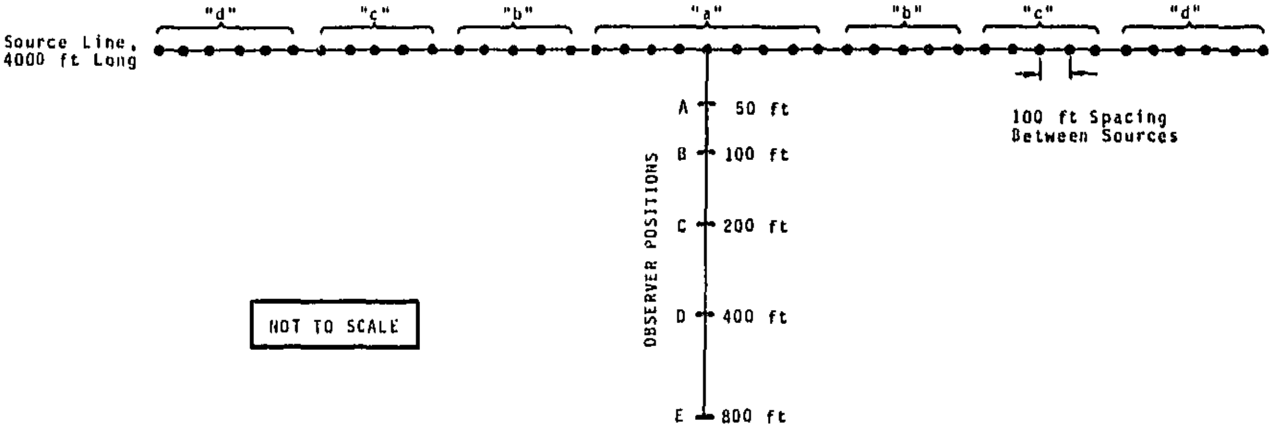
CALCULATED A-SCALE SOUND LEVELS AT OBSERVER POINTS A, B, C, D, AND E FOR 21 SOUND SOURCES EQUALLY SPACED AT 100 FT INTERVALS ALONG A 2000 FT SOURCE LINE. EACH SOURCE PRODUCES SOUND LEVEL OF 80 dBA AT 50 FT DISTANCE.



Point	Total Sound Level (dBA)	Difference, Drop-off Rate (dBA/DD)
A	82.4	
		3.6
B	78.8	
		3.4
C	75.4	
		3.6
D	71.8	
		4.4
E	67.4	

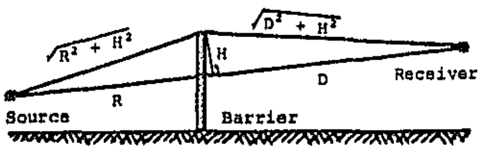
FIGURE 1.9

CALCULATED A-SCALE SOUND LEVELS AT OBSERVER POINTS A, B, C, D, AND E FOR 41 SOUND SOURCES EQUALLY SPACED AT 100 FT INTERVALS ALONG A 4000-FT SOURCE LINE. EACH SOURCE PRODUCES SOUND LEVEL OF 80 dBA AT 50 FT DISTANCE.



	Sound Level Contributions (dBA)					
Point	Group "a" Central 9 Sources, Within 400 ft of Center	Group "b" Next 10 Sources, 500-900 ft from Center	Group "c" Next 10 Sources, 1000-1400 ft from Center	Group "d" Next 12 Sources, 1500-2000 ft from Center	Total Sound Level (dBA)	Difference, Drop-Off Rate/DD (dBA)
A	82.1	67.6	62.2	59.0	82.3	3.5
B	78.3	67.4	62.2	59.0	78.8	3.1
C	74.6	67.2	62.1	58.9	75.7	3.5
D	70.2	66.1	61.7	58.7	72.2	3.8
E	65.0	63.4	60.3	57.8	68.4	

FIGURE 1.10
PROCEDURE FOR ESTIMATING PATH LENGTH DIFFERENCE AND SOUND ATTENUATION FOR A SIMPLE SOUND BARRIER



Path Length Difference:

$$\delta = (\sqrt{R^2+H^2} + \sqrt{D^2+H^2}) - (R+D)$$

$$\delta = (\sqrt{R^2+H^2} - R) + (\sqrt{D^2+H^2} - D)$$

$$\delta = \delta_R + \delta_D$$

where

$$\delta_R = \sqrt{R^2+H^2} - R,$$

$$\delta_D = \sqrt{D^2+H^2} - D$$

1. Construct the two-dimensional plot as indicated by the sketch above. Determine the distances R, D, and H in feet.

2. If the user is familiar with taking square roots, the total path length difference can be determined directly from:

$$\delta = (\sqrt{R^2+H^2} + \sqrt{D^2+H^2}) - (R+D)$$

3. If the user cannot readily determine these square roots, use the following procedure.
   a. Determine H/R and H/D: H/R = __________; H/D = __________.
   b. If H/R is between 0.0 and 0.20:

      $\delta_R = 1/2\ H^2/R = 1/2$ _____/_____ = _____ ft.

      If H/D is between 0.0 and 0.20:

      $\delta_D = 1/2\ H^2/D = 1/2$ _____/_____ = _____ ft.

      Then $\delta = \delta_R + \delta_D =$ _____ + _____ = _____ ft.
   c. If H/R or H/D is greater than 0.20, refer to chart A on the following page:
      (1) Enter graph at left axis with value of H/R or H/D;
      (2) Move horizontally to the right across the chart to the curve;
      (3) Drop vertically from that point of the curve to the axis at the bottom of the chart, and read the value of M (the multiplier).
      (4) The partial path difference δ_R or δ_D is determined by multiplying M by the value of R or D in feet. Thus,

      $$\delta_R = MR; \quad \delta_D = MD$$

      (This procedure is first followed to obtain δ_R, using its value of M and R, and is then repeated to obtain δ_D, using its value of M and D. Each δ may have a different M value.)
   d. Add δ_R and δ_D to obtain the total δ in feet.

4. With the total path length difference δ from steps 2 or 3 above,
   a. Enter chart B on the following page with the value of δ at the bottom axis of the graph;
   b. Move vertically up from that point to the curve;
   c. Now, move horizontally to the left across the chart to the left-hand axis, and read the value of Barrier Attenuation in dBA.

Note: It is current practice, as recommended by NCHRP Report 117, to use a 15 dBA maximum value for automobile traffic and a 10 dBA maximum value for truck traffic as the barrier attenuation in traffic noise analyses, because of various atmospheric, geometric, and environmental limitations on many practical barrier designs. This should not be construed, however, to mean that a barrier should be designed to only achieve these design values. Many good barriers can be more effective than these limitations imply.

FIGURE 1.10 (CONTINUED)
CHARTS A AND B USED FOR ESTIMATING PATH LENGTH DIFFERENCE AND SOUND ATTENUATION FOR A SIMPLE SOUND BARRIER

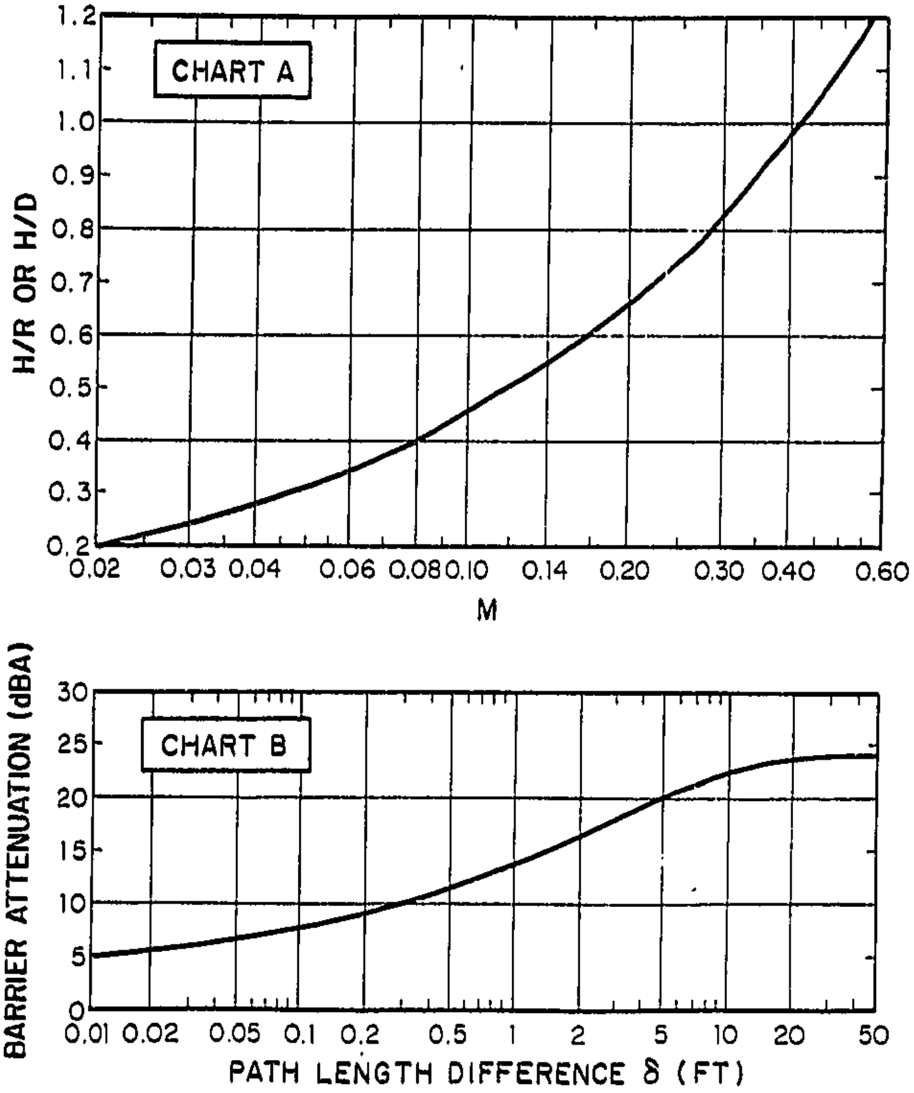


TABLE 1.1

RULES FOR COMBINING SOUND LEVELS BY "DECIBEL ADDITION"

A. For noise levels known or desired to an accuracy of ±1 decibel:

When two decibel values differ by	Add the following amount to the higher value
0 or 1 dB	3 dB
2 or 3 dB	2 dB
4 to 9 dB	1 dB
10 dB or more	0 dB

B. For noise levels known or desired to an accuracy of ±½ decibel:

When two decibel values differ by	Add the following amount to the higher value
0 or ½ dB	3 dB
1 or 1½ dB	2½ dB
2 to 3 dB	2 dB
3½ to 4½ dB	1½ dB
5 to 7 dB	1 dB
7½ to 12 dB	½ dB
13 dB or more	0 dB

(For greater accuracy, refer to chart in Figure 1.1)

TABLE 1.2

DECIBEL EQUIVALENTS OF NUMBERS

N	10 log N (dB)	N	10 log N (dB)	N	10 log N (dB)
.10	-10	2.24	3.5	250	24
.112	- 9.5	2.51	4	320	25
.126	- 9	2.82	4.5	400	26
.141	- 8.5	3.16	5	500	27
.158	- 8	3.55	5.5	630	28
.178	- 7.5	3.98	6	800	29
.200	- 7	4.47	6.5	1,000	30
.224	- 6.5	5.01	7	1,250	31
.251	- 6	5.62	7.5	1,600	32
.282	- 5.5	6.31	8	2,000	33
.316	- 5	7.08	8.5	2,500	34
.355	- 4.5	7.94	9	3,200	35
.398	- 4	8.91	9.5	4,000	36
.447	- 3.5	10	10	5,000	37
.501	- 3	12	11	6,300	38
.562	- 2.5	16	12	8,000	39
.631	- 2	20	13	10,000	40
.708	- 1.5	25	14	12,500	41
.794	- 1	32	15	16,000	42
.891	- 0.5	40	16	20,000	43
1.000	0.0	50	17	25,000	44
1.12	0.5	63	18	32,000	45
1.26	1	80	19	40,000	46
1.41	1.5	100	20	50,000	47
1.58	2	125	21	63,000	48
1.78	2.5	160	22	80,000	49
2.00	3	200	23	100,000	50

Note: By simply remembering the relationship that,

10 log 1 = 0 dB
10 log 1.25 = 1 dB
10 log 1.6 = 2 dB
10 log 2 = 3 dB

the above table can be extended up or down to get "10 log" of any number desired. Note the simple sequence: for each doubling of a quantity, there is an increase of 3 dB for "10 log" of that quantity, or each time a quantity is changed by a factor of 10, there is a change of 10 dB for "10 log" of that quantity.

TABLE 1.3

REDUCTION OF A-SCALE SOUND LEVEL AT VARIOUS DISTANCES FROM A VEHICULAR "POINT SOURCE", RELATIVE TO 50 FT DISTANCE, USING THE DROP-OFF RATE OF 6 dBA PER DOUBLE DISTANCE

$$\text{dBA REDUCTION} = 20 \text{ LOG } \frac{D}{50} + \underset{\text{for } D>1000}{\left|\frac{D-1000}{1000}\right|} + \underset{\text{for } D>2000}{\left|\frac{D-2000}{1000}\right|}$$

DISTANCE (ft)	REDUCTION (dBA)	DISTANCE (ft)	REDUCTION (dBA)	DISTANCE (ft)	REDUCTION (dBA)
50	0	237	13.5	1,100	27
53	0.5	251	14	1,150	27.5
56	1	266	14.5	1,210	28
60	1.5	282	15	1,270	28.5
63	2	299	15.5	1,330	29
67	2.5	316	16	1,400	29.5
71	3	335	16.5	1,470	30
75	3.5	355	17	1,540	30.5
79	4	376	17.5	1,610	31
84	4.5	398	18	1,690	31.5
89	5	422	18.5	1,770	32
94	5.5	447	19	1,850	32.5
100	6	473	19.5	1,930	33
106	6.5	500	20	2,010	33.5
112	7	531	20.5	2,090	34
119	7.5	562	21	2,170	34.5
126	8	596	21.5	2,250	35
133	8.5	631	22	2,330	35.5
141	9	668	22.5	2,420	36
150	9.5	708	23	2,510	36.5
158	10	750	23.5	2,600	37
168	10.5	794	24	2,690	37.5
178	11	841	24.5	2,780	38
188	11.5	891	25	2,870	38.5
200	12	944	25.5	2,960	39
211	12.5	1,000	26	3,050	39.5
224	13	1,050	26.5	3,140	40

TABLE 1.4

REDUCTION OF A-SCALE SOUND LEVEL AT VARIOUS DISTANCES FROM A VEHICULAR "LINE SOURCE," RELATIVE TO 50 FT DISTANCE, USING THE DROP-OFF RATE OF 3.0 dBA PER DOUBLE DISTANCE

$$\text{dBA REDUCTION} = 10 \text{ LOG } \frac{D}{50} + \underbrace{\left|\frac{D-1000}{1000}\right|}_{\substack{\text{for}\\ D>1000}} + \underbrace{\left|\frac{D-2000}{1000}\right|}_{\substack{\text{for}\\ D>2000}}$$

DISTANCE (ft)	REDUCTION (dBA)	DISTANCE (ft)	REDUCTION (dBA)	DISTANCE (ft)	REDUCTION (dBA)
50	0	398	9	2,340	18.5
56	0.5	447	9.5	2,480	19
63	1	500	10	2,630	19.5
71	1.5	562	10.5	2,780	20
79	2	631	11	2,930	20.5
89	2.5	708	11.5	3,080	21
100	3	794	12	3,230	21.5
112	3.5	891	12.5	3,380	22
126	4	1,000	13	3,530	22.5
141	4.5	1,100	13.5	3,690	23
158	5	1,200	14	3,850	23.5
178	5.5	1,310	14.5	4,010	24
200	6	1,420	15	4,170	24.5
224	6.5	1,540	15.5	4,330	25
251	7	1,660	16	4,490	25.5
282	7.5	1,790	16.5	4,660	26
316	8	1,920	17	4,830	26.5
355	8.5	2,060	17.5	5,000	27
		2,200	18		

TABLE 1.5

REDUCTION OF A-SCALE SOUND LEVEL AT VARIOUS DISTANCES FROM A VEHICULAR "LINE SOURCE," RELATIVE TO 50 FT DISTANCE, USING THE DROP-OFF RATE OF 4.5 dBA PER DOUBLE DISTANCE

$$\text{dBA REDUCTION} = 15 \text{ LOG } \frac{D}{50} + \underbrace{\left|\frac{D-1000}{1000}\right|}_{\text{for } D>1000} + \underbrace{\left|\frac{D-2000}{1000}\right|}_{\text{for } D>2000}$$

DISTANCE (ft)	REDUCTION (dBA)	DISTANCE (ft)	REDUCTION (dBA)	DISTANCE (ft)	REDUCTION (dBA)
50	0	316	12	1,670	23.5
54	0.5	339	12.5	1,770	24
58	1	367	13	1,880	24.5
63	1.5	397	13.5	2,000	25
68	2	428	14	2,090	25.5
74	2.5	463	14.5	2,190	26
80	3	499	15	2,290	26.5
86	3.5	538	15.5	2,400	27
93	4	582	16	2,500	27.5
100	4.5	629	16.5	2,610	28
108	5	676	17	2,720	28.5
117	5.5	731	17.5	2,840	29
126	6	790	18	2,960	29.5
136	6.5	847	18.5	3,080	30
147	7	922	19	3,200	30.5
158	7.5	998	19.5	3,330	31
170	8	1,070	20	3,460	31.5
184	8.5	1,140	20.5	3,590	32
199	9	1,215	21	3,730	32.5
215	9.5	1,290	21.5	3,860	33
233	10	1,380	22	3,990	33.5
251	10.5	1,470	22.5	4,130	34
270	11	1,570	23	4,270	34.5
292	11.5			4,410	35

TABLE 1.6

NOISE REDUCTION PROVIDED BY A BUILDING (FROM PPM 90-2)

BUILDING TYPE	WINDOW CONDITION	NOISE REDUCTION DUE TO BUILDING STRUCTURE (dBA)
All	Open	10*
Light Frame	Ordinary Sash	
	Closed	20
	With Storm Windows	25
Masonry	Single Glazed	25
	Double Glazed	35

*APPROXIMATE NOISE REDUCTION OF EXTERIOR WALL HAVING VARIOUS OPEN-WINDOW AREAS (This portion not in PPM 90-2)

PERCENT OF EXTERIOR WALL HAVING OPEN WINDOWS	APPROXIMATE NOISE REDUCTION
1%	17 dBA
2%	14 dBA
4%	11 dBA
8%	8 dBA
16%	5 dBA
32%	2 dBA
50%	0 dBA

TABLE 1.7

A. MAXIMUM L_{50} A-SCALE NOISE LEVELS THAT WILL PERMIT ACCEPTABLE SPEECH COMMUNICATION FOR VOICE LEVELS AND LISTENER DISTANCES SHOWN

DISTANCE (ft)	VOICE LEVEL*			
	LOW	NORMAL	RAISED	VERY LOUD
1	60 dBA	66 dBA	72 dBA	78 dBA
2	54 dBA	60 dBA	66 dBA	72 dBA
3	50 dBA	56 dBA	62 dBA	68 dBA
4	48 dBA	54 dBA	60 dBA	66 dBA
5	46 dBA	52 dBA	58 dBA	64 dBA
6	44 dBA	50 dBA	56 dBA	62 dBA
12	38 dBA	44 dBA	50 dBA	56 dBA

B. MAXIMUM L_{10} A-SCALE NOISE LEVELS THAT WILL PERMIT BARELY ACCEPTABLE SPEECH COMMUNICATION FOR VOICE LEVELS AND LISTENER DISTANCES SHOWN

DISTANCE (ft)	VOICE LEVEL*			
	LOW	NORMAL	RAISED	VERY LOUD
1	66 dBA	72 dBA	78 dBA	84 dBA
2	60 dBA	66 dBA	72 dBA	78 dBA
3	56 dBA	62 dBA	68 dBA	74 dBA
4	54 dBA	60 dBA	66 dBA	72 dBA
5	52 dBA	58 dBA	64 dBA	70 dBA
6	50 dBA	56 dBA	62 dBA	68 dBA
12	44 dBA	50 dBA	56 dBA	62 dBA

*Based on men's voices, standing face-to-face outdoors.

TABLE 1.8
QUALITY OF TELEPHONE USAGE IN THE PRESENCE OF STEADY-STATE INTERFERING NOISE

NOISE LEVEL (dBA)	TELEPHONE USAGE
30-50	Satisfactory
50-65	Slightly Difficult
65-75	Difficult
Above 75	Unsatisfactory

TABLE 1.9
RECOMMENDED DESIGN CRITERIA AS TAKEN FROM NCHRP REPORT 117

OBSERVER			L_{50} (dBA)		L_{10} (dBA)	
CATEGORY	STRUCTURE	LOCATION	DAY	NIGHT	DAY	NIGHT
1	Residences	Inside*	45	40	51	46
2	Residences	Outside*	50	45	56	51
3	Schools	Inside*	40	40	46	46
4	Schools	Outside*	55	--	61	--
5	Churches	Inside	35	35	41	41
6	Hospitals,	Inside	40	35	46	41
7	convalescent homes	Outside	50	45	56	51
8	Offices:					
	Stenographic	Inside	50	50	56	56
	Private	Inside	40	40	46	46
9	Theaters:					
	Movies	Inside	40	40	46	46
	Legitimate	Inside	30	30	36	36
10	Hotels, motels	Inside	50	45	56	51

*Either inside or outside design criteria can be used, depending on the utility being evaluated.

TABLE 1.10
DESIGN NOISE LEVELS AND LAND USE RELATIONSHIPS SPECIFIED IN PPM 90-2 (TABLE 1 OF APPENDIX B)

LAND USE CATEGORY	DESIGN NOISE LEVEL - L_{10}	DESCRIPTION OF LAND USE CATEGORY
A	60 dBA (Exterior)	Tracts of lands in which serenity and quiet are of extraordinary significance and serve an important and public need, and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose. Such areas could include amphitheaters, particular parks or portions of parks, or open spaces which are dedicated or recognized by appropriate local officials for activities requiring special qualities of serenity and quiet.
B	70 dBA (Exterior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, picnic areas, recreation areas, playgrounds, active sports areas, and parks.
C	75 dBA (Exterior)	Developed lands, properties or activities not included in categories A and B above.
D	--	For requirements on undeveloped lands see paragraphs 5a(5) and (6), this PPM.
E*	55 dBA (Interior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.

* See Paragraph 1c of Appendix B of PPM 90-2 for method of application. Partial quotation from Paragraph 1c: "The interior design noise level in Category E applies to indoor activities for those situations where no exterior noise sensitive land use or activity is identified."

CHAPTER 1 HOMEWORK PROBLEMS

1. Determine the sum of the following sound levels by "decibel addition" to an accuracy of ± 1 dB:

a. 86 dB
89 dB
72 dB
77 dB

Ans. 91 dB

b. 81 dB
81 dB
81 dB

86 dB

c. 90 dB
76 dB
78 dB
80 dB

91 dB

2. Determine the sum of the following sound levels by "decibel addition" to an accuracy of ± 1/2 dB:

a. 81 dB
78 dB
73 dB

Ans. 83 dB

b. 76 dB
59 dB
35 dB
69 dB
73 dB

78 dB

c. 89 dB
89 dB
89 dB

94 dB

3. Determine the sum of the following sound levels by decibel "addition" to an accuracy of ± .1 dB. Check the answer by comparing with the sum obtained by using both parts of Table 1.1.

a. 88 dB
92 dB
90 dB
84 dB

Ans. 95.4 dB (± .1)
95.5 dB (± 1/2)
96 dB (± 1)

b. 75 dB
75 dB
75 dB

80.1 dB
80 dB
80 dB

c. 81 dB
86 dB
73 dB
90 dB

_____ dB
_____ dB
_____ dB

4. Suppose the noise level from one noise source (assume a "point source") is 56 dB at a certain distance away. Now, suppose that 16 of those same noise sources were turned on at the same location as the first source. What noise level would you expect at the same distance away?

Ans. 68 dB

5. Suppose highway traffic produces an average noise level of 64 dB at a certain position from the road for a traffic flow of 2000 vehicles per hour. What noise level could be expected for the various rates of flow listed below, assuming the same general type of traffic?

Ans. 5000 vehicles per hour ________ dB

1800 vehicles per hour ________ dB

600 vehicles per hour ________ dB

6. Suppose the octave band sound pressure levels of an auto horn are as listed below. Find the overall sound level and the A-scale sound level for the horn (± 1 dB accuracy is adequate)

Octave Frequency Band (Hz)	Sound Pressure Level (dB)
63	44
125	58
250	70
500	78
1000	86
2000	81
4000	72
8000	56

Ans. _____ dB overall, _____ dBA

7. Suppose the octave band sound pressure levels of a truck are as listed below. Find the overall sound level and the A-scale sound level for the truck (± 1 dB accuracy is adequate).

Octave Frequency Band (Hz)	Sound Pressure Level (dB)
31	74
63	90
125	89
250	84
500	82
1000	80
2000	74
4000	72
8000	65

Ans. _____ dB overall, _____ dBA

8. Suppose the A-scale sound level of a barking dog is about 76 dBA. Make a guess at the overall sound level of the barking dog.

Ans. _____ dB overall

9. Suppose the A-scale sound level of a large propeller-driven commercial aircraft is about 76 dBA. Make a guess at the overall sound level of the aircraft.

Ans. _____ dB overall

10. A building located near a road is 22 ft high. How high is this building in terms of wavelengths of sound?

at 50 Hz Ans. _____ (wavelength)

at 500 Hz _____

at 5000 Hz _____

11. Suppose a single automobile produces a sound level of 65 dBA at 50 ft distance. What would its sound level be at the following distances, assuming good sound propagating atmospheric conditions?

at 200 ft Ans. _____ dBA

at 500 ft _____ dBA

at 1000 ft _____ dBA

at 2000 ft _____ dBA

12. Suppose the noise level of a passing truck is found to be 80 dBA when measured at a distance of 100 ft. What would be the A-scale sound level of that truck at 50 ft distance?

Ans. _____ dBA

13. Suppose the sound level of a bus is found to be 76 dBA at 160 ft distance. What would be its A-scale sound level at 800 ft distance?

Ans. _____ dBA

14. A continuous flow of traffic is found to produce an average noise level of 80 dBA at the reference 50 ft distance. For a drop-off rate of 4.5 dBA/DD, what average A-scale sound level would be expected at 800 ft distance? What sound level would be expected for a 3 dBA/DD drop-off rate?

Ans. _____ dBA for 4.5 dBA/DD

_____ dBA for 3 dBA/DD

15. Suppose a continuous flow of traffic produces an average noise level of 72 dBA in the backyards of a row of houses having unobstructed view of the roadway. The distance from the yards to the center of the main traffic lane is 125 ft. The houses average 60-70 ft width and they are located on 100-ft width lots. What average noise level might be expected at a 400 ft distance from the roadway, with the row of houses acting as a partial barrier. Use Table 1.4 for "cylindrical spreading" of sound, i.e. 3 dBA drop-off/double distance.

Ans. _____ dBA

16. Estimate the A-scale noise reduction provided by a solid barrier wall for noise from a single source for the dimensions: $R = 60$, $D = 200$, $H = 4$

Ans. _____ dBA

17. Suppose the average noise level produced at a 400 ft distance from an existing highway is about 72 dBA. The highway now handles about 1200 vehicles per hour. Following a proposed improvement program, it is expected that the highway traffic will increase to 3200 vehicles per hour. Assuming 3 dBA drop-off per double distance, at what distance from the improved highway will the 72 dBA level apply.

Ans. _____ ft

18. A school building is located 300 ft from a highway and has unobstructed view of the nearest several hundred feet of the roadway. Typical truck passages produce peak levels of about 70-75 dBA and steady-state auto noise produces average levels of about 60-63 dBA just outside the school building. Will this noise interfere with normal classroom speech communication if the classroom windows are open? Ans. _____. Can normal classroom speech communication take place if the classroom windows are closed? Ans. _____.

19. If the L_{10} noise level of Problem 18 is approximately 72 dBA outside the school, will the classroom meet the exterior and interior Design Noise Levels given in PPM 90-2?

Ans. no (exterior)

69 no (interior, windows open)

55 yes (interior, windows closed)

20. A large number of residences located at 250 ft distance along an existing highway now receive average nighttime noise levels of 68 dBA. Future traffic is expected to quadruple the present traffic. The present neighbors are already unhappy with the 68 dBA noise levels. The future noise will expose still more people to 68 dBA or higher. If nothing is done about the increased noise, how far from the road will the 68 dBA levels be heard for the increased traffic condition, assuming 3 dBA/DD drop-off and assuming that the houses are far enough apart that they do not provide any appreciable barrier effect.

Ans. ______ ft

CHAPTER 2

TRAFFIC NOISE SOURCES

In this chapter, noise level data are given for typical single automobiles and trucks, including the factors that influence noise output: speed, acceleration, grade, and roadway surface. The three major components of vehicular noise (engine noise, exhaust noise, and tire noise) and their height above the road surface are also discussed. Then, it is shown that traffic quantity and distance to the roadway influence both the noise levels and the variation in noise levels as heard at an observer position near the road.

The radiated noise from a highway is characterized statistically by the median noise level (L_{50}) and by an indicator of the degree of fluctuations in the noise level (L_{10}-L_{50}). These levels in combination provide a means for describing highway noise as heard and judged by the highway neighbor. In a very general sense, the L_{50} noise level is a statistical value that is somewhat representative of near-average noise and the L_{10} noise level is a statistical value that is somewhat representative of near-peak noise. It has been determined that noises with large variations in level are considered more disagreeable than noises of fairly constant level. Since the (L_{10}-L_{50}) value represents a statistical measure of the degree of noise level fluctuations, it becomes an indicator of the potential annoyance of the noise. For noises with considerable variation in level, the L_{10} value will be higher than the L_{50} value by several decibels, and the (L_{10}-L_{50}) value will be relatively large. Highway traffic that consists of a fairly steady flow of automobiles, but interspersed with occasional trucks, may produce relatively large values of (L_{10}-L_{50}). In this case, the trucks essentially produce the near-peak L_{10} values while the autos produce the near-average L_{50} values. The trucks are clearly identifiable because their noise stands out in sharp contrast above the lower steady-state noise of the automobiles.

On the other hand, when the (L_{10}-L_{50}) value is quite low, it means that the noise levels of the peak events (L_{10}) are comparable to the noise levels of the steady-state flow (L_{50}). Under these conditions, the discrete truck passages are not so noticeable, and the total noise may not be considered as objectionable (relative to situations having comparable values of L_{50} but higher values of L_{10}-L_{50}). Thus, both the L_{10} and the (L_{10}-L_{50}) values are important in evaluating the total impact of highway noise and noise control. In this chapter, the L_{10} and L_{50} levels are introduced by considering idealized lines of moving vehicles and by noting the influence of traffic quantity and observer distance on the L_{10} and L_{50} noise levels and noise level differences.

2.1 NOISE EMISSION LEVEL

In Chapter 1 it is indicated that 50 ft is the measurement distance used for many traffic noise measurements and that 50 ft is used as a reference distance from which noise levels can be extrapolated to other distances. For example, Tables 1.3, 1.4 and 1.5 provide noise level reductions starting from the 50 ft reference distance. This distance is in general use as the reference distance for highway noise evaluations. Hence, the A-scale noise level of a vehicle at this reference 50 ft distance is defined as the "Noise Emission Level." This term and the 50-ft reference distance will be used in this text, unless specifically stated otherwise.

2.2 NOISE EMISSION LEVEL OF AUTOMOBILES

The noise emission level (dBA at 50 ft distance) of a typical passenger automobile on an average roadway surface is found in NCHRP Report 78 to be

$$L_{auto} = 16 + 30 \log V$$

where V is the auto speed in miles per hour (mph). This yields the following sound levels (rounded off to the nearest integer over a range of typical speeds:

at 30 mph	60 dBA
40 mph	64 dBA
50 mph	67 dBA
60 mph	69 dBA
70 mph	71 dBA

The octave band frequency spectrum of this typical automobile is shown by the solid curve of Figure 2.1 for the conditions of 50 ft distance and 50 mph. The spectrum *shape* does not vary significantly for the speed range of 35-65 mph, although, of course, the noise level changes with speed as indicated. The spectrum *shape* does change slightly as a function of road surface.

If the total noise of the typical auto (the solid curve of Figure 2.1) were passed through the A-scale filter of a sound level meter, the resulting octave band contributions would be as shown by the dashed curve of Figure 2.1. This dashed curve then shows approximately the relative importance of the various octave bands in terms of their contributions toward the loudness or disturbance of the noise to people. It is seen that the center frequency region of 500-2000 Hz is the strongest contributor in terms of A-scale readings.

In NCHRP Report 78, it is also found that the condition of the road surface makes a difference in the noise level radiated by automobiles at the higher speeds where tire noise becomes the dominant noise. Very rough, course-grain road surfaces produce higher noise levels, up to 5 dBA above "average" road surfaces; and very smooth, fine-grain road surfaces produce lower noise levels, as much as 5 dBA below "average" road surfaces. In addition, since tire noise is predominantly high frequency noise, very smooth road surfaces cause slightly less high frequency noise and very rough road surfaces cause slightly larger amounts of high frequency noise compared to the generalized spectrum of Figure 2.1. These effects of road surface apply to automobiles, which are typically equipped with rib-type tire treads. These variations should not be presumed here to apply also to truck noise.

At conditions of high acceleration, automobiles make increased noise. NCHRP Report 78 presents limited data on this effect. At 35 mph, for maximum acceleration, a small group of automobiles was found to produce approximately 8 dBA higher noise levels than for normal cruise condition at that same speed. This would be significant for ramp approaches to main highways, where high acceleration is required to enter the high speed traffic lanes.

An extensive noise measurement program on traffic noise has been carried out and reported* by N. Olson of the National Research Council of Canada. Olson's data are used extensively in the TSC Computer Program. His findings on passenger automobiles are summarized in Figure 2.2. The spectrum *shape* changes only slightly over the speed range of 30-69 mph. The sound level change with speed appears to be about 3 dB/10 mph going from 35 to 45 mph, 4.5 dB/10 mph going from 45 to 55 mph, and 1.5 dB/10 mph going from 55 to 65 mph. The distribution of automobile types in this Canadian study would be approximately the same as a typical cross-section of automobiles in the U. S. The large number of autos measured (1010) makes it possible to quote significant statistical data for the sample. The standard deviation for Olson's data is approximately 2.5 dBA. This suggests that about 68% of any random sampling of autos will fall within ±2.5 dB of the average level and that about 32% of the sample will fall outside this range. Further, approximately 95% of the autos sampled will have noise levels within 2 standard deviations, or ±5 dB, of the average level.

The automobile noise spectra used in the TSC Computer Program are given in Figure 2.3 for speeds of 30 mph and 70 mph. These curves are similar to Olson's curves, with the exception that the TSC 30 mph curve is 2-4 dB below Olson's 30-39 mph curve and the TSC 70 mph curve is 1-3 dB above Olson's 60-69 mph curve. The TSC curves, for 50 ft distance, yield A-scale values of 61 dBA and 75 dBA, respectively for the two speeds. An equation for auto noise given in Appendix A of the TSC Report† reduces to the following version for any speed V in mph:

$$L_{auto} = 5 + 38 \log V.$$

[Note that 38 log V = 3.8 x 10 log V, and that the 10 log V values can be obtained in Table 1.2.]

This produces the following noise levels (rounded off to the nearest integer) for a range of typical speeds:

at 30 mph	61 dBA
40 mph	66 dBA
50 mph	70 dBA
60 mph	73 dBA
70 mph	75 dBA.

These may be compared with the values given earlier in this Section as taken from NCHRP Report 78. It is seen that the TSC values range 1-4 dBA above the NCHRP values over the low to high speeds. Olson's values of standard deviation are used in the TSC approach, and may be assumed as representative for any current population of automobiles on U. S. roads.

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*"Statistical Study of Traffic Noise", Report APS-476 (1970), National Research Council, Ottawa, Canada; also summarized in the paper "Survey of Motor Vehicle Noise", N. Olson, Journal of the Acoustical Society of America, Vol. 52, No. 5, pp. 1291-1306 (November 1972).

†Identified in the footnote on page 1-11.

All known comprehensive studies of auto traffic noise show that tire noise becomes a dominant source at high speed. NCHRP Report 78 contains data on the influence of road surface on the tire noise, as mentioned briefly earlier in this Section. In turn, NCHRP Report 117 suggests a road surface adjustment as follows:

Surface Type	Description	Adjustment
Smooth	Very smooth, seal-coated asphalt	-5 dBA
Normal	Moderately rough asphalt and concrete	0 dBA
Rough	Rough asphalt with large voids 1/2 in. or larger; also grooved concrete	+5 dBA

There is no standard for rating roadway surface roughness or smoothness, but it is seen here that for auto noise the surface smoothness can be a small factor in noise control design. It is left to the discretion of the user to apply an adjustment, where appropriate, but it is questionable that a -5 dBA adjustment should ever be used. For very smooth surfaces, some truck tires become excessively noisy (to be discussed later); and a surface that is smooth enough to justify a -5 dBA adjustment for auto noise would likely be too smooth (or slippery when wet) to be safe. Thus, the following range of adjustments are considered acceptable, if the user can make the correct selection:

Adjustment of auto noise to reflect road surface:

Surface Description	Add to Auto Noise Level
Very rough surface	+5 dBA
Medium rough surface	+2 dBA
Average surface	0 dBA
Medium smooth surface	-2 dBA

It is cautioned that a judgement of road surface condition should not be based solely on how it "sounds" to the occupant inside a car when the road is driven on. Small changes in surface texture can yield significant changes in the "rumble" heard inside the car. Noise heard inside the car is due to structure-borne noise transmitted through the auto's suspension system, which essentially transmits low frequency noise or vibration quite well and hence gives an exaggerated low frequency level. This is not necessarily related to the amount of high frequency sound radiated externally by the tires. In no case should a -5 dBA adjustment be used merely because the road *sounds* smooth to the occupant inside his auto.

2.3 NOISE EMISSION LEVEL OF TRUCKS

NCHRP Report 117 and some of its references provide a rather detailed summary of diesel truck noise as a function of speed, engine power and muffler configuration. Olson's study also contains a large quantity of noise data on truck noise. In addition, several studies have been carried out on truck tire noise. All of this material will be reviewed here briefly.

Total truck noise is made up of three major sources: engine noise, engine exhaust noise, and tire noise. Each of these sources is strong enough that it must always be considered as a potential contribution to the total noise. For example, engine noise alone (exclusive of the exhaust noise) probably falls in the range of 75-85 dBA (at 50 ft distance); engine exhaust noise probably falls in the range of 90-100 dBA (at 50 ft) without mufflers or in the range of 80-90 dBA with good stock mufflers; and finally, tire noise is very dependent on tire tread and speed and can range somewhat predictably over the full range of 70-95 dBA. For any particular truck taken at random, any one of these noise sources might dominate, or a mixture of all three could contribute to the total. Figure 2.4 shows a hypothetical example of how the three sources could combine to produce a typical truck spectrum shape as well as a fairly realistic total level of 82 dBA. With three such strong sources present, it is not surprising that trucks are not readily quieted. The components shown in Figure 2.4 are listed here:

Tires	77 dBA
Exhaust	79 dBA
Engine	75 dBA
Total	82 dBA

Now, suppose an improved muffler could reduce engine exhaust noise by 6 dBA:

Tires	77 dBA
Exhaust	73 dBA
Engine	75 dBA
Total	80 dBA

Only a 2 dBA reduction is achieved in total noise. Suppose the exhaust were not quieted, but that a quieter tread could achieve a 6 dBA quieting of tire noise. Then:

Tires	71 dBA
Exhaust	79 dBA
Engine	75 dBA
Total	81 dBA

For this effort, only 1 dBA reduction is achieved in the total noise.

This example serves to illustrate the necessity for an all-out attack on all three major noise components, if a large reduction is to be obtained. This does not suggest, however, that we should take a resigned attitude about the problem because it seems difficult to solve. Good mufflers exist and quiet tire treads exist; it is important to continue to strive for the use of these quieter products in everyday truck operations. Figure 2.5 is a schematic representation of these typical noise sources, showing that they occur at different locations. Their height above the road surface will be discussed in more detail later.

The generalized truck spectrum developed in NCHRP Report 78 and used in NCHRP Report 117 is shown in Figure 2.6. This is based on a collection of noise data taken by Bolt Beranek and Newman Inc., Los Angeles, when a number of controlled trucks were driven beside a known test set-up at specified speeds. The tests were conducted on level roads, and on up-grade and down-grade roads. Various mufflers and engines were included in the tests, and some tests were checked on dynamometer stands. Full acceleration runs and coasting down-hill runs were also measured. Several trucks were also recorded on level and up-grade runs under normal freeway operation, without the drivers knowing they were being tested. The mean spectrum of 26 diesel trucks on a level roadway was selected for use in NCHRP Reports 78 and 117. This mean gives an A-scale level of 82 dBA. In the tests, it was found that noise output increased with up-hill grades, and, so, a noise adjustment was included:

Adjustment for Increased Noise Level of Trucks on Gradients

Gradient %	Adjustment dBA
≤ 2	0
3 to 4	+2
5 to 6	+3
≥ 7	+5

It was also found that during high acceleration, truck noise may be about 6 dBA above the noise at normal cruise condition. In general, no significant change of noise with speed was reported.

Olson's measurements of tractor trailer units are summarized in Figure 2.7. In this group, for speeds in the range of 50-69 mph, average noise levels are in the vicinity of 85 to 88 dBA, and a small but significant noise level change with speed is seen. Olson also measured noise levels of a large number of various kinds of heavy trucks during acceleration from a traffic light, although it is not clear that there was any particularly high power used during acceleration. For several tractor trailers the average noise level was 81.9 dBA during acceleration, which would represent noise comparable to that at cruising speeds of about 35-45 mph.

The truck spectrum used in the TSC Computer Program is shown in Figure 2.8. The solid curve is the complete spectrum and the dashed line is the spectrum as it would appear when passed through the A-scale filter. This average curve yields an A-scale sound level of 87 dBA, and in the TSC Computer Program it is used for all highway speeds. The standard deviation for the truck data, based on the Olson collection, is 3.5 dBA. Neither the Olson data nor the TSC Program applys a noise adjustment for up-grade roadways.

In several recent extensive studies of truck noise for various projects in the United States, BBN personnel have found basic agreement with Olson's data. Statistical averages of the noise of many over-the-road highway trucks give support to 86 and 87 dBA values.

A comparison of the basic 82 dBA value plus grade adjustments used in the NCHRP Report 117 procedure and the 87 dBA value with no grade or speed adjustment for the TSC approach suggests a difference in noise data, yet there is some degree of compatibility between them. There is the possibility that the drive-by tests in the BBN-California measurements contained in the NCHRP reports involved truck-driver situations in which the controlled trucks were just maintaining the desired speeds for the drive-bys and the drivers were not actually following normal highway practice of "trying to get there" in a hurry. This could result in lower throttle settings, lower power levels, and less attempt at pressing for higher speed, all resulting in lower noise. Under actual intentional acceleration tests and normal up-grade climbs, higher power was used and the resulting increase in noise levels agrees quite well with Olson's data for his normal powered runs at speeds of 50-59 and 60-69 mph, with no changes reported for grades or high-power accelerations. This may not serve as a complete explanation of the differences in the data, for some of this does involve some conjecture on details not known about the California tests. However, with this attempt at explanation, the data are seen to work toward each other and possibly the differences become quite small for the runs of trucks operating under high powered conditions and with a time schedule and an objective to meet.

2.4 TRUCK NOISE COMPONENTS

In the introductory paragraphs of Section 2.3, a broad range of possible noise levels is given for each of the three major noise sources. It is of interest to review available data on these sources, where they can be separated or partially separated from the other sources usually present.

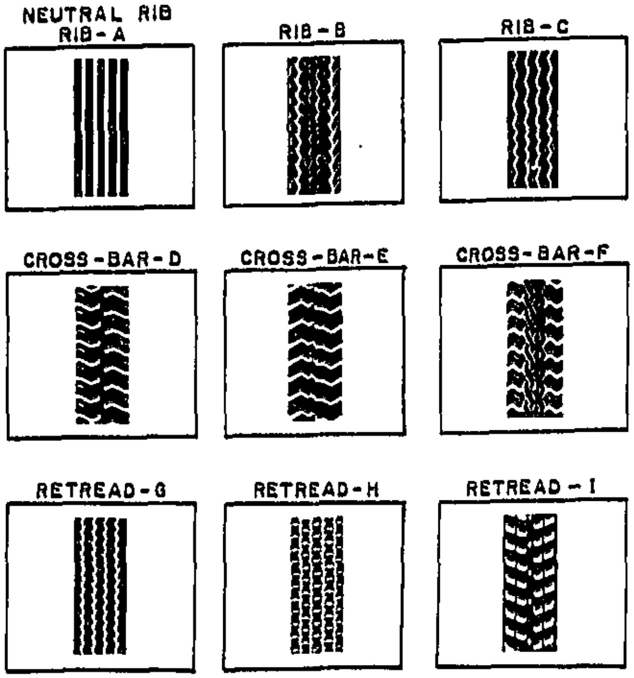
a. Tire Noise

Tire noise has been studied fairly extensively with rather conclusive results. The

National Bureau of Standards has conducted a valuable study* on truck tire noise. A brief summary is included here. Sketch 2.1 shows the "footprints" of nine tire treads tested on two test vehicles in drive-by tests over a speed range of about 30-60 mph. Prior to each measurement portion of the test, the truck was brought up to the desired speed. Then, just before entering the noise measurement road section, the truck engine was turned off and the vehicle coasted through the 1000-ft length test section. A series of photosensors was used to determine the truck speed at several points during the coast-down, and a series of microphones was used to record the noise radiated by the tires. Two road surfaces were included in the tests which were carried out on a research runway at the NASA Wallops Island, Virginia airfield: one was of smooth concrete finish, and the other was of "textured asphalt". The table that follows summarizes the test findings for the single-chassis vehicle fitted with test tires on the four rear drive wheels (one drive axle, dual tires each side). For all these tests, each drive tire was supporting a load of approximately 4400 lbs, the vehicle speed was approximately 55 mph (coasting), and the data are quoted for the 50 ft microphone. All tires were essentially new at the beginning, following a suitable break-in and warm-up sequence, and some tires were also tested after their treads had been worn down (by real-life over-the-road wear) to "half-worn" and "fully-worn" condition.

The front tires of the truck were of Rib A tread, the quietest tread, so that the rear tires would represent the major source of noise. Noise levels are in dBA.

Tread Type	Road Surface	New Tread	Half-Worn	Fully Worn
A	Concrete	73		
	Asphalt	75		
B	Concrete	77	81	
	Asphalt	77	79	
C	Concrete	76		
	Asphalt	77		
D	Concrete	84	91	87
	Asphalt	83	86	85
E	Concrete	84		
	Asphalt	82		
F	Concrete	81	88	
	Asphalt	81	86	
G	Concrete	73		
	Asphalt	75		
H	Concrete	81	86	86
	Asphalt	82		
I	Concrete	96	94	
	Asphalt	88	90	



SKETCH 2.1

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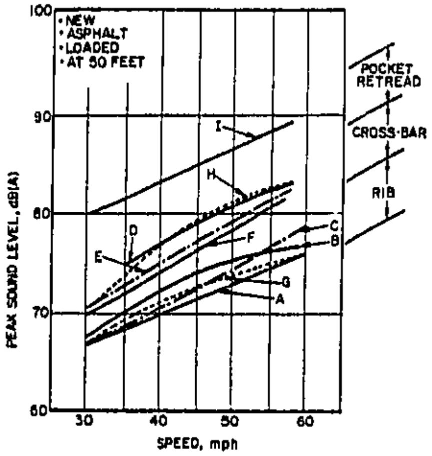
*"Truck Noise--I, Peak A-Weighted Sound Levels due to Truck Tires," Report OST-ONA 71-9, dated September 1970, prepared for the Department of Transportation by the National Bureau of Standards.

Note that Treads A, B, C, and G are rib-type, Treads D, E, F, and H are cross-bar-type, and Tread I is a "pocket design" tread. The four rib-type treads, when new, produced noise levels within the range of 73-77 dBA for both road surfaces. The four cross-bar treads, when new, produced noise levels within the range of 81-84 dBA for both road surfaces. For these rib and cross-bar designs, there was little consistent difference between the road surfaces. For the "pocket design" Tread I, the smooth concrete surface yielded a 96 dBA level and the textured asphalt yielded a level of 88 dBA.

In general, a quiet tread design is one in which the air inside the grooves of the tread can escape slowly as the tread blocks come into contact with the road surface. This is provided in the rib-type treads by the fact that the circumferential grooves in the surface always provide escape routes for the air. A noisy tread design is one in which the air is trapped or has difficulty in escaping as the air cavities move into contact with the road surface. The cross-bar design does not provide the ease of escape of the rib design, and the escape must take place much more rapidly as the tread block instantly makes its contact to the road surface. Of course, with the "pocket design" there is no escape path, and the air trapped and compressed inside the pocket literally "pops" out when an escape route first appears. The coarse-grain textured asphalt provides better escape paths than the smooth concrete, so the asphalt surface yields a lower noise level than the concrete for the pocket design tread.

As the tire becomes half-worn, the air escape passages become smaller, so the noise generally increases. When the tire becomes nearly fully worn, there is less air to be trapped in the grooves, so the noise begins to decrease again.

The tire noise data summarized in the table above represents a single speed of approximately 55 mph for all treads, whereas the complete series of tests includes speeds over the range of about 30-60 mph. Sketch 2.2 shows a brief summary of the noise level change with speed for the various new treads (letters identify the treads shown in Sketch 2.1) traveling on the asphalt road surface under the tire load condition mentioned above (4400 lb per tire). It is reasonably apparent from Sketch 2.2 that rib-tread tires would be the quietest and that they probably would not dominate truck noise at high speed, based on the 82-87 dBA levels for the total noise of trucks in highway operation. However, it seems highly probable that many cross-bar treads (especially when half-worn) could prove to be dominant noise sources at highway speeds of 60-70 mph. Of course, the "pocket" retread would be a "screamer" on the highways. The Bureau of Standards report states that the nine treads tested represent 70-80% of the total truck tire population in use on the road today. Cross-bar tires are generally used on drive wheels for better traction, and rib-type tires are generally used on front wheels for better steering.



SKETCH 2.2

A somewhat similar study was carried out at General Motors and reported by Tetlow[*]. The findings also show greater noise from cross-bar treads, greater noise as the tires become worn, increasing noise with increasing speed; and the pocket design retread is the outstandingly noisy tread. The Tetlow paper also shows that the half-worn cross-bar tires of his tests produced higher A-scale noise at speeds above 55-60 mph than was produced by the truck engine that was used.

b. Engine Noise and Engine Exhaust Noise

In an earlier study[†] of diesel engine noise for the Corps of Engineers of the Department of the Army, Laymon Miller obtained and analyzed data for approximately 50 diesel and natural gas reciprocating engines covering a power range of about 150-6000 hp. Fourteen of the tested engines fell in the rated power range of 225-600 hp. From the entire collection of data, sound *power* level data were derived and a procedure was generated for estimating the noise of (a) the engine casing, (b) the unmuffled engine exhaust, and (c) the air intake to the engine.

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[*] "Truck Tire Noise," Derek Tetlow, Sound and Vibration, August 1971.

[†] "Power Plant Acoustics," Technical Manual TM 5-805-9, December 1968; prepared for the Department of the Army by Bolt Beranek and Newman Inc.

From that procedure it is possible to estimate the octave band noise levels and then the A-scale levels at 50 ft distance for such a diesel engine. This has been done for an engine power in the range of 375-480 hp with the following results. An unhoused bare engine (excluding exhaust noise), free to radiate uniformly in all directions, has an estimated A-scale sound level of 84 dBA (with a standard deviation of about 2.5 dB) at 50 ft. The cowl cover of a truck engine may provide a small amount of sound energy absorption, but it is more likely that it modifies the directionality pattern of the engine noise. Thus, it would not be unreasonable to expect that the engine would have an average radiated noise toward the side of the road of about 78 to 82 dBA depending on the details of the engine cover. It was also found in the study that for reasonably constant engine speed, the noise did not change appreciably for various engine power settings less than the full rated power of the engine. Of course, all of these tests were for steady-state, stationary operation, so no data were recorded for conditions comparable to engine acceleration.

The estimated unmuffled engine exhaust noise for an engine in this size range (375-480 hp) is approximately 91 dBA for engines fitted with exhaust-driven turbochargers or 97 dBA for engines without turbochargers. A fairly poor grade of low-pressure-drop muffler would reduce these sound levels by 8-12 dBA and a fairly good muffler could reduce these levels by 16-20 dBA. Thus, depending on turbocharger and muffler, the exhaust noise radiated by a diesel truck engine could fall almost anywhere within the range of 75-100 dBA at 50 ft distance, including the spread due to the standard deviation.

An additional study of interest is contained in a report* by W.H. Close and R.M. Clarke of the Department of Transportation. In this study, 14 diesel trucks, borrowed from cooperating truck users, were given a series of noise tests including the SAE J366a acceleration test.† The test includes maximum vehicle acceleration to 35 mph within a 100-ft test course. For the 14 trucks, the average A-scale sound level was 87 dBA, with all trucks falling within the range of 83-90 dBA. The significance of the test is that perhaps this short acceleration run may give a noise level representative of high-speed highway operation. It is also probable that the noise radiated is due to engine and exhaust and does not include tire noise at this low speed.

c. Summary

Figure 2.9 summarizes a number of the findings mentioned above. The basic 82 dBA and 87 dBA values of the NCHRP and TSC procedures are shown independent of speed. However, several studies indicate a real dependence of noise on speed: the Olson data, the Bureau of Standards study on tire noise and the Tetlow study on tire noise. The Miller estimate of engine noise merely suggests that the engine is probably the quieter of the present three major noise sources, and the Miller estimate of unmuffled exhaust noise indicates a clear need for good mufflers on engine exhausts if any traffic noise control is to take place. In addition to the speed effect, the N.B.S. and Tetlow data emphasize the need for the truck and tire manufacturers to develop and use quieter tire treads than the present cross-bar and pocket-type treads.

The following brief summary is given for the benefit of the engineer using the NCHRP Report 117 noise evaluation procedure.

(1) The noise emission level of a diesel truck at normal cruise condition at highway speeds is 82 dBA.

(2) During acceleration and high power needs, diesel truck noise increases approximately 5 dBA over normal cruise conditions.

(3) For up-hill grades, truck noise increases as follows (relative to the basic 82 dBA value)

3-4% grade	+2 dBA
5-6% grade	+3 dBA
≥ 7% grade	+5 dBA

(4) Even though engine power may be somewhat reduced on down-hill grades, the tire noise remains a serious noise component. Therefore, noise should not be considered to decrease on down grades.

(5) Road surface condition should not be treated as a factor in truck noise. Very smooth roads and very rough roads should be avoided.

The following brief summary is given for the benefit of the engineer using the TSC Computer Program noise evaluation procedure.

(1) The noise emission level of a diesel truck at all speeds and for all grade conditions is 87 dBA.

(2) For off-highway use, these trucks may be assumed to have 82 dBA sound level.

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*"Truck Noise--II, Interior and Exterior A-Weighted Sound Levels of Typical Highway Trucks," Report OST-TST-72-2, July 1972, Department of Transportation.

†"Recommended Practice J366a - Exterior Sound Level for Heavy Trucks and Buses," Society of Automotive Engineers, Inc., 1971.

2.5 OTHER VEHICLES

Five categories of "other vehicles" are identified in NCHRP Report 78 as additional vehicular noise sources: motorcycles, sport cars, light trucks, large gasoline-engine trucks, and busses. Motorcycles and sport cars are generally noisier than conventional passenger automobiles, due to higher engine speeds and poorer standards in muffling and due to operational practices of their drivers. Light trucks are usually somewhat comparable to automobiles in terms of noise output. Large gasoline-engine trucks are generally quieter than diesel engines of equal size and performance. Buses seem comparatively noisy when heard at the downtown street corner, but on the highway they are much less noisy than diesel trucks as a result of better muffling and maintenance. Altogether, these "other vehicles" represent a relatively small quantity of the total traffic flow on main highways, and since their noise falls mostly within the range of auto and diesel truck noise, they are not separately identified and treated in highway noise evaluations. Rather, their noise is assumed to be contained within the total mix of highway noise generally associated with automobiles and diesel trucks.

For use in the analysis procedure, it is suggested that when the quantities of smaller trucks (say, under 10,000 lb gross weight) and buses are separately identified and known, that their total number be divided into two equal parts; one part should then be added to the automobile quantity and one part should be added to the truck quantity.

For local (off-highway) traffic problems, it may be necessary to have a better definition of the quantity, size, use, and noise of trucks serving the local streets.

2.6 HEIGHT OF VEHICULAR NOISE SOURCES

For purposes of calculating the effect of berms, walls and other barrier structures, it is necessary to know approximately the location of the noise source or sources. For automobiles, tire noise and engine exhaust noise are the major sources and these occur close to the road surface. For calculation purposes, all auto noise is assumed to be located at the surface of the highway.

There are three major components of truck noise: engine noise, exhaust noise, and tire noise. The relative strength of these three sources may vary from truck to truck, and no study has been completed that shows statistically the distribution of these sources in a large truck population. For the present, it is assumed that when no mufflers or poor mufflers are used, the major cause of truck noise is engine exhaust. When good mufflers are used, it may be generally assumed that all three potential noise components are present, although from truck to truck each component may play a strong or submerged role. In terms of frequency distribution, (a) muffled exhaust noise is usually strong in the 125 Hz band and its 63- and 250-Hz neighboring bands; (b) engine noise is broadband and extends across the full frequency spectrum, although it drops off systematically in the upper octave bands; and (c) tire noise, and especially tire "whine", is most noticeable in the upper octave bands (say 500—4000 Hz).

In terms of height, obviously, tire noise originates at the road surface and engine noise may be taken to be located about 3—4 ft above the road surface. Engine exhaust noise radiates from the end of the exhaust pipe, and this can vary from 2 ft above the ground for some trucks up to 8—11 ft above the ground for large transport trucks. For calculation purposes, it is suggested that truck noise be assumed to be located 8 ft above the road surface. This will yield a conservative barrier design for trucks with good mufflers and short stacks, but it will yield an inadequate barrier for trucks with poor muffling and tall stacks.

Some automobiles have aerodynamically induced "whistles" at medium and high speed, some truck engines radiate turbo-charger noise at their air intakes and some truck or trailer bodies radiated body noise due to rattling parts inside empty shells or due to body vibration excited by rough roads. These extraneous noises probably will not modify the L_{10} noise levels for highway traffic, but the identifiable sounds may add to the annoyance of the noise. For local (off-highway) traffic, these noises may be of concern.

For the sake of simplicity, all vehicular noise sources are assumed to be omnidirectional (noise radiated uniformly in all directions), although this is not entirely correct.

2.7 NOISE OF MOVING NOISE SOURCES

Figure 1.3 of Chapter 1 introduced the concept of the "inverse square law" drop-off of sound level with distance from a point source. Now, consider the same general geometry, but let the point source move from left to right along the dotted line (the source line). Consider first the sound level that will be produced at Observer Point A in Figure 1.3 (50 ft from the source line). Suppose, at the start, that the point source is off to the left at a distance of 1600 ft from Point 1. Assume that the point source still produces a sound level of 80 dBA at a 50 ft distance. (This level was selected as a somewhat arbitrary level of the right order of magnitude, but it need not be construed as the noise level of an average truck.) Table 1.3 of Chapter 1 gives the sound level reduction for various distances relative to the reference 50 ft distance. From Table

1.3 it is seen that a distance of 1600 ft will have a sound level reduction of about 31 dBA, relative to a 50 ft value. Thus, for that starting condition, the sound level at Point A would be approximately 80 - 31 = 49 dBA.

Now, let the point source move toward Point 1 a distance of 800 ft. The source is now 800 ft from Point A and the sound level, according to Table 1.3, would be 80 - 24 = 56 dBA at Point A. [Note the 7 dBA difference in coming from 1600 ft to 800 ft. Why is it not 6 dBA as the "inverse square law" states? Recall that air absorption and atmospheric effects add a small amount of excess attenuation for distances beyond 1000 ft.]

Next, let the point source move into a 400 ft distance from Point 1. The sound level at A then becomes 80 - 18 = 62 dBA. Then, move into 200 ft. The sound level at A becomes approximately 80 - 12 = 68 dBA. Continue this sequence until the moving point source arrives at Point 1 where it is 50 ft from the observer at A, and the sound level is 80 dBA. [Note: When the noise source gets near Point A, it is necessary to estimate the true distance — the hypotenuse of the right triangle — between the source and the receiver at Point A.]

As the source continues to move along the source line to the right of Point 1, the distance between the source and the receiver begins to increase, and the sound level drops off in the same manner as it had built up while approaching the receiver. This entire sequence is shown in Figure 2.10. Let the moving point source be a vehicle moving along a straight road that passes within 50 ft of the Observer Point A. As the vehicle approaches, the sound level builds up; when the vehicle gets to the point of closest approach, the sound level reaches its maximum; when the vehicle moves away, the sound level drops off.

Suppose a graphic level recorder is used to make a permanent record of this event. The trace on the recorder would appear generally similar to the trace shown on Figure 2.10, where the horizontal distance along the trace can be related to the distance of the vehicle from Point 1, and the vertical scale is the sound level produced by the vehicle. A second horizontal scale is shown below the distance scale on Figure 2.10; this lower scale is a time scale. Suppose the vehicle has a speed of 60 mph as it travels along the source line (60 mph = 88 ft/sec). Knowing the speed of the vehicle, or the speed of the advancing graphic level recorder trace, it is possible to construct the time scale shown. In this case, "0" time is taken to be the time at which the vehicle passes closest to Observer Point A; then 1-sec divisions are marked off to the right and to the left from that "0" reference time. For a vehicle speed of 60 mph, each second of time represents a distance interval of 88 ft. Thus, when the vehicle is 880 ft to the left of Point 1 (on Figure 2.10), this represents a time of 10 seconds before the vehicle reaches Point 1. When the vehicle has moved 880 ft to the right of Point 1, the corresponding time is 10 seconds after passing Point 1. Depending on the known data, either a distance or a time scale can be used.

To illustrate the determination of a typical point on the "noise trace" of Figure 2.10, suppose the vehicle is located along the source line (the road) at a point 150 ft before arriving at Point 1. This point is shown by an asterisk at 150 ft on the line source and also on the enlarged detail. When the vehicle is at the 150 ft position, it is actually 158 ft from Point A, the real point of interest where the noise record is being made. According to Table 1.3 (for a point source), the sound level reduction at 158 ft is 10 dBA below the reference value of 80 dBA at 50 ft distance. Thus, the noise trace would show a 70 dBA sound level at a point 150 ft before Point 1. This data point is indicated by the asterisk on the noise trace. The entire trace can be so constructed.

Referring briefly to the time scale at the bottom of Figure 2.10, note that near the point of closest approach to Point A, the noise trace moves rather rapidly up to its peak value and then drops off equally rapidly. For this particular trace, in 2 seconds of time the sound level rises approximately 11 dBA to its peak. This rapid change is caused by the rapid closing of distance between the vehicle and Point A during the last 2 seconds of the approach. This illustrates an important fact: when the observation point is near the highway, noise levels change quickly during the time immediately before and after the vehicle arrives at the point of closest approach. Thus, for close distances, the noise levels are high and the noise level changes are rapid.

Next, let us repeat the same construction procedure for a point that is farther away from the roadway. Using the same observer point designations used in Tables 1.3 - 1.9 of Chapter 1, suppose we construct a noise trace for a vehicle that passes 200 ft to the side of Observer Point C. This is done in Figure 2.11. Notice here that the peak sound level change is lower (as we have already learned), and that the sound level change is less abrupt at the time of closest approach. Here, during the last 2 seconds of approach, the sound level rises only 2-3 dBA.

Using a different format and a different scale of distance and sound level, similar types of "noise traces" are drawn in Figure 2.12. Curves A and C are the same as the traces constructed in Figures 2.10 and 2.11, except for the change of scales. Curves B, D, and E represent noise traces that could be expected from an idealized point source (vehicle) that passes 100, 400, and 800 ft, respectively, to the side of Observer Points B, D, and E in the Chapter 1 figures. The five curves on Figure 2.12 practically bracket the most sensitive neighbor areas beside a busy highway. These curves are to be used to help demonstrate L_{10} and L_{50} sound levels, and to show that (a) distance to the highway and (b) quantity of traffic are controlling factors in determining L_{10} and L_{50} values.

2.8 INTRODUCTION OF L_{10} AND L_{50} SOUND LEVELS

Continuing the discussion from the last section, suppose now a continuous line of moving vehicles along a straight level road. For the first example, suppose that the vehicles are uniformly spaced at 800 ft intervals, that all vehicles are exactly alike acoustically, and that all vehicles are traveling in the same direction in the same lane at equal speed. A graphic level recorder set up at Point A, 50 ft to the side of the road would yield a repetitive series of peaks and valleys in the noise trace somewhat similar to the sample portion shown in Figure 2.13. The dotted portions of the curve show the rise and fall of the noise of each individual vehicle, and the solid curve shows the total noise of the continuing line of noise sources. The distance scale is used primarily to indicate the distance interval between sound sources, but it could be related to a known time scale, such as from the speed of the advancing paper of the graphic level recorder or from timer marks superimposed on the trace.

Recall that L_{10} is the noise level that is exceeded for 10% of any specified suitable sampling time. For the uniform repetitive flow of vehicles used for this example, a sampling time can be quite short (it could include as little as exactly one complete cycle of signal variation). Now, suppose that the length of the sample trace is assigned an arbitrary time interval of 100 units. We can then determine the length of 10 time units and 50 time units on that sample trace. It then becomes necessary to find the noise level whose total duration just equals the 10 time units; this noise level is L_{10}. It is next necessary to find the noise level whose total duration just equals 50 time units; this noise level is L_{50}. In Figure 2.13, this procedure is followed, and by approximate fitting it is found that, L_{10} = 78.0 dBA and L_{50} = 68.5 dBA approximately. Although the procedure appears quite simple here, due to such an ideal noise trace, it is not this simple in practice. The concept is of concern here, rather than the actual values. For this illustration, notice that the total noise level varies between 65 and 80 dBA, a 15 dBA swing, and that the difference between the L_{10} and L_{50} values is also quite large (9.5 dBA). Large differences, such as these, are characteristic of sparse traffic and close distance to the roadway.

Next, let us increase the traffic flow by providing a 400 ft interval between vehicles. This is shown in the lower half of Figure 2.14. For this spacing, the new vehicles fill in the valleys between the noise peaks of the vehicles formerly at 800 ft spacing. This results in a smaller total change in sound level and a smaller difference between L_{10} and L_{50}, although both L_{10} and L_{50} are larger than in the first illustration. Finally, in the upper portion of Figure 2.14, vehicle separation is reduced to 200 ft. As expected, the sound level differences are smaller, but the L_{10} and L_{50} values are larger. Thus, increased traffic flow smooths out fluctuations in sound levels, although the total sound levels themselves increase.

Figure 2.15 presents a similar series of constructed noise traces for Position C (of Figures 1.3 to 1.9 in Chapter 1), located 200 ft from the roadway. As vehicle spacing decreases from 1600 ft to 800 ft to 400 ft, the L_{10} and L_{50} levels rise but the fluctuations decrease. For 400 ft spacing, the total spread in levels is approximately 1 dBA and the difference between the L_{10} and L_{50} levels is approximately 0.5 dBA.

For all these constructed noise traces, the assumed vehicle has a noise emission level of 80 dBA at 50 ft distance.

In real-life highway situations, autos have variable noise levels, trucks have variable noise levels, and the mixing of autos and trucks yields noise level variations of 10-20 dBA. Thus, the simple noise traces sketched here are seen to be idealized and will not be found in the field. Statistical sampling techniques will be offered later, however, to permit reasonable approximations of the L_{10} and L_{50} sound levels without requiring graphic level recording equipment. The constructed noise traces have been used here merely to illustrate the nature of noise level changes as a function of the various distances involved and to observe generally the trend toward more uniform noise levels with increased traffic quantity.

Later in the text, tables of data taken from NCHRP Report 117 and the TSC Report will provide a means for estimating the L_{50} sound levels for both autos and trucks, as a function of quantity of traffic (in vehicles per hour), average speed of the traffic, and distance to the highway. A procedure is then given for estimating the difference (L_{10} - L_{50}) in dBA, which is a function of the quantity of traffic (in vehicles per mile) and the distance from the highway to the neighbor area in question. We have already seen somewhat intuitively from the idealized "noise traces" that the factors of quantity and distance are involved.

In summary, this chapter has been devoted to (a) the noise of individual automobiles and trucks, (b) the secondary parameters that influence noise, and (c) an introduction to the use of L_{10} and L_{50} values using simple idealized moving noise sources. In Chapter 3, noise measurement techniques will be presented, aimed at taking data that can yield the L_{10} and L_{50} values for specific situations. Then, Chapter 4 will be devoted to the noise radiated by highways carrying various quantities of the auto and trucks considered singly in Chapter 2. The NCHRP and TSC methods for analyzing highway noise will be presented and discussed in Chapter 4.

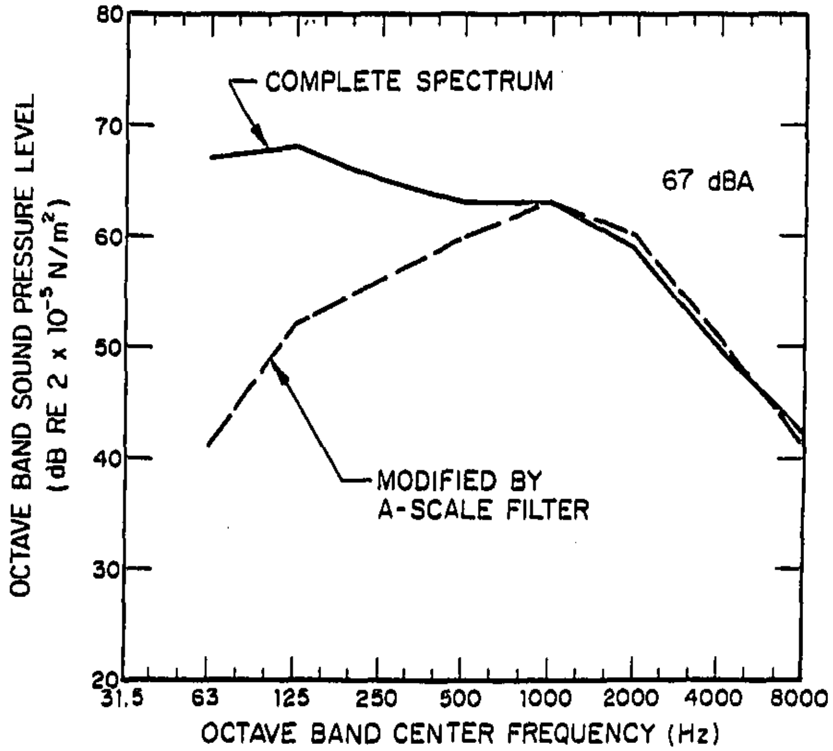
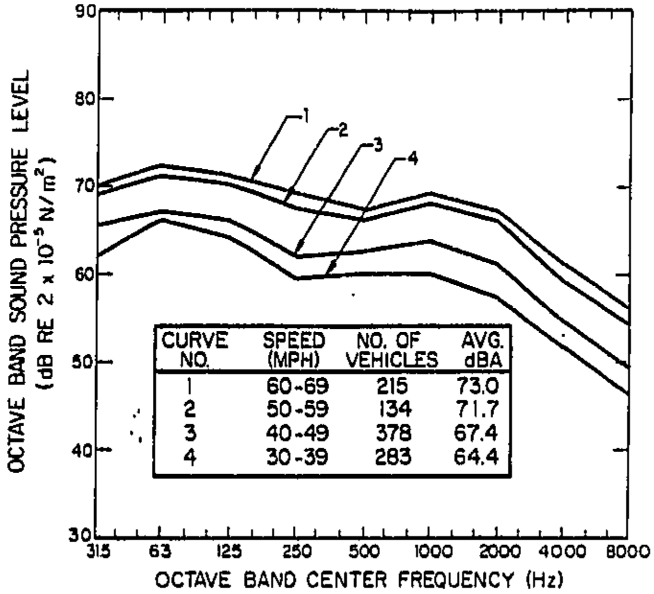


FIGURE 2.1 GENERALIZED SPECTRUM OF TYPICAL PASSENGER AUTOMOBILE AT 50 MPH SPEED AND AT 50 FT DISTANCE -- FROM NCHRP REPORT 78



CURVE NO.	SPEED (MPH)	NO. OF VEHICLES	AVG. dBA
1	60-69	215	73.0
2	50-59	134	71.7
3	40-49	378	67.4
4	30-39	283	64.4

FIGURE 2.2 . SUMMARY OF SOUND LEVELS FOR PASSENGER VEHICLES AT 50 FT DISTANCE -- MEASURED AND REPORTED BY N. OLSON OF CANADA

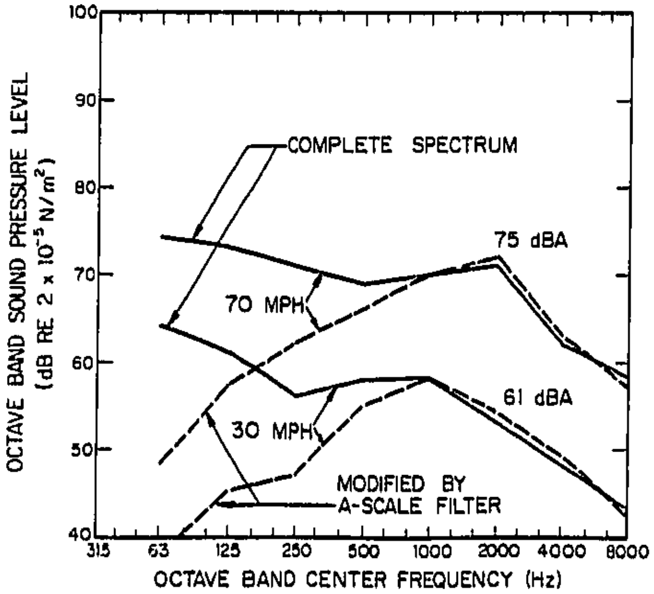


FIGURE 2.3 GENERALIZED SPECTRA OF AUTOMOBILE NOISE AT 30 MPH AND 70 MPH FOR 50 FT DISTANCE -- FROM TSC REPORT

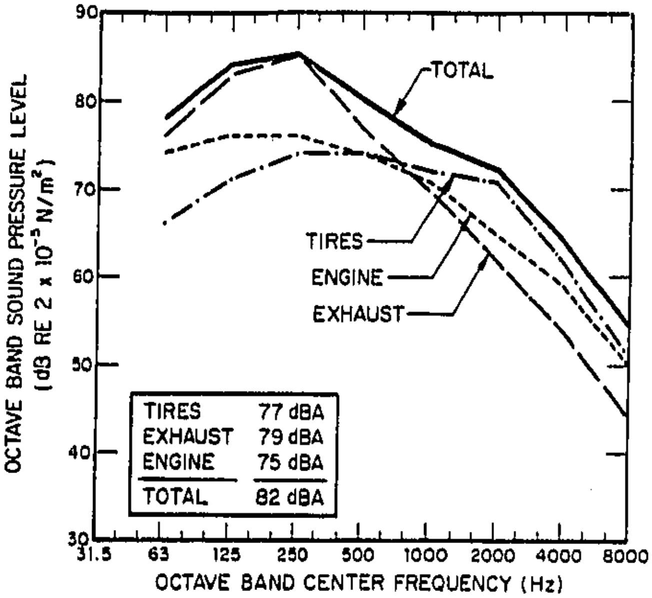


FIGURE 2.4 HYPOTHETICAL MIXTURE OF THE THREE PRINCIPAL SOURCES OF TRUCK NOISE. NOISE LEVELS WILL VARY FOR DIFFERENT COMPONENTS IN DIFFERENT TRUCKS

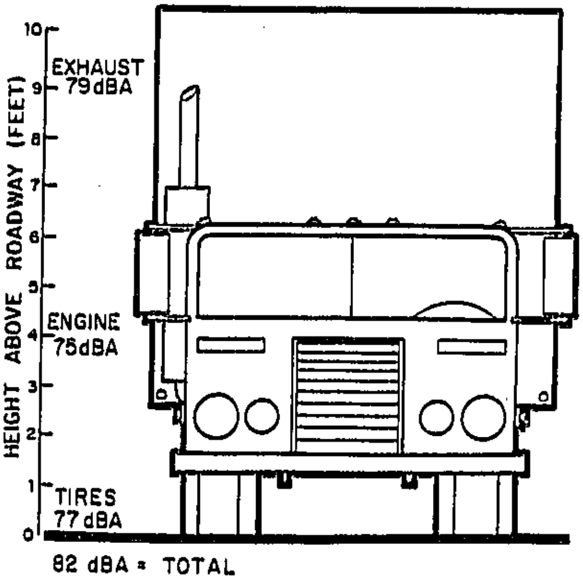


FIGURE 2.5 REPRESENTATION OF TRUCK NOISE COMPONENTS OF FIGURE 2.4, RELATIVE TO HEIGHT ABOVE THE ROADWAY

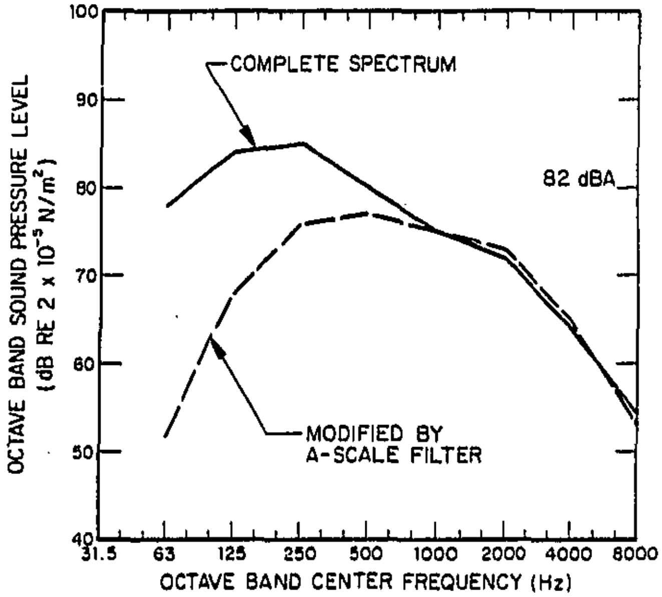
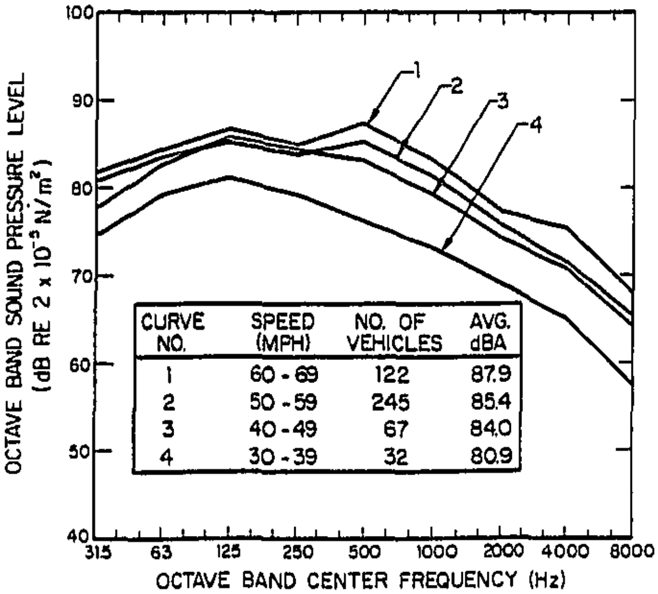


FIGURE 2.6 GENERALIZED SPECTRUM OF TYPICAL DIESEL TRUCK AT 50 FT DISTANCE ON LEVEL ROADWAY AT HIGHWAY CRUISING SPEEDS -- FROM NCHRP REPORT 78



CURVE NO.	SPEED (MPH)	NO. OF VEHICLES	AVG. dBA
1	60 - 69	122	87.9
2	50 - 59	245	85.4
3	40 - 49	67	84.0
4	30 - 39	32	80.9

FIGURE 2.7 SUMMARY OF SOUND LEVELS FOR TRACTOR TRAILERS AT 50 FT DISTANCE -- N. OLSON OF CANADA

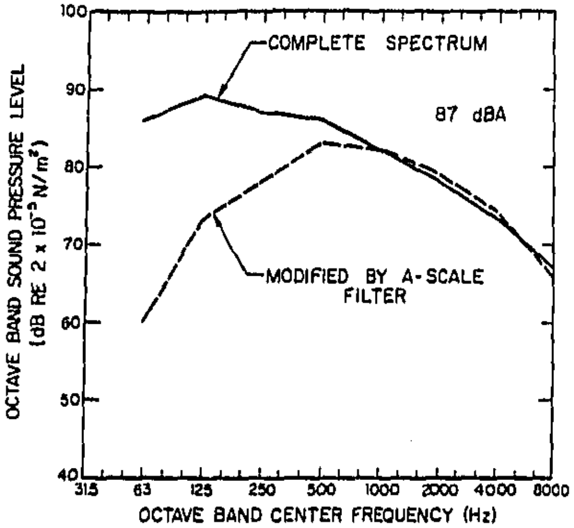


FIGURE 2.8 GENERALIZED SPECTRUM FOR DIESEL TRUCK NOISE AT 50 FT DISTANCE FOR ALL SPEEDS -- FROM TSC REPORT

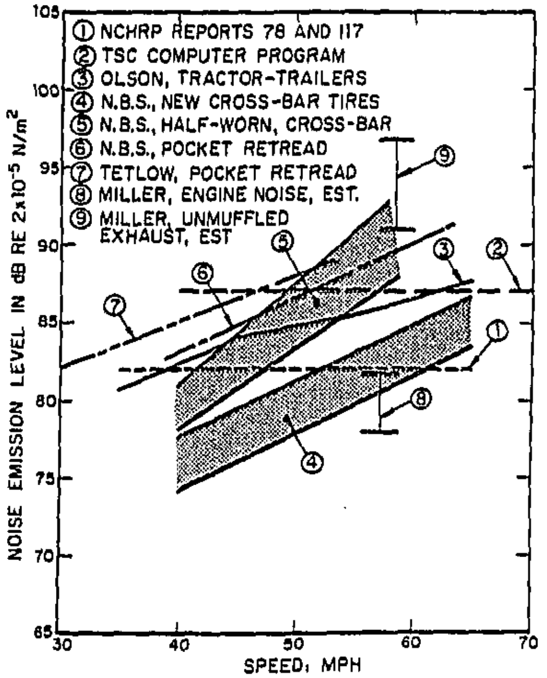


FIGURE 2.9 COMPARISON OF VARIOUS NOISE LEVELS FOR TRUCKS AND TRUCK COMPONENTS, PLOTTED AGAINST SPEED

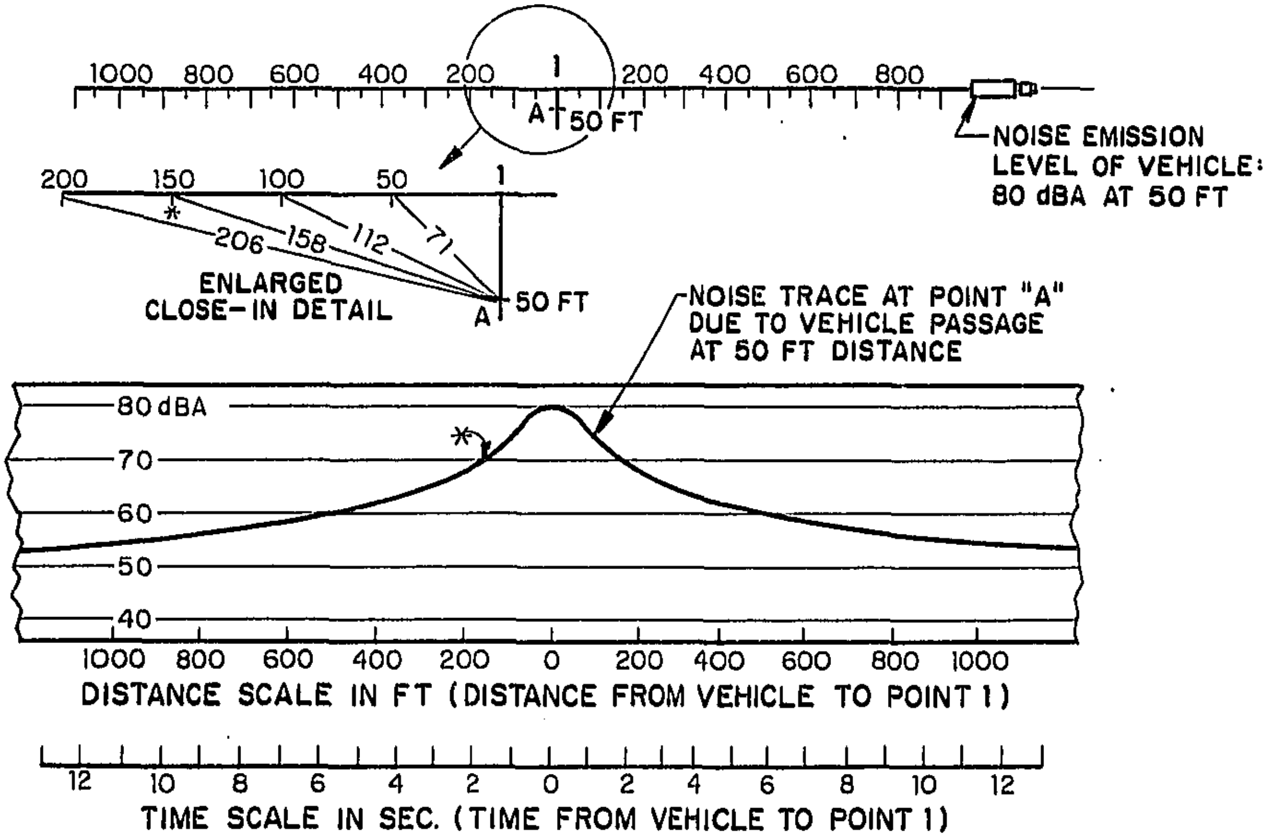


FIGURE 2.10 CONSTRUCTION OF NOISE TRACE FOR VEHICLE PASSAGE 50 FT FROM OBSERVER POINT "A"

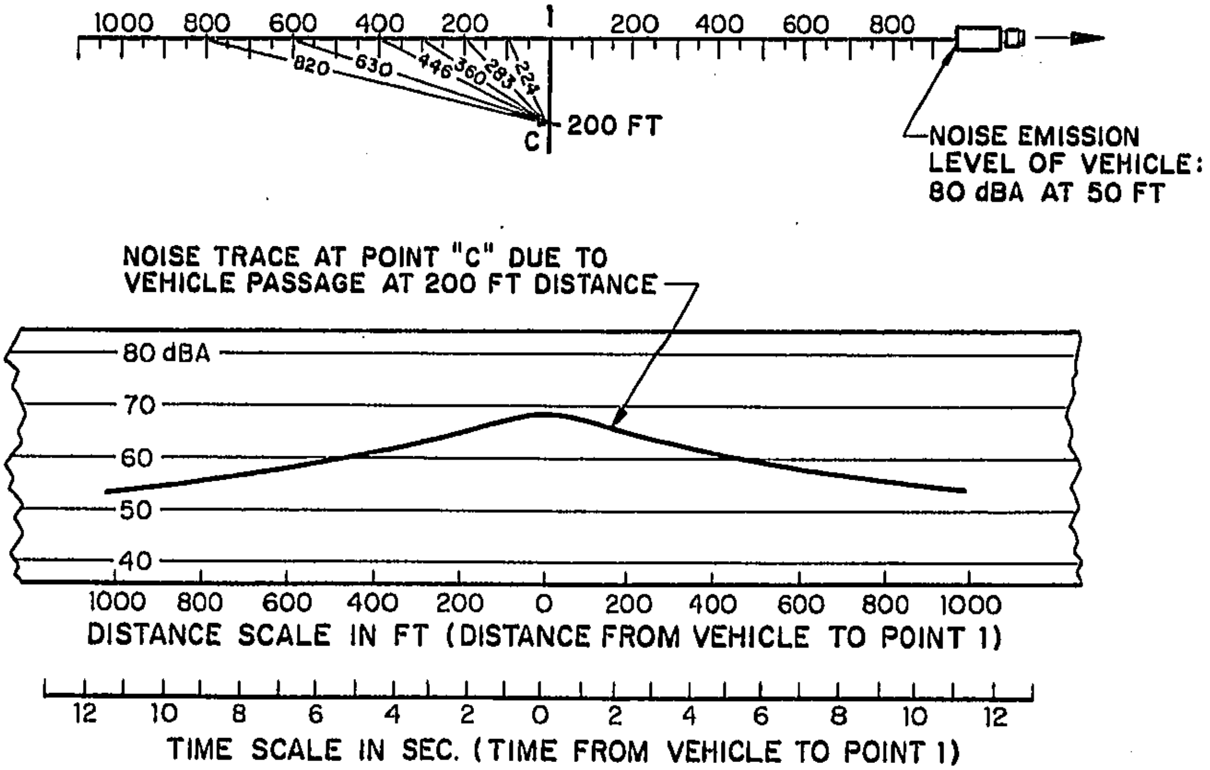


FIGURE 2.11 CONSTRUCTION OF NOISE TRACE FOR VEHICLE PASSAGE 200 FT FROM OBSERVER POINT "C"

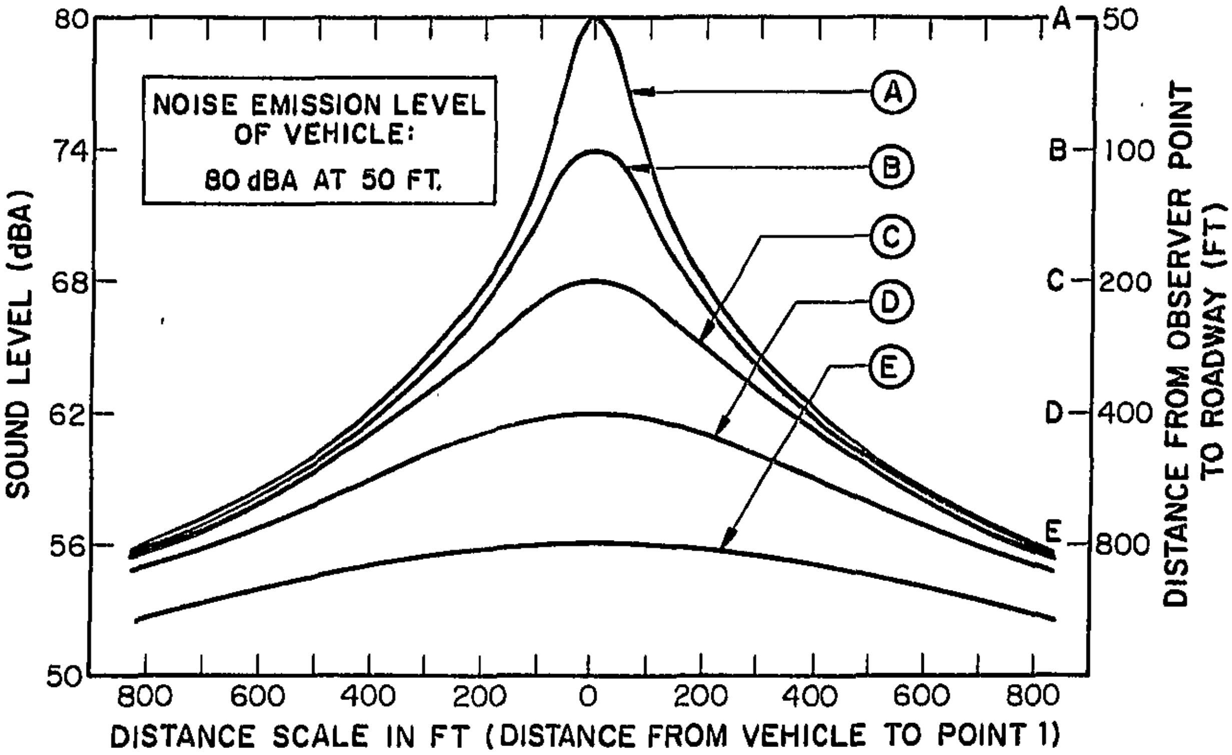


FIGURE 2.12 IDEALIZED NOISE TRACES FOR VEHICLE PASSAGE AT INDICATED DISTANCES FROM INDICATED OBSERVER POINTS (A - E) FOLLOWING CONSTRUCTION TECHNIQUES USED FOR FIGURES 2.10 AND 2.11

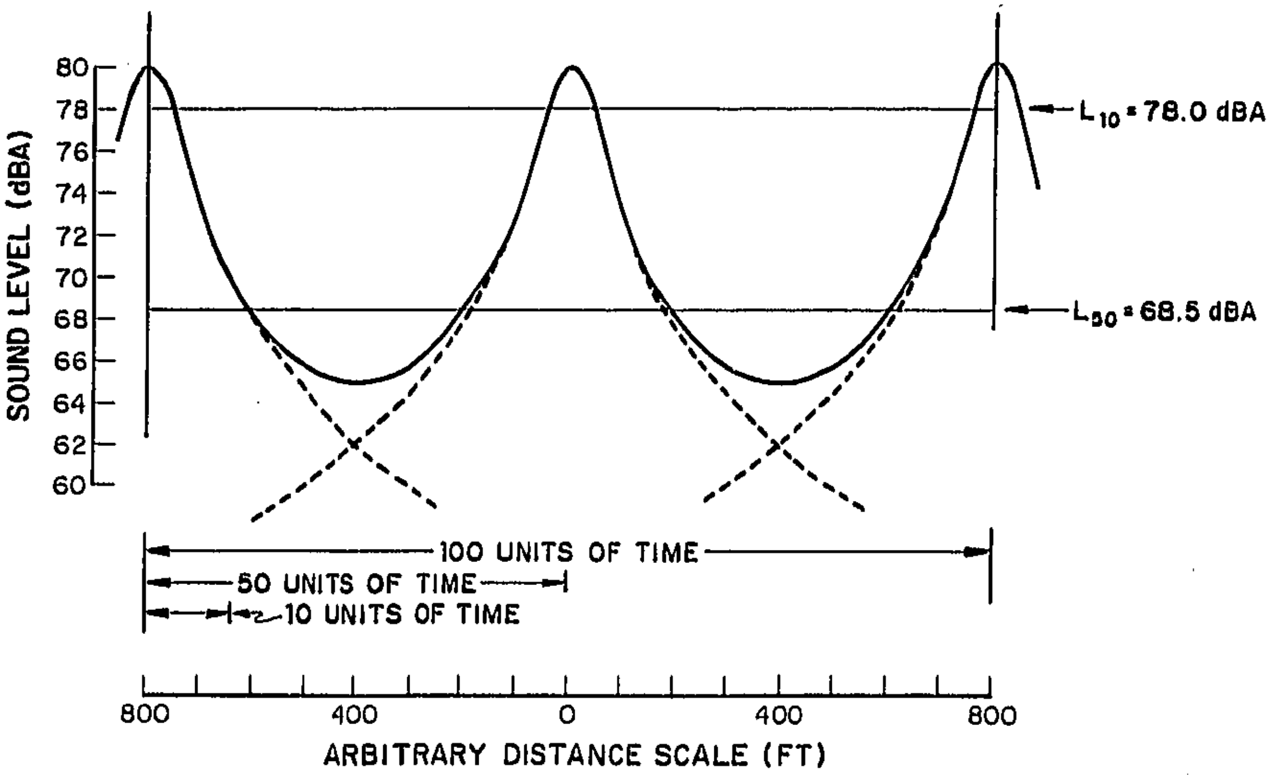


FIGURE 2.13 EXAMPLE OF PORTION OF IDEALIZED NOISE TRACE DUE TO CONTINUAL FLOW OF ASSUMED VEHICLES WITH 800 FT SEPARATION, AS OBSERVED AT POSITION "A", 50 FT TO SIDE OF ROAD. SEE TEXT FOR DETAILS.

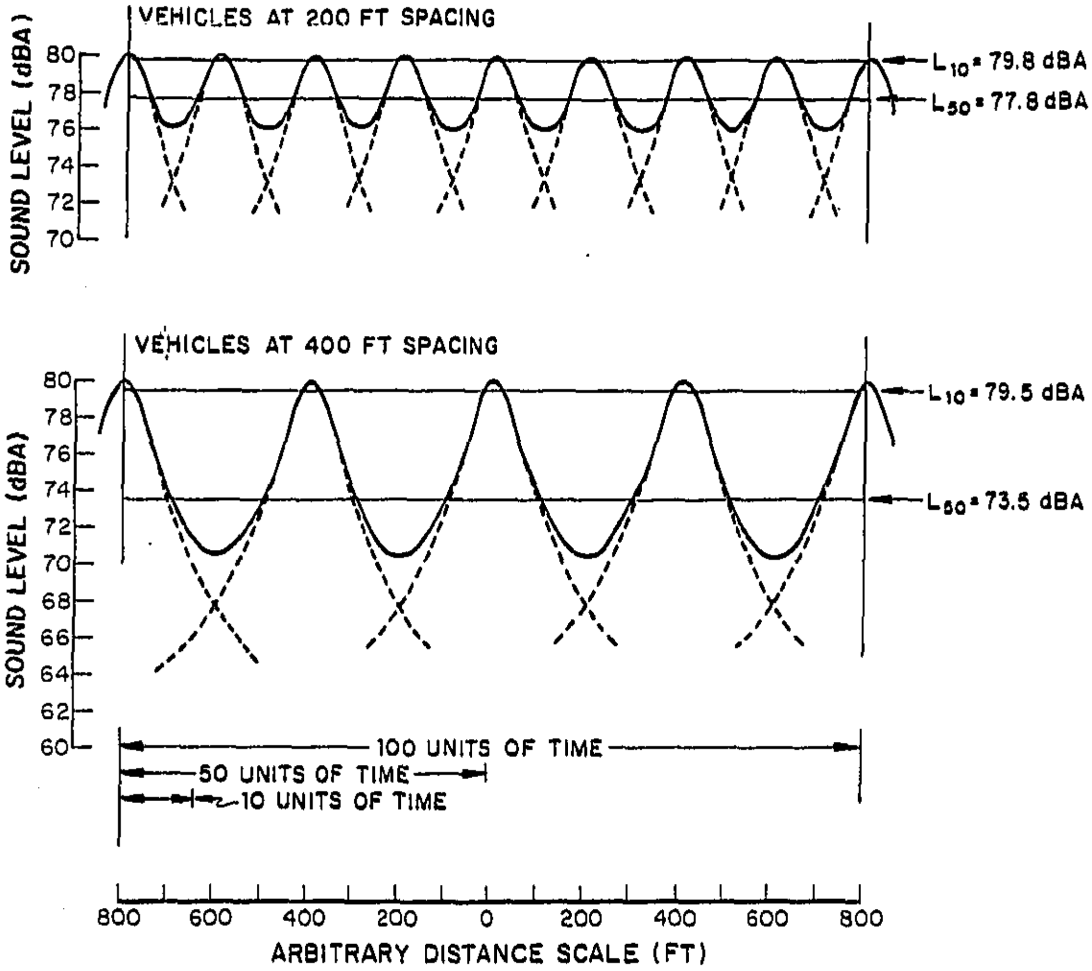


FIGURE 2.14 CONTINUATION OF FIGURE 2.13, WITH CLOSER SPACING OF VEHICLES. REFER TO TEXT FOR DETAILS.

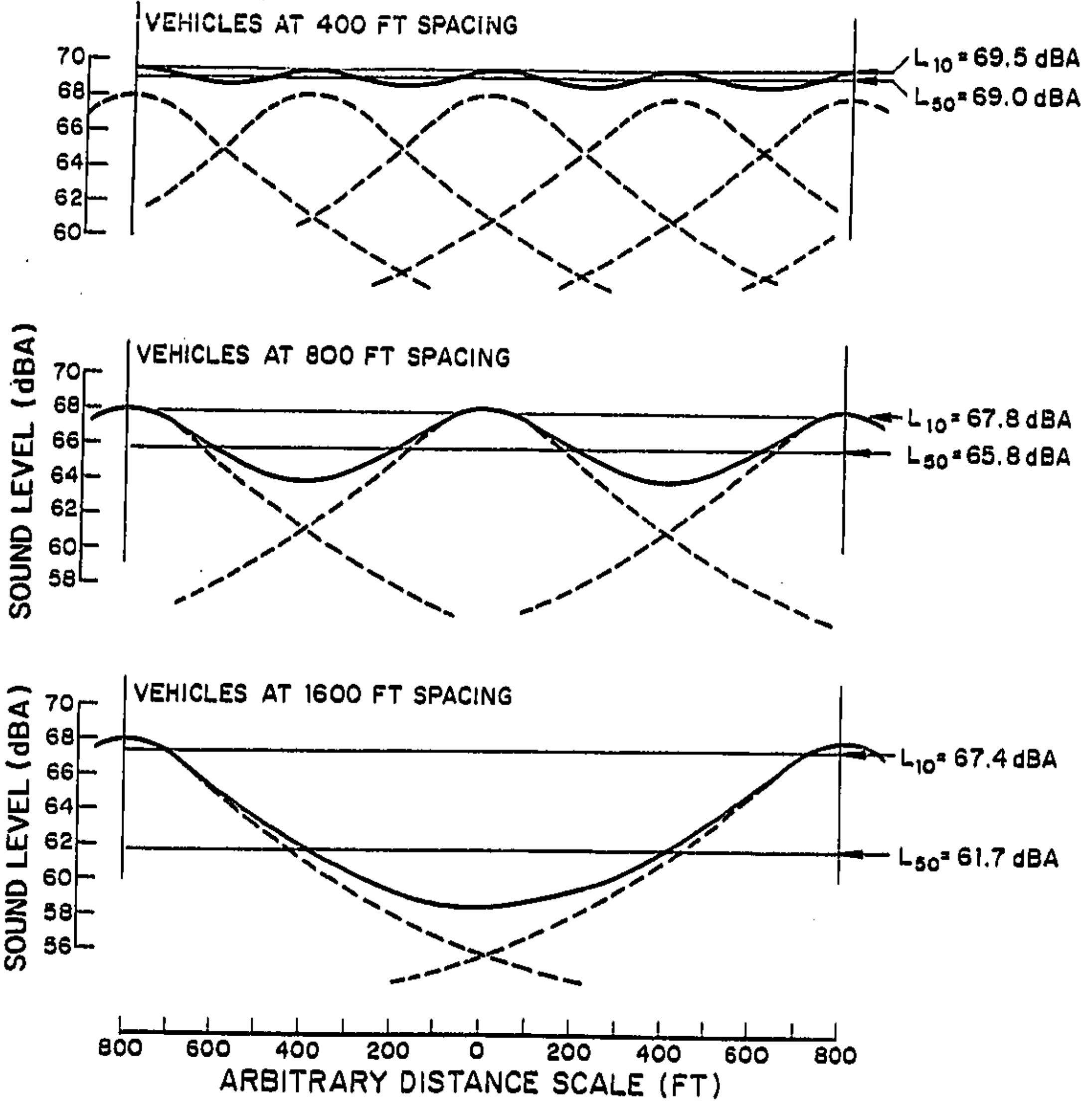


FIGURE 2.15 IDEALIZED NOISE TRACES FOR ASSUMED VEHICLES AT UNIFORM SPACING, AS OBSERVED AT POSITION "C", 200 FT TO SIDE OF ROAD. REFER TO TEXT FOR DETAILS.

CHAPTER 2 PROBLEMS

1. One lane of a highway handles 1200 vehicles per hour. Assume that all traffic is uniformly spaced along the lane.

   a. How many vehicles pass a given point on that lane during one minute, if the average traffic speed is 30 mph?
   Ans. ____________

   b. How many vehicles pass a given point on the lane during one minute, if the average traffic speed is 60 mph? (Think about it!)
   Ans. ____________

   c. How many seconds of time elapse between vehicle passages, for the 30 mph average speed?
   Ans. ____________ sec.

   d. How many seconds of time elapse between vehicle passages, for the 60 mph average speed?
   Ans. ____________ sec.

2. Continue considering the conditions of Problem 1, in which one lane handles 1200 vehicles per hour, and all traffic is uniformly spaced along the lane. (Recall that 60 mph = 88 ft/sec.)

   a. What is the average center-to-center spacing of the vehicles for an average traffic speed of 30 mph?
   Ans. ____________ ft

   b. What is the average center-to-center spacing of the vehicles for an average traffic speed of 60 mph?
   Ans. ____________ ft

   c. How many vehicles are in a one-mile length of the lane, when the average traffic speed is 30 mph?
   Ans. ____________

   d. How many vehicles are in a one-mile length of the lane, when the average traffic speed is 60 mph?
   Ans. ____________

3. Refer to Figure 1.9 on page 1-27. Forty-one sound sources are shown distributed uniformly along a 4000 ft line source, with a spacing of 100 ft between sources. Each sound source in that illustration is taken to have a "noise emission level" of 80 dBA at 50 ft distance.

   a. For that layout, what does the table at the bottom of the figure give for the total sound level at Point C located 200 ft to the side of the line of sources?

      Ans. ____________ dBA

   b. Now, suppose that instead of the somewhat fictitious level of 80 dBA, we are to have autos traveling along the source line (road) at 60 mph, and each auto has a noise emission level of 73 dBA, as taken from the TSC data. Each individual sound source along the line is then 7 dBA lower than the 80 dBA value assumed originally in Figure 1.9. For this new condition, what total sound level would you expect at Point C, 200 ft to the side of the road?

      Ans. ____________ dBA

   c. Continuing the new condition of 73 dBA autos instead of 80 dBA fictitious sources, approximately what sound level would you expect at Point C, if there were twice as many autos on the 4000 ft length of road (i.e., a 50 ft spacing between sources)?

      Ans. ____________ dBA

   d. What sound level would you expect at Point C, if there were half as many autos on the 4000 ft length of road (i.e., a 200 ft spacing between sources)?

      Ans. ____________ dBA

   e. For a uniform vehicle spacing of 100 ft along one lane of a roadway, what would be the traffic count for that lane, in vehicles per hour, for an average speed of 60 mph?

      Ans. ____________ vph

   f. Considering the general trend of the idealized noise traces shown in Figure 2.15 on page 2-21, and taking into account the total sound level estimated above in Problem 3b, give a rough estimate of the L_{10} and L_{50} values that might be expected for a line of 73 dBA autos at 100 ft uniform spacing as heard at Observer Position C, 200 ft to the side of the road.

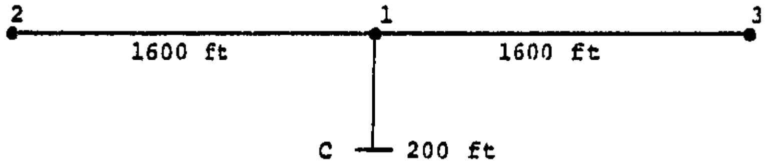
      Ans. $L_{10} \doteq$ __________ dBA; $L_{50} \doteq$ __________ dBA

4. Refer to Figure 1.3 on page 1-24. At Point C, 200 ft from the source line, the total sound level is 68 dBA for a single sound source at Point 1, when that sound source has a "noise emission level" of 80 dBA at 50 ft distance.

   a. Suppose we now substitute a diesel truck for that stationary sound source. Let the diesel truck have a "noise emission level" of 87 dBA at 50 ft distance, as taken from the TSC approach. What would be the sound level at Point C for the single truck.

      Ans. ___________dBA

   b. Now, suppose the source line of Figure 1.3 is extended 1600 ft in both directions beyond Point 1, and let a truck be placed on the extended source line 1600 to the left of Point 1, and another truck 1600 ft to the right of Point 1. We now have a source line 3200 ft long, with three trucks on the line at uniform 1600 ft spacing, as shown here.



      For the sake of identification, label the trucks "2" and "3" as shown. Using the "inverse square law" table for sound level reduction from <u>point</u> sources (Table 1.3 on page 1-32), estimate the sound level at Point C for trucks "2" and "3". Remember that each truck has a noise emission level of 87 dBA at 50 ft distance.

      Ans. ___________ dBA for truck 2

      ___________ dBA for truck 3

   c. What is the total sound level at C due to trucks 2 & 3?

      Ans. ___________ dBA

   d. What is the total sound level at Point C due to all three trucks along the source line?

      Ans. ___________ dBA

5. Using Figure 1.9 as a model for auto traffic in a one-lane highway, we have estimated in Problem 3b above the total sound level at Point C due to a 4000 ft line of 73 dBA autos with 100 ft spacing. Repeat that answer here:

   ______________ dBA.

   Using Figure 1.3 as a model for truck traffic in a one-lane highway, we have estimated in Problem 4d above the total sound level at Point C due to a 3200 ft line of 87 dBA trucks with 1600 ft spacing. Repeat that answer here:

   ______________ dBA.

   a. Considering the general shape of the idealized noise trace at the bottom of Figure 2.15 on page 2-21 for 1600 ft spacing of vehicles (as applicable to Problem 4d above), and considering the results of Problem 3 above for a flow of autos at 100 ft spacing, estimate roughly the approximate L_{10} and L_{50} sound levels for a merging of the autos and trucks onto a single roadway. Remember that the sound level of each of the assumed sources of Figure 2.15 is 80 dBA at 50 ft, whereas the autos and trucks considered here have noise emission levels of 73 and 87 dBA, respectively.

      Ans. L_{10} = __________ dBA; L_{50} = __________ dBA

   b. For a uniform truck spacing of 1600 ft and an average speed of 60 mph, what would be the traffic count of trucks in vehicles per hour?

      Ans. ____________ vph

Note: The individual auto and truck "noise emission levels" used in the above problems are those used in the TSC program. The L_{10} level derived in Problem 5 by considering the data and procedures of Chapter 2, based on single vehicles and idealized conditions, can be checked against the TSC Nomograph after the TSC procedure has been presented and discussed. By using single-source noise data taken from the NCHRP procedure, these problems could also be worked out using the Chapter 2 material, and the answers checked against the values obtained from the NCHRP analysis procedure. These checks are left for the reader to perform at a later time, if desired.

CHAPTER 3

ENVIRONMENTAL NOISE MEASUREMENTS

This chapter contains (1) a discussion of the characteristics and general use of sound level meters for making outdoor ambient noise measurements, (2) a discussion of the factors involved in the selection of locations and times for carrying out ambient noise measurements, and (3) a suggested sampling technique for obtaining ambient noise data in a form that permits reasonably valid determination of representative L_{10} and L_{50} noise levels. This material is directed toward the use of simple equipment, and the procedures are restricted to the type of field measurements deemed necessary for highway noise studies. More sophisticated equipment set-ups and methods of data analysis may be used by persons or groups having more experience or expert knowledge in this field. In the classroom coverage of noise measurements, a few samples of tape-recorded ambient and highway sounds will be played, and course attendees will be given an opportunity to make noise measurements of these selected samples.

3.1 SOUND LEVEL METER FOR NOISE MEASUREMENTS

For several years, the American National Standards Institute ("ANSI") and its forerunner, the American Standards Association ("ASA"), have had suitable specifications and authority to control the acoustical and electrical response of sound level meters. ANSI Standard S1.4-1971 specifies four types of sound level meters:

Type 1	Precision
Type 2	General Purpose
Type 3	Survey
Type S	Special Purpose

The Type 2 instrument has performance characteristics that are considered acceptable for ambient noise measurements for FHWA highway noise studies. The Type S instrument can be used for any special application, but it must then meet the appropriate specifications of one of the other three types, and it must be labeled to indicate which type. For example, a Type S2A meter would also be suitable for highway and ambient measurements, since it would meet the Type 2 specifications and would contain an A-scale filter. The Type 1 Sound Level Meter has a greater accuracy than required, and the Type 3 meter has a lower grade of accuracy than desired for this work. The total tolerance limits for sound at random incidence for the Type 2 meter with A-scale filter are approximately as follows (see ANSI S1.4-1971 for more precise values):

20-40	Hz	±4 dB
50-80	Hz	±3 dB
100-250	Hz	±2½ dB
315-1600	Hz	±2 dB
2000-2500	Hz	±3 dB
3150-10,000	Hz	±6 dB

For ambient and traffic noise measurements, the A-scale filter of the sound level meter should be used (do <u>not</u> use B- or C-scale filters). The meter <u>should</u> have both a "slow" and "fast" meter response movement.

It is recommended that the sound level meter be purchased from a reliable manufacturer who has been in the field of sound measurement equipment for many years and who has an established service organization for taking care of equipment servicing and repair.

The Instruction Manual of the sound level meter should be studied carefully while learning to use the instrument, and it should be referred to when questions arise on use, testing, maintenance and care of the equipment. In addition, handbooks and text books are available on noise measurement equipment, procedures and data analysis*

In the general discussion that follows, several suggestions are made that may be helpful in planning and carrying out field measurement work, and that may resolve some problems encountered during field work. This is not to be construed, however, as a complete set of instructions on instrumentation and field testing.

In addition to a sound level meter, at least

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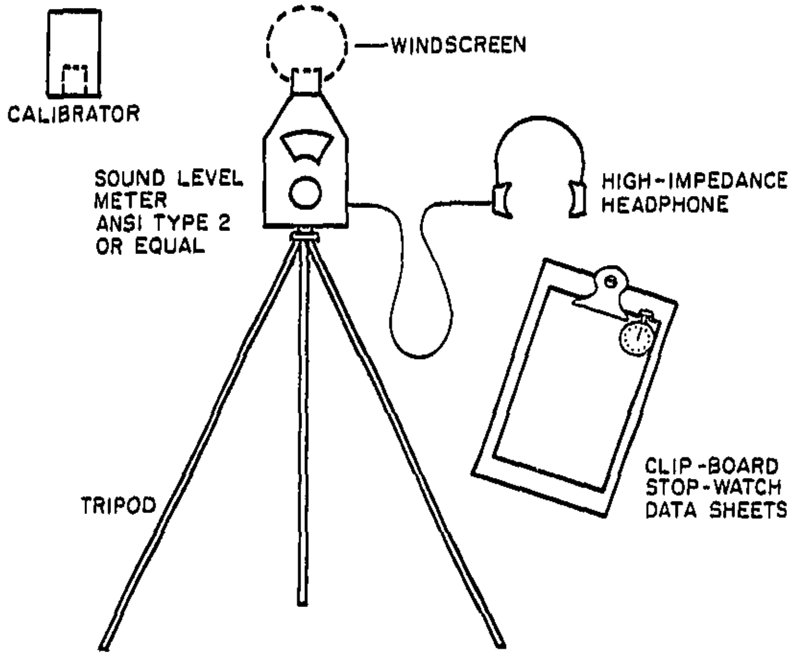
*For example: "Handbook of Noise Measurement" by Arnold Peterson and Ervin Gross (General Radio Company, 1972); "Acoustic Noise Measurements" by Jens Trampe Broch (Brüel and Kjaer Company, 1971); "Measurements in Mechanical Dynamics" by David N. Keast (McGraw-Hill Book Co. 1967).

four pieces of auxiliary equipment are required for making the desired outdoor measurements: a calibrator, a windscreen, a set of head phones, and a tripod (see Sketch 3.1).

The calibrator is a "must" for all noise measurements. A calibrator is a standardized, stable sound source that produces a certain known sound pressure level at the microphone of the sound level meter when the calibrator is coupled to the meter. It is good practice to calibrate the meter before and after taking each set of noise data, and to make any small adjustments in the "gain" of the sound level meter to keep it reading correctly. A "small adjustment" might be up to ±1 dB. Before making any adjustment to the gain of the sound level meter, it is suggested that the sound level meter have a warm-up time of at least 2 minutes and the calibrator have a warm-up time of at least one-half minute (or follow the procedure recommended in the Instruction Manual). If a quick check calibration shows meter agreement with the calibrator level (within about ±½ dB), it is not necessary to make an adjustment or to wait through the entire warm-up time. Also, before making any adjustment to the sound level meter, check the battery level of the meter. If the needle deflection is below the appropriate lower limit line of the meter scale on battery check, new batteries should be installed in the sound level meter. The batteries of the calibrator should also be checked periodically and replaced when necessary. If, at the time of a calibration, the sound level meter appears to have shifted more than about 3 dB from its last calibration, this is a clue that something may be wrong with either the calibrator or the sound level meter. In this event, check the batteries again or even replace the batteries, making sure that the battery contact points are clean. If this does not return the instrument to reasonably correct condition, refer to the Instruction Manual for assistance or send the meter and calibrator back to the manufacturer for a check or repair. It is fool-hardy to take questionable data.

A windscreen is a porous sphere that covers the microphone to reduce the wind turbulance without reducing the sound signal. Without a windscreen, even low-speed wind movement over the microphone produces turbulence noise that may be greater in level than the quiet ambient noise that is to be measured. In high winds and/or in quiet ambients, false sound level readings may by obtained even with the windscreen in place. To listen for wind noise, or other false non-acoustic signals, a set of well-fitted high-quality, high-impedance earphones should be used when ambient noise levels are being taken. (Low impedance headphones load down the output of the sound level meter so that falsely low readings are obtained.) The headphones



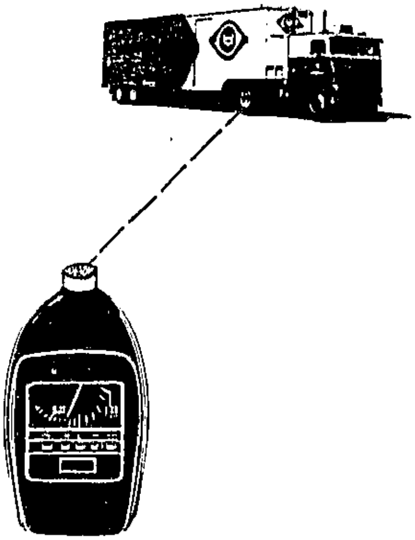
SKETCH 3.1

should be connected to the outlet terminal or monitoring terminal of the sound level meter. The headphones should be fitted with ear caps that seal out sounds not coming through the headphones themselves. Listening tests in the presence and absence of wind noise will help the user learn to identify this type of interfering noise. Noise level readings should not be taken when wind noise overrides the true ambient levels. In fact, ambient noise readings should be avoided, if at all possible, during windy periods, because the wind can cause unreasonably high high-frequency noise levels due to rustling leaves, if trees are nearby, and because the wind can influence sound transmission paths, as mentioned earlier in Section 1.11.

During periods of high humidity, condenser-type microphones produce popping sounds and the sound level reading is unreliable. The headphones can help identify these popping sounds also. If the popping persists and the relative humidity is known to be relatively high (say, above about 90%), the sound measurements should be discontinued, and the microphone stored in a dry place until normal operation is recovered.

The tripod is recommended as a means for supporting the sound level meter during measurements, to free the hands for recording of data. It is normal procedure to position the microphone at a height of about 4 to 5 feet above the ground for more-or-less ground level ("first floor") ambient noise measurements. However, if it is desired that the measurements also represent building occupants who live or work at upper floor elevations, it is necessary to take measurements at those upper elevations. Upper floor ambient noise levels may sometimes be as much as 5-10 dBA above ground level values, depending upon the general geometry of the area. Ground level sound absorption and low-height barriers tend to reduce ambient noise levels near the ground, but upper floor sites usually have better line-of-sight paths to the sound sources. In such situations, the microphone may be supported outside upper floor windows, but held out away from the exterior wall of the building as far as possible, at least 3 to 4 feet.

A few simple points should be mentioned regarding the positioning of the sound level meter and the meter reader for measurements. First, the microphone should be oriented relative to the sound source in accordance with the Instruction Manual, to provide minimum signal change due to directivity effects of the microphone and the meter. For most sound level meters, microphone directionality is quite uniform when the meter is held or supported in a vertical position perpendicular to a line to the sound source (see Sketch 3.2). For this position, the sound wave passes with "grazing incidence" just across the top of the microphone face.



Hold the meter perpendicular to a line to the sound source, so that the sound wave "grazes" the top of the microphone (hence, "grazing incidence").

SKETCH 3.2

It is good practice for the person taking the readings to stand back as far as possible from the meter, so that his body reflects minimum sound energy back to the meter. The body will represent minimum frontal area to the sound wave and minimum possible interference with the sound field near the microphone, if the meter reader will stand to the side of the meter, somewhat as shown schematically in Sketch 3.3. Of course, when the ambient is made up of sound from many possible sound sources coming from many directions, the meter reader should locate himself so that he represents a minimum barrier or reflector for the sound that is being measured.

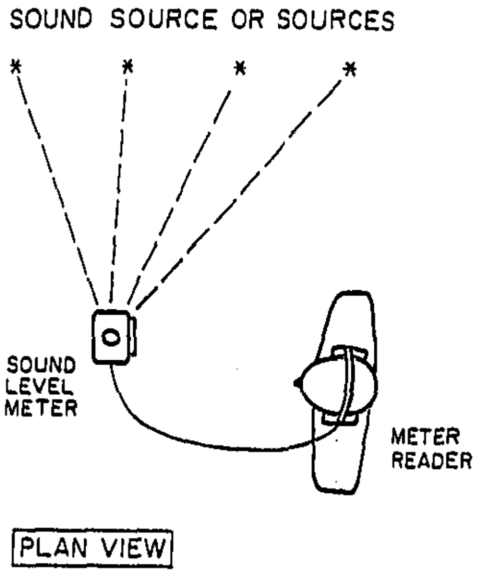
Recall, also, from Section 1.11 that atmospheric effects may influence sound levels at any one location. Without fairly sophisticated meteorological field equipment, it is not possible to know the wind and thermal gradients that sometimes play an important role in the bending of sound waves. Thus, it is wise to include enough readings near and on opposite sides of known sound sources to know if reasonable values are being measured.

If there is any question about the validity of the noise levels, relative to atmospheric effects, additional check readings should be taken at later times.

As shown in Sketch 3.1, a clipboard, a stopwatch (or a watch with a large readable sweep-second hand), and a pad of data sheets complete the auxiliary materials needed for the ambient measurements. The need for these materials will become more obvious when specific procedures are discussed in later sections of this Chapter.

3.2 AMBIENT NOISE

The "ambient" noise in any area is the "background" noise made up of all the natural and man-made noises generally considered to be contained within the acoustical environment of that general area. Near an airport, the ambient may include aircraft noise, either from nearby flights or from ground operations at the airport. Near a railroad track, the ambient may include frequent or occasional train passages. Near a fire-station or a hospital, sirens may be a part of the acoustical environment. In or near industrial areas, various kinds of industrial noises make up large parts of the total ambient. In suburban and rural areas, barking dogs, rustling leaves, chirping birds, and crickets may be a significant part of the ambient. Near lakes, motorboats in the daytime and "peepers" and frogs at night may be a part of the ambient. Near school grounds, recreation areas, parks and swimming pools, children's voices may be a part of the ambient. Similarly, near streets, major arteries, and highways, traffic noise may be a part of the ambient.



SKETCH 3.3

Some ambient noises vary from day to night; some ambients differ by the day of the week; and some ambients vary from summer to winter. Where ambients involve commuter traffic routes, these ambients can even vary by the hour.

For purposes of highway noise studies, ambient noise measurements are taken in order to establish a base for existing noise conditions. This makes it possible to have a reference for comparison when roadway changes, improvements, or new highways are contemplated for an area. The difference in noise levels "before" and "after" the change gives an indication of the impact of the noise on the area affected. In addition, the number of people, or residences, or acoustically sensitive buildings in the area affected by the change represents another dimension of the extent of the impact. Of course, it is desirable that the highway changes have minimum impact on the area; it is the intent of PPM 90-2 to minimize impact by highway design considerations, and it is the purpose of this textbook and course to provide data and procedures for helping the highway designer and planner to carry out this objective.

So, in order to have a fair reference base for the "before" or existing conditions, a representative collection of ambient noise data must be taken. Perhaps, one of the more difficult questions to be faced is: What should be measured and what should not be measured as ambient noise? Should a chirping bird, barking dog, fire-engine siren, aircraft flyover, jackhammer, snow-mobile, motor boat, forging hammer, policeman's whistle, screeching brakes, bus start-up, or piledriver be included? Should the crickets, rustling leaves, screaming children, or a neighbor's loud radio or hi-fi be measured? Should a single car passing along a quiet residential street, but near the sound level meter, be measured? Should the mail truck, or the school bus, or the garbage pick-up truck, or a passing dump truck be included in the ambient? Each of these may be a fairly normal sound at one time or another, at one place or another.

The answer to the above questions must be provided by the person taking the data. The real question to be asked and answered first is: Is it representative?

If a house is being built on the last available lot in several blocks of residential area, the hammering and the power saw and the dump truck removing debris probably are not representative of continued sounds in that area, so those sounds should not be considered as representing long-time ambients and they should not be measured. A fire-truck siren in a quiet residential area may be the most exciting outdoor sound all day, and it is a completely reasonable sound, but fire trucks make rather infrequent visits into residential areas (remote from fire stations), and that sound would not be representative and perhaps should not be measured for that particular area. Yet, near a fire station or near a hospital, with frequent emergency ambulance arrivals, sirens may be quite commonplace and should be measured as a real part of the environment.

Near industrial areas of long-standing, industrial noises of either day or night occurrences should be included in the ambient of that area. The sounds of a passing school bus or a garbage pick-up truck are completely reasonable in a community. But are they representative of the ambient environment to be described? Do they occur every hour?

If a dog starts barking at you because you have set up your noise measurement equipment in his front yard, you are a part of the cause of the noise and that dog's barking should not be measured.

If the wind blows so hard that rustling leaves produce controlling sound levels, measurements should be discontinued at that site until less wind and less noise is present.

A relatively slow private plane at its cruising altitude or a commercial airliner at its cruising altitude can be the dominant sound in a very quiet background for a limited time. Should it be included in the ambient reading? This is one of the more difficult questions. Aircraft noise is commonplace almost everywhere, but for some "out-of-the-way" places that are not at all near principal air traffic routes, aircraft flyovers do not occur frequently. Yet, one such flyover during a 10-minute monitoring period could completely dominate the peak noise and establish the L_{10} noise level. That would not appear reasonable; whereas along principal air traffic routes, a few aircraft per hour might pass by, and so that noise would appear to be a reasonable part of the ambient of the area. For such types of noises, it is wise to record the noise level (using a special designation such as "a" for aircraft, or "t" for truck, or "d" for dog, or "s" for siren, etc.) during each monitoring time interval (to be discussed in a later section), and to determine later if that noise is representative or not. For example, while setting up the equipment, be aware of the sounds in the area; begin to decide what sounds seem typical, begin to formulate the symbols -- the "a's", "t's", "d's", etc.-- to be used for special sounds. If an aircraft passes over during the first monitoring period, stay for a second monitoring period; and then while preparing to leave the site, continue to be alert to possible repeat events. This will give some assistance in helping decide what sounds are representative. A further note on aircraft noise: you will undoubtedly be making several measurements in a general location; that will give additional time to learn if flights are common or unusual.

Finally, of course, near highways, traffic noise is a significant part and sometimes a controlling part of the ambient noise. This should be measured at appropriate locations and times, as discussed next.

3.3 SELECTION OF MEASUREMENT SITES FOR AMBIENT NOISE MEASUREMENTS

When selecting measurement sites, keep in mind that the objective of the ambient noise survey is to collect the information required to assess the impact of the new highway project on the community in terms of the expected change in the noise environment. The noise report will have to describe this impact in a way that is sufficiently detailed and specific, but also in a way that presents the results in summary form from which the reader can easily draw meaningful conclusions. The noise level cannot be measured at every point in the study area. Further, separate descriptions of the expected noise impact for every point in the study area would be more information than the report reader could assimilate in his mind.

All especially noise sensitive locations should be studied separately and in detail. But, for most projects covering large land areas, a way has to be found to divide the study area into representative sections within each of which the noise environment can be typified by a single, or a few noise measurements. For the noise report, the study area must also be divided into representative sections within each of which the impact of the new highway project can be typified by a single number, or a range of numbers, indicating the change in the noise environment. The engineer will find the objectives of the ambient noise survey better served if he tentatively divides the study area into the above representative sections before selecting his measurement sites.

Land use maps should be used in this planning phase to help identify the present noise sources in the area. The traffic noise prediction methods discussed in Chapter 4 can be used to get a rough approximation of the existing noise environment due to traffic, and to estimate the noise levels expected from the new highway project. Preliminary noise contours for both the existing noise environment and the new highway project noise can be sketched on the land use map. From this data, those noise sensitive locations can be identified where impact is likely. Also the study area can tentatively be divided into smaller areas throughout which the existing noise environments are approximately uniform, and/or the anticipated noise impacts are approximately uniform. Measurement sites should be distributed within these representative areas as required.

Essentially, for most highway projects (excluding those through dense urban areas), four general categories of measurement site areas can be defined as described in the following paragraphs.

a. Especially Critical Noise-Sensitive Sites. Schools, hospitals, and places of worship are three specific types of buildings that must be sought out for ambient measurements in any neighborhood. These sensitive areas rely strongly on the maintenance of adequate quiet to be able to carry on speech communication indoors (and to some degree outdoors as well) and to have minimum disturbance of sleep. School playgrounds and parks and certain civic or commercial interests, such as outdoor theaters, outdoor music shells, outdoor sports arenas, recreation parks, etc., have need for consideration of the effects of noise on the functions they serve.

Specific measurement sites should be located at the side of the building or along the side of the outdoor area that will face the proposed roadway. Additional sites may be selected on more remote parts of these land spaces if future noise may be of concern there also. Remember the importance of taking upper floor outdoor readings, also, as mentioned in Section 3.1.

All of these ambient noise levels should be identified as to exact location, and included in the final Noise Report.

b. Residential Areas. This category includes primarily the places where people live, relax, and sleep; namely, their homes. In addition to private residences, it includes apartment buildings, hotels and motels, nursing homes, etc. Several city blocks of an area may be involved, so it is necessary to select representative sites that are meaningful. Meaningful site selection requires the general knowledge of the existing and future noise sources provided by the preliminary noise contour estimates. If the residential area is too large to be typified by a single ambient noise level or a single range of levels, it should be subdivided into appropriate smaller areas.

For example, a large residential area near an existing traffic arterial may be broken down into three groups of sites: one group located at the edge of the area adjacent to the existing highway where the ambient noise is clearly due to the highway traffic; a second group located toward the interior of the residential area where the arterial traffic is still a major factor in establishing the noise environment, but other noises of the community are beginning to make significant contribution; and a third group deep enough into the community that the only noise measured is from the community itself, and perhaps very distant traffic and aircraft. At the conclusion of the measurement survey, the ambient noise environment in the community can be summarized by the noise levels typical of these three areas.

The precise location of the measurement site is determined by the answer to the question posed in Section 3.2 above, regarding the determination of what constitutes ambient noise: Is it representative? Just as the ambients to be measured should be representative, so also should the sites be representative. Site selections that are so unique as to appear to show bias one way or the other are to be avoided. Fair representation is essential. For the residential sites, it is preferred that ambient measurements be made in the locations where human use typically occurs, i.e., in the front or back yards, (as appropriate) of the houses or buildings selected, usually within 10 to 20 feet of the building. The exact location will make little difference for most of the ambient levels but it can make a difference on noise levels arriving at the sound level meter from vehicles on the road or street only a short distance away.

c. Sites Near Noise Sources. A number of sites should be specifically selected near noise sources in the study area. These sites serve to help calibrate and refine the preliminary noise level contours. Several sites should be selected having as nearly as possible full view of any existing major roadways in the area. These measured values can then be compared with the estimated levels for those positions. It will be gratifying to find moderately good agreement (say, with ±5 dBA) between the measured and calculated values, and it will lend confidence to the engineer and credence to the method. In fact, if the measured levels and calculated levels do not agree reasonably well (and if it is clear that the ambients are largely made up of known traffic noise), this is an indication that either the calculated values do not properly represent the operational data or the measured levels do not correctly reflect the traffic, and that some unusual effects should be sought and explained.

If the special sites near the road have yielded good agreement between measured and calculated levels, calculations should also be attempted for a few of the sites measured under Items *a* and *b* above. It adds strength to the prediction method to be able to show that it confirms existing measured conditions. Of course, the agreement will become poorer as one penetrates into the deeper parts of the community because other sources may begin to control, and the prediction method is too general to handle all the variables of specific locales.

If other sources are known to contribute to the ambient noise in any of the community locations, it is desirable to locate those sources and make noise measurements at one or two sites having essentially full view of them. Then, using the general outdoor noise reduction effects with distance (discussed in Sections 1.10 - 1.14), estimate the drop-off of that noise as it penetrates into the community and check its calculated levels against the measured ambients where it was heard and known to exist. Again, it adds strength to the study to be able to show agreement between actual measured and estimated levels, and it shows that sources other than highways sometimes influence the acoustic environment.

d. Remote Areas for "Noise Floor". Select several sites in areas that are remote from obvious and identifiable existing noise sources. These sites will probably yield the lowest ambients (or the "noise floor") of the area. This noise floor should represent the quietest regions in the whole area under consideration.

It does not matter whether the ambient is due to natural or man-made sources. It is desirable to identify on the data sheets the sources of the sounds that are heard at these positions.

If the noise environment differs so greatly within the area that it cannot be typified by a single ambient noise level, or a single range of levels, the area should be subdivided into smaller representative areas that, together, can summarize the situation for the whole area.

3.4 SELECTION OF MEASUREMENT TIMES FOR AMBIENT NOISE MEASUREMENTS

The design noise levels given in Table 1 of Appendix B of PPM 90-2 (reproduced as Table 1.10 on page 1-36 of this text) are based on L_{10} levels for the design hourly volume of traffic. For comparison purposes, then, this suggests that as many measurements as possible should be made at or near current peak hourly volumes. When this is done, the "before" and "after" comparisons are most meaningful because a minimum of other adjustments are made to the data. However, when current traffic flow rates are quite variable from hour to hour and from day to night, it is not practical to wait many days just for measurements to be made at those peak hour conditions. Thus, as a practical matter, it is usually necessary to take many ambient readings at off-peak traffic conditions and attempt to make reasonable extrapolations to the current peak-hour traffic or to expected future conditions.

When ambient measurements are made during off-peak periods, and it is known that the noise is largely attributable to traffic on the highway in question, it is possible with the Chapter 4 procedures to calculate rough L_{10} estimates for the measured off-peak flow (assuming the traffic count is known) as well as for the probable peak flow rate. This calculated difference can then be applied to the actual measured off-peak condition to obtain a reasonable estimate of the peak condition. The current peak hour noise can then be compared with the calculated or predicted future design hour noise.

By the same general approach, ambient readings at peak daytime flow can be compared to nighttime average or minimum flow, giving a general trend between daytime and nighttime ambients.

Thus, through this process of adjustment, it is possible both by calculation and by measurement to arrive at reasonable estimates of traffic noise that varies over a range of peak to off-peak or day to night traffic volumes. For these adjustments to be fairly accurate, it is necessary to make a traffic count simultaneously with the measured ambient.

To illustrate the procedure, suppose that a set of ambient noise measurements is made at a given location near a highway and that the L_{10} level is found to be 71 dBA for a measured off-peak flow of 2420 autos and 163 trucks per hour. Suppose that by calculation (a Chapter 4 prediction method), it is found that the peak hourly volume of 3800 autos and 420 trucks per hour will produce approximately 3 dBA greater L_{10} than that calculated for 2420 autos and 163 trucks per hour. This suggests, then, that for that particular measurement site a peak-hour flow would yield an L_{10} level of approximately 71 + 3 = 74 dBA.

Comparison of peak and off-peak measurements and calculations are also valuable because they show how much the L_{10} values may be expected to drop below the peak values for certain parts of the day or night. For example, if peak hour commuter traffic is calculated or measured and found to produce an L_{10} level of 68 dBA in a given community location, and nighttime L_{10} levels are calculated to be 8-10 dBA below this value, it can be predicted with moderate confidence that nighttime L_{10} levels may range 58-60 dBA.

In the ambient survey, a number of off-peak ambients should be specifically included where critical nighttime conditions exist, and where these off-peak hours are the most important times of day for some of the noise sensitive locations. These measured results should then be compared to estimated levels for the same traffic volumes to further establish the validity of the overall analysis system.

3.5 CHECKLIST OF "DO'S" AND "DON'TS" IN NOISE MEASUREMENTS

By way of summary of many earlier suggestions, this list of practical reminders is offered. For reference purposes, the location in which the suggestion appeared is given in parenthesis.

1. The minimum required pieces of noise measurement equipment are: a sound level meter, a calibrator, a pair of headphones, a windscreen and a tripod (Section 3.1).
2. A-scale sound levels are specified. The "slow" meter response will be used for most measurements, but the "fast" response may be used on occasion to obtain short samples of desired sounds in the midst of unwanted interfering sounds.
3. Meter calibrations should be made before and after each set of measurements (Section 3.1).
4. When reading the meter, stand back away from the meter as far as practical and place the meter and your body in such a way as to represent minimum interference with the sound field (Section 3.1).
5. Avoid noise measurements in high winds, during rain, and at times of very high humidity if the microphone produces popping sounds (Sections 1.11, 3.1). Tire noise on wet streets has a higher-than-usual amount of high frequency noise and could produce misleading results (Section 1.11).
6. Be aware that rustling leaves, katydids, crickets, peepers and bird chirps are rich in high frequency noise (influencing the A-scale readings), and may give false readings when other ambient sources are presumably being measured (Sections 1.11, 3.2).
7. When setting up for ambient measurements at each site, listen for the sounds of the neighborhood and make a list of those to be considered reasonable and representative as opposed to those that are not (Section 3.2).
8. Select ambient measurement sites to meet the four categories listed (Section 3.3).
9. Outdoor ambient measurements should be made at upper floor elevations if those elevations represent inhabited spaces (Section 3.1).
10. Select ambient measurement times to coincide with peak hourly volume of traffic for key sites, but also include off-peak and some nighttime measurements (Section 3.4).
11. Repeat some ambients at a later time (several days later) as a check against the first data and as a test of whether or not unknown atmospheric effects may have altered significantly some of the data (Sections 1.11, 3.1).
12. Follow carefully the measurement routines given in the material that follows for determining and testing the validity of the L_{10} levels (Section 3.6).

3.6 NOISE MEASUREMENT PROCEDURE

This section describes a suggested method for measuring the L_{10} noise level in "real time" (without the need of tape recording equipment).

The statistical basis for calculating the confidence limits and accuracy follows in an appendix to this chapter. No assumptions concerning the time pattern of the noise are made. (The noise is not assumed to be Gaussian.)

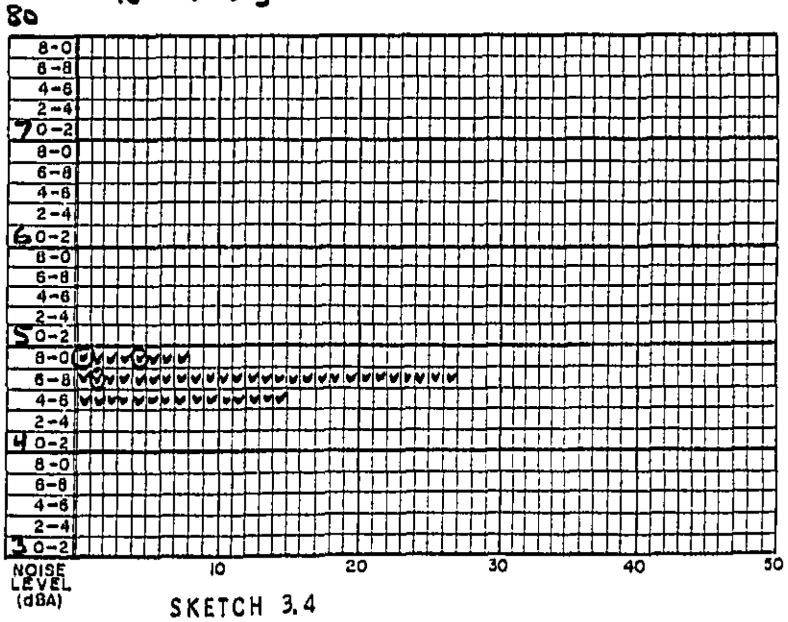
a) Setup

A suggested setup for the instrumentation is described here (see Sketch 3.1): The sound level meter is mounted on the tripod so that the person taking the readings has both hands free. A watch (or stop watch) is strapped to the top of a clipboard holding the data sheets (Figure 3.1). With the clipboard in one hand, the sweep second-hand can be watched, and the A-level recorded on the data sheet every ten seconds. The earphones, which are connected to the sound level meter output, should be worn at all times. The meter should generally be set on "slow response" (see paragraphs 3.1 and 3.7 for exceptions).

b) Procedure

- Every ten seconds, on the mark, read the A-level from the sound level meter. For this survey technique, the A-levels are grouped into "windows" - each two decibels wide (see the data sheet, Figure 3.1). The range of noise levels between 50 and 60 dBA, for example, is divided into these windows: 50-52 dBA, 52-54 dBA, 54-56 dBA, 56-58 dBA, and 58-60 dBA.
- Record the A-level on the data sheet as a check-mark in the appropriate window. Work from left to right within each window, as shown in Sketch 3.4.
- After 50 samples (8 minutes, 20 seconds), test the samples by the criterion discussed below. If the samples meet the criterion, then the measurement is complete. If not, then another 50 samples must be taken and the test repeated.

$L_{10} = 49 {}^{+1}_{-3}$ dBA



SKETCH 3.4

c) Evaluation and Criterion

After each group of 50 samples has been taken, the following test is made:

- Counting down from the top of the data sheet (and from left to right within each window), circle the "test samples" shown in the accompanying table.

  For instance, after 50 samples have been taken, then the 1st, the 5th, and the 10th samples from the top are circled. These three test samples constitute the L_{10}, flanked by its upper and lower error limits.

- Criterion: If these three test samples fall into three contiguous windows, then the measurement is complete. Otherwise, another 50 samples must be taken and tested again. (Sometimes the test samples will be even more closely packed, falling into only two (or perhaps just one) contiguous windows. In these cases, the criterion is also met.)

- If 100 or more samples have been taken, a process called skewing is allowed. By this process, the two outer test samples (the error limits) can be shifted by one sample (not one window), both in the same direction.

  For example, if the criterion is not met after 100 samples by testing the 5th, 10th and 17th samples, the criterion can be tested with the 4th, 10th and 16th samples or the 6th, 10th and 18th samples. Although this skewing procedure will not change the L_{10} value - nor will it change the number of samples between the upper and lower error limits - it can sometimes provide the necessary accuracy without requiring further sampling. However, if the criterion is still not met after skewing, then another 50 samples must be taken, and so on.

d) Results

Once the test criterion has been met, then the L_{10} has been determined with 95 percent confidence to fall between the upper and lower error limit test samples.

The final step is taken by assigning A-level values to the three test samples. It is not possible to know exactly what noise level each of these three check marks represents, since this information was lost when the two-dBA window was chosen. To be conservative, A-level values are assigned to overestimate the error. This is done by choosing the highest A-level in the upper limit window and the lowest A-level in the lower limit window. For uniformity, the L_{10} is chosen to be the center of the L_{10} window. For example, in Sketch 3.4 the results would be stated as follows:

L_{10} = 49 dBA, within maximum limits of 46 dBA and 50 dBA

In another notation,

$$L_{10} = 49 {}^{+1}_{-3} \text{ dBA}$$

In Figure 3.2, a more complex sequence of ambient readings is shown - in 50-sample increments. As can be seen, the error window becomes progressively narrower the more samples are taken. Note that the test samples have been skewed downward for the 100-sample test.

TABLE OF TEST SAMPLES

Total Number of Samples	Upper Error Limit	L_{10}	Lower Error Limit	Allowable Skewing
50	1st sample	5th sample	10th sample	none
100	5th	10th	17th	one
150	8th	15th	23rd	one
200	12th	20th	29th	one
250	16th	25th	35th	one
300	20th	30th	41st	one
350	25th	35th	47th	one

3.7 MEASUREMENT HINTS

a) Attenuator Setting

Be prepared to make quick changes in the attenuator setting of the sound level meter as trucks or cars, passing quickly by, cause significant changes in sound levels. For example, a close truck passby may cause the noise level to rise quickly from 70 dBA to 90 dBA. In this case, you should anticipate the higher level and shift the attenuator ahead of time. After a bit of practice, you should be able to anticipate the attenuator setting that will be required when the second hand of the timing watch reaches its 10-second point. It is better to lose some 10-second readings off the bottom end of the scale than off the top. The readings missed off the top of the scale are more likely to be important in determining the (near-peak) L_{10}.

b) Fast Meter Response

Sometimes certain noises will not be considered part of the ambient to be measured (see Section 3.2 above). When this is the case, it is necessary to read between these noises. If one of these noises controls the noise level at a 10-second mark, then the mark is skipped and no reading is taken until the next mark. The "metronome" character of the 10-second marks should be retained, since it is important to avoid introducing operator bias into the sampling procedure.

Erroneous readings due to some unwanted noises, such as wind noise on the microphone or barking dog noise, are difficult to avoid. For this type noise, it is recommended that the meter be switched to the "FAST" response. On this response, the meter will quickly settle back to the ambient noise level between wind gusts or dog barks, to allow readings on intermediate 10-second marks.

Remember that the measured L_{10} is the L_{10} for the measurement time period only. For example, if 100 samples were taken before the criterion was met, then the noise was sampled over 1000 seconds (approximately 20 minutes). The L_{10} pertains to that 20-minute period only. It says nothing about the prior or subsequent time periods. For this reason, it may be desirable to collect further samples, to extend the total time period. As discussed above, the accuracy depends only upon the number of samples taken. Therefore, if it is desired to sample over a longer time period, then the sample interval may be changed to 20 or 30 seconds, to save work. In this manner, a smaller number of samples will be spread uniformly over a longer time period, that might more realistically be said to typify the measurement site.

3.8 MATHEMATICAL BASIS

An examination of Figure 3.2 visually indicates the meaning of the L_{10} noise level. Graphically it is apprent that the noise exceeded the L_{10} for 10 percent of the time. Notice that the total time period was of no importance in determining the L_{10}. Whatever the time period is, the L_{10} is exceeded for 10 percent of the total time.

For any time period, we wish to sample the noise to determine the L_{10}. If we sample it continuously, then we obtain the exact L_{10} for that time period. If we do not sample it continuously - but at 5- or 10-second intervals, for instance - then we obtain only an approximation of the exact L_{10} for that time period. The error involved depends upon the number of samples we take. The more samples, the less error.

The mathematicians can tell us our error if we sample in the proper manner. The most straightforward sampling procedure is to sample randomly, i.e., to space the samples randomly over the total time period. This is a very inconvenient procedure to follow in the field. Luckily, the mathematics is equally valid if the sampling is performed at regular time intervals, say every 5 or 10 seconds, provided the noise level itself varies randomly; we are going to assume it does in computing our measurement error. Because this assumption is not strictly correct, the actual error is less than computed; so we are erring on the safe side.

The full mathematical basis for determining the measurement error is contained in the appendix to this chapter. It requires uniform sampling, i.e., spaced equally in time. The procedure then predicts the 95 percent confidence limits of the L_{10}, independent of the character of the noise fluctuations. (The distribution does not have to be Gaussian, for instance.) All that is of importance is the number of samples taken. The more samples, the greater the accuracy.

AMBIENT NOISE SURVEY DATA SHEET

POSITION:
ENGINEER:
JOB NO. ________
DAY OF WEEK: ________ DATE: ________ TIME: BEGIN ________ FINISH: ________
CAL: BEGIN ________ FINISH: ________
NOTES AND SKETCH:
SKY: ________
WIND: ________
dBA L_{10}: ________
LIMITS, dBA: ________

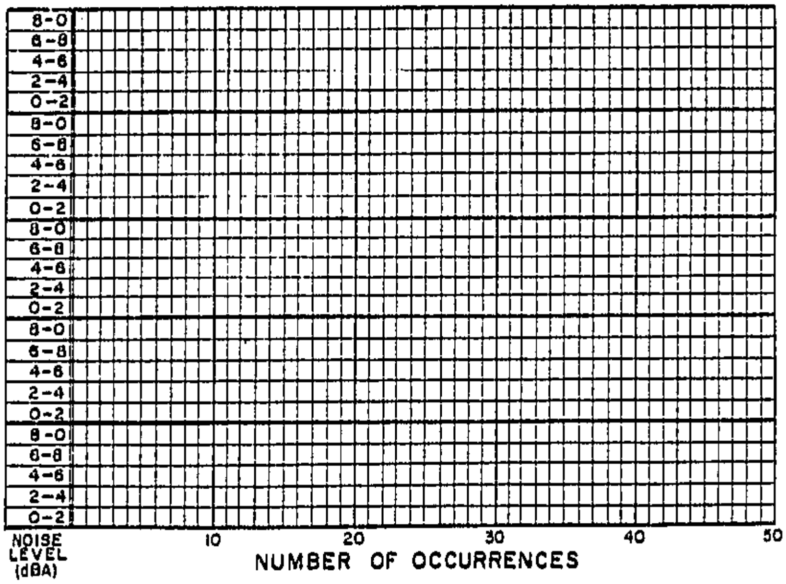
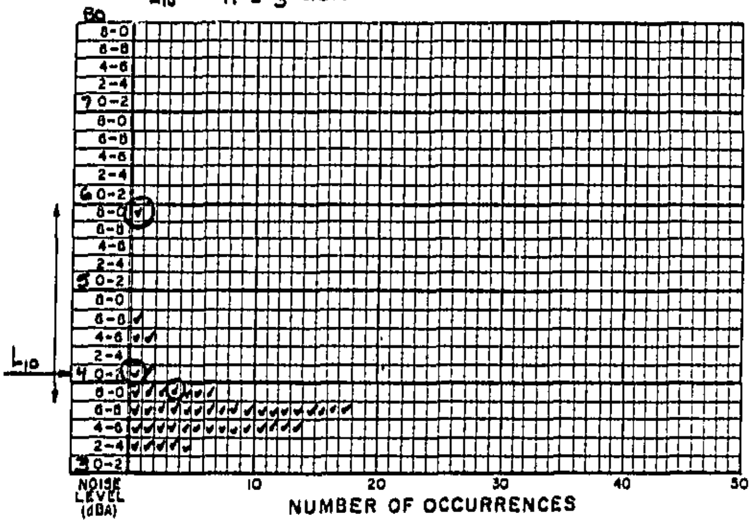


FIGURE 3.1

(a) AFTER 50 SAMPLES

$L_{10} = 41 {}^{+19}_{-3}$ dBA



(b) AFTER 100 SAMPLES

$L_{10} = 43 {}^{+5}_{-3}$ dBA

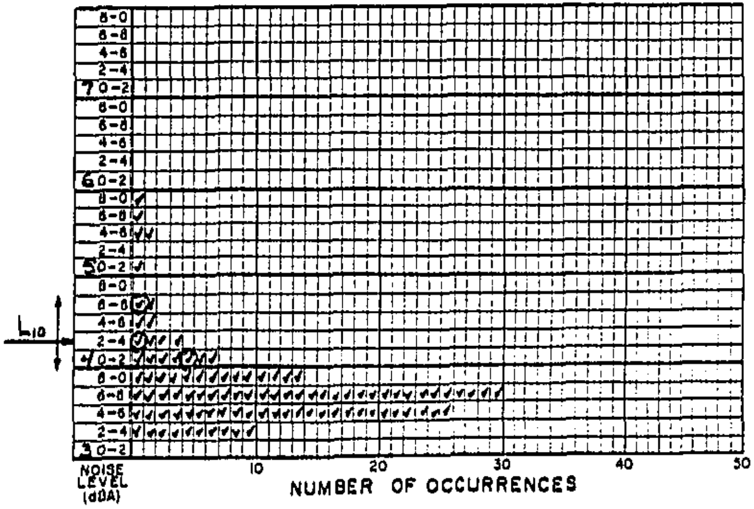
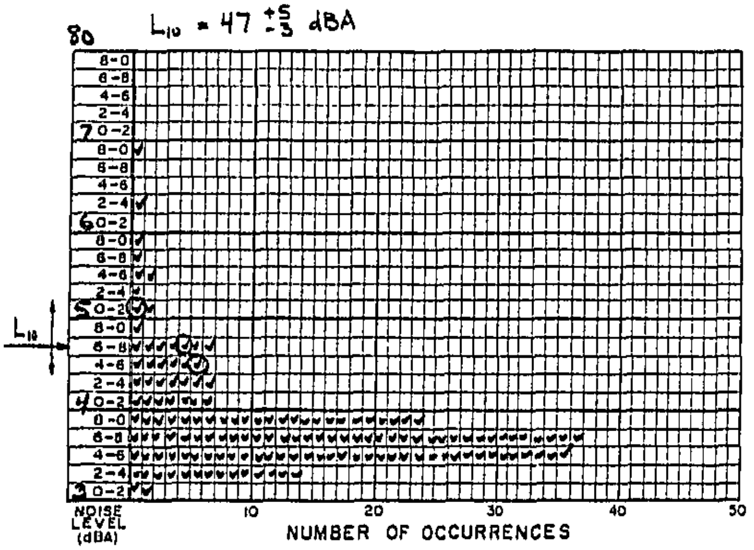


FIGURE 3.2 SEQUENCE OF AMBIENT READINGS - IN 50-SAMPLE INCREMENTS

(c) AFTER 150 SAMPLES

$L_{10} = 47 \, ^{+5}_{-3}$ dBA



(d) AFTER 200 SAMPLES - CRITERION MET

$L_{10} = 47 \pm 3$ dBA

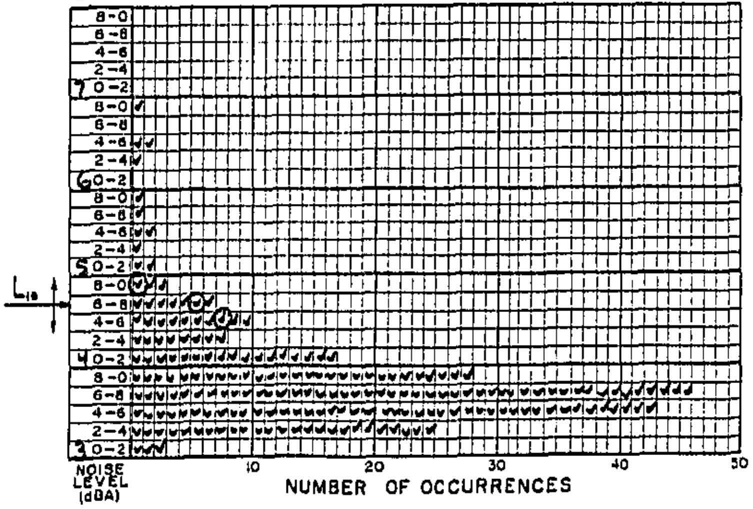


FIGURE 3.2 (continued)

APPENDIX
METHOD OF DETERMINATION OF CONFIDENCE LIMITS AND COEFFICIENTS

Assume that a total of n statistically independent noise levels l have been measured from the same population. Assume, further, that these noise levels are ordered according to their magnitudes, and let the sequence of these ordered levels be denoted by l_1, $l_2, \ldots l_n$, where the highest measured level is denoted by l_1 and the lowest is denoted by l_n.

Let L_p denote the p*th* percentile noise level as determined by the infinite population from which the n samples have been drawn. L_p is defined by,

$$\int_{L_p}^{\infty} f(l)dl = p, \tag{1}$$

where $f(l)$ is the probability density function of the noise levels from which the samples have been drawn. Thus, the probability is p that a randomly drawn sample will have a level l higher than the level L_p. The problem is to estimate L_p, for a given value of p, from a finite set of ordered samples l_1, $l_2, \ldots, l_n$.

Assume that n samples have been drawn and ordered as described above. Consider the event $l_r > L_p > l_s$ where $r<s$; that is, the event that the r*th* noise level is higher than L_p and the s*th* noise level is lower than L_p. This event is equivalent to the compound event that exactly r measured levels are higher than Lp *or* exactly r+1 measured levels are higher than Lp *or* ... *or* exactly s-2 measured levels are higher than L_p *or* exactly s-1 measured levels are higher than L_p. These events are mutually exclusive; therefore, the probability of this compound event is the sum of the probabilities of the individual events. Now, according to Eq. 1, the probability is p that any one noise level measurement is larger than L_p. Since the measured levels are assumed statistically independent, the probability that exactly k of the measured levels are higher than L_p is the probability of exactly k "successes" in a set of n Bernoulli trials, where the probability of the "success" of a single trial is p. In such a situation, the probability of k successes is

$$\binom{n}{k} p^k (1-p)^{n-k} , \tag{2}$$

where

$$\binom{n}{k} = \frac{n!}{(n-k)!k!} . \tag{3}$$

Thus, the probability of the above described compound event is obtained by summing the probabilities (2) for k=r, r+1, ..., s-2, s-1; that is

$$\Pr\left[l_r > L_p > l_s\right] = \sum_{k=r}^{s-1} \binom{n}{k} p^k (1-p)^{n-k} \tag{4}$$

Equation 4 expresses the probability that at least r but less than s noise level measurements fall above the level L_p. Notice that at no point have we made any assumptions about the form of the noise level probability density function $f(l)$.

Let us now designate $\Pr\left[l_r > L_p > l_s\right]$ by γ; i.e.,

$$\Pr\left[l_r > L_p > l_s\right] = \gamma . \tag{5}$$

Then, by definition, γ is the confidence coefficient that the r*th* and s*th* measured levels satisfy the relationship $l_r > L_p > l_s$; l_r and l_s are known as the upper and lower confidence limits for the p*th* percentile noise level L_p.

Table 3.1 lists values of γ for selected sets of values of n, r, and s, where all values listed are for the case where p = 0.10. The values were computed using the right-hand side of Eq. 4.

TABLE 3.1 - CONFIDENCE COEFFICIENTS

Number of Samples, n	Lower Error Limit, r	Upper Error Limit, s	Confidence Coefficient, γ
350	24	46	0.949
350	25	47	0.950
350	26	48	0.944
300	19	40	0.952
300	20	41	0.957
300	21	42	0.955
250	15	34	0.950
250	16	35	0.956
250	17	36	0.952
200	11	28	0.949
200	12	29	0.956
200	13	30	0.952
150	7	22	0.950
150	8	23	0.960
150	9	24	0.955
100	4	16	0.952
100	5	17	0.956
100	6	18	0.932
50	1	10	0.970
50	2	10	0.942

SAMPLE NOISE MEASUREMENTS

1. AUTO PASSAGE (Record Peak Sound Level during repeated passes)

Slow: ________, ________ dBC ________, ________ dBA

Fast: ________, ________ dBC ________, ________ dBA

2. TRUCK PASSAGE (Record Peak Sound Level during repeated passes)

Slow: ________, ________ dBC ________, ________ dBA

Fast: ________, ________ dBC ________, ________ dBA

3. PILE DRIVER (Peak Sound Level during continuous operation)

Slow: ________, ________ dBC ________, ________ dBA

Fast: ________, ________ dBC ________, ________ dBA

4. DOG BARKING (Record Peak Sound Level in each series of barks)

Slow: ________, ________ dBC ________, ________ dBA

Fast: ________, ________ dBC ________, ________ dBA

5. BIRD CHIRPS (Record Peak Sound Level of various calls)

Slow: ________, ________, ________, ________, ________ dBA

Fast: ________, ________, ________, ________, ________ dBA

6. CONDENSER MICROPHONE "POPPING" DUE TO HUMIDITY
(Do not record; listen only)

7. AUTOS ON WET STREET
(Do not record; listen for high frequency noise)

8. WIND NOISE ON MICROPHONE

Slow: ________, ________ dBC ________, ________ dBA

Fast: ________, ________ dBC ________, ________ dBA

9. RECORD TRAFFIC NOISE BETWEEN WIND NOISE BURSTS

Slow: (all dBA) ________, ________, ________, ________

Fast: (all dBA) ________, ________, ________, ________

10. TRAFFIC NOISE (Record "Snapshot" Reading every 10 seconds)
Use Slow, A-Scale:

________ ________ ________ ________ ________ ________

________ ________ ________ ________ ________ ________

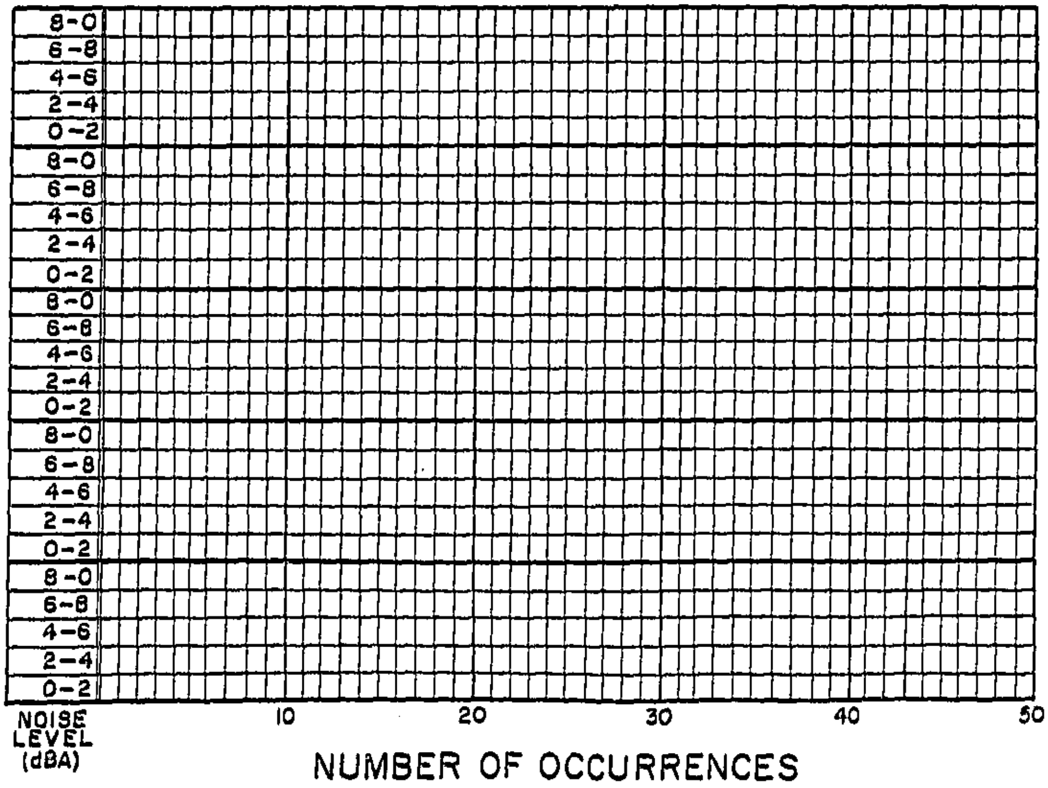
________ ________ ________ ________ ________ ________

AMBIENT NOISE SURVEY DATA SHEET

POSITION:
ENGINEER:
JOB NO. ________
DAY OF WEEK: ________ DATE: ________ TIME: BEGIN ________ FINISH: ________
CAL: BEGIN ________ FINISH: ________
NOTES AND SKETCH:
SKY: ________
WIND: ________
dBA L_{10}: ________
LIMITS, dBA: ________

Total # Samples	Upper Limit	L_{10}	Lower Limit
50	*1st*	*5th*	*10th*
100	*5th*	*10th*	*17th*
150	*8th*	*15th*	*23rd*
200	*12th*	*20th*	*29th*
250	*16th*	*25th*	*35th*
300	*20th*	*30th*	*41st*
350	*25th*	*35th*	*47th*

sample from the top

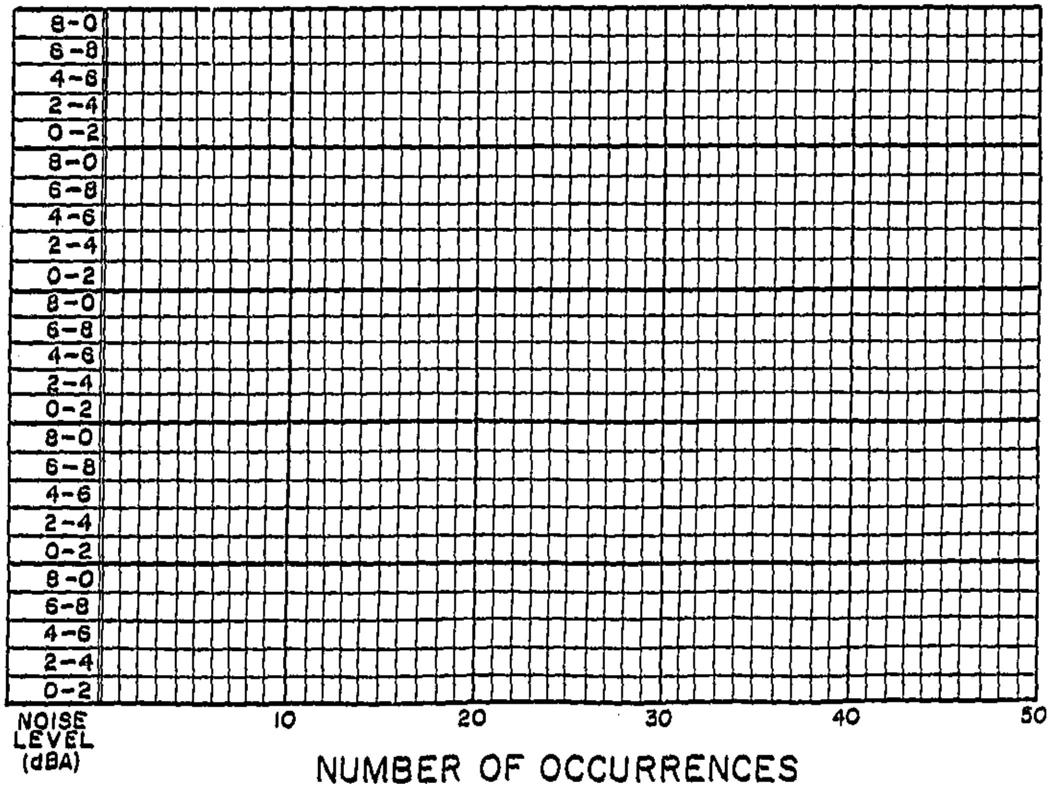


AMBIENT NOISE SURVEY DATA SHEET

POSITION:
ENGINEER:
JOB NO. ________
DAY OF WEEK: ________ DATE: ________ TIME: BEGIN ________ FINISH: ________
CAL: BEGIN ________ FINISH: ________
NOTES AND SKETCH:
SKY: ________
WIND: ________
dBA L_{10}: ________
LIMITS, dBA: ________

Total # Samples	Upper Limit	L_{10}	Lower Limit
50	1st	5th	10th
100	5th	10th	17th
150	8th	15th	23rd
200	12th	20th	29th
250	16th	25th	35th
300	20th	30th	41st
350	25th	35th	47th

sample from the top



CHAPTER 4

TRAFFIC NOISE PREDICTION

The material presented in the first three chapters was intended to provided the reader with an understanding of the fundamental concepts of sound and sound propagation, and a facility with the measurement of sound out-of-doors. In the present chapter, it is assumed that the reader has now acquired a working familiarity with these basic concepts because the fundamentals will be applied to the tasks of predicting the traffic noise level at some point given the vehicle volume and speed data, roadway characteristics, and a description of the path of sound propagation from the highway to the receiver.

4.1 PARAMETERS OF HIGHWAY NOISE

Before turning directly to the highway noise prediction method, perhaps some time should be devoted to relating the fundamental concepts of sound to vehicle and traffic noise situations.

4.1.1 Source Characteristics

The sources of highway noise are, of course, the vehicles themselves and the interaction between the vehicle tires and the roadway. In Chapter 2, the principal vehicle noise sources were identified and compared. It was shown, for example, that for trucks the principal noise sources are the exhaust noise propagated up the stack and the noise from the tire-roadway interaction, followed by the engine casing radiated noise. Although in the general method of traffic noise prediction, these individual source contributions are often lumped together as a single truck noise level, there are several reasons why it is important to differentiate between the several separate vehicle noise sources.

Our ears and the A-weighted sound level respond differently, not only to the different noise levels produced by the various sources, but also to the different frequency spectra, e.g., the low frequency stack noise versus the mid- and high frequency tire noise. Moreover, most available mechanisms of sound attenuation work more effectively on the mid- and high frequency components of sound. Thus, over long distances, for example, tire noise is reduced more than stack noise.

Different noise sources are at different heights. The tire noise typical of the high speed sound of automobiles may be attenuated quite nicely by a low wall or berm; whereas, the truck stacks may project over the top of the wall and propagate the exhaust noise directly to the area to be protected.

Tire noise is rather strongly dependent upon speed. But, since in the interest of efficiency, the trucker selects a transmission gear ratio that causes the truck engine to operate at nearly constant engine speed, the exhaust noise is thought to be almost independent of the vehicle speed. Any useful traffic noise prediction scheme must take account of the great difference in speed dependence between these two noise sources.

In order to simplify the method, most traffic noise schemes lump the contributions of the various noise sources into one source typical of trucks and one source typical of cars. The single source associated with the truck noise is assigned a single noise emission level, spectrum, height, and speed dependence. Similar properties are assigned the single, lumped car noise source. When traffic noise predictions are required for usual and uncomplicated traffic, roadway and propagation path situations, the lumped source assumption causes only minor error in the computed noise level. However, where adjustments are made to the general method to account for special complexities, e.g., special road surface material or barrier walls, care should be taken that the adjustments are applied correctly to the proper source. More will be said about this subject during later discussions of noise prediction methods and noise reduction design.

In the general prediction methods, the only distinction made between highway noise sources is the recognition of the two rather gross classifications, cars and trucks. This classification comes about naturally through the difference in the sources typical of the two vehicle types. Automobile noise is typically generated at pavement level, is speed dependent, and contains a predominance of mid- and high frequency sound energy. Truck noise is typically 15 or so decibels higher in level than automobile noise at highway speeds, is emitted both at pavement level and from the top of exhaust stacks some 8 to 10 feet high, is only partially speed dependent, and contains a predominance of low frequency sound energy.

Of course, there are a lot of vehicles, e.g., light trucks and buses that do not fall clearly into either classification. Fortunately, in most highway situations these vehicles are comparatively small in number and the predicted traffic noise levels do not suffer large errors because of the imprecise classification of these vehicles. It was recommended in Chapter 2 that when separate volumes of such vehicles are available, 50% of their number be assigned to trucks and 50% to automobiles.

The classification definitions differ slightly according to the prediction method used. For the NCHRP Report 117 method, automobiles are defined as, "passenger vehicles other than motor cycles, trucks of less than 10,000-lb gross vehicle weight, buses having capacity for 15 or less passengers." Trucks make up the remaining vehicles, "trucks of greater than 10,000-lb gross vehicle weight, buses having a capacity for more than 15 passengers."

The TSC Computer Program method defines the vehicle classifications in conformance with the *Highway Capacity Manual 1965** classifications, where a passenger car is normally defined as "a free-wheeled, self-propelled vehicle generally designed for the transportation of persons, but limited in seating capacity to not more than nine passengers, including taxicabs, limousines, and station wagons. Also included, for capacity purposes, are two-axle, four-tired pickups, panel and light trucks, which have operating characteristics similar to those of passenger cars, but not motorcycles." A highway truck is defined as "a free-wheeled vehicle having dual tires on one or more axles, or having more than two axles, designed for the transportation of cargo rather than passengers. Includes tractor-trucks, trailers and semi-trailers when used in combination. Excludes those two-axle, four tired vehicles that may be classified as a truck for registration purposes, but which have operating characteristics similar to those of a passenger car." For noise prediction purposes, buses are included in the definition of trucks.

PPM 90-2† defines a truck as a vehicle having a gross vehicle weight in excess of 10,000 lbs or a bus having a seating capacity in excess of eight passengers.

On the average, noise emission levels for automobiles range from 60 dBA to 75 dBA at 50 feet, depending upon the speed and pavement type. The average noise emission levels for highway trucks range from 82 dBA to 87 dBA at 50 feet, depending upon the speed, the road gradient, and general state of repair of the trucks.

So much for this review of individual vehicle noise sources, at least for the present. The purpose of this chapter is to instruct the reader on the methods for making predictions of traffic noise as emanating from many vehicles together. The reader may remember, at this point, that the traffic noise level at any point is continually fluctuating, and that in an attempt to describe the fluctuating level in terms of a single number, the descriptors L_{50}, L_{10}, L_{90}, L_e etc., were introduced. In order not to weaken the instructional worth of the next few paragraphs with statistical complications, the parameters of traffic noise to follow will be discussed in terms of their effect on the mean energy noise level, L_e, or generally, some descriptor of what could be thought of as the "average" noise reaching the observation point independent of the fluctuations.

Knowing the noise emission levels and positions of all the vehicles on a road, one could calculate the resulting noise level at any point of observation using the computational methods introduced in Chapter 1. Unfortunately, even vehicles very far away may have a significant effect on the observed average noise and the required calculation would become long and cumbersome. If the traffic is fairly dense, it could be assumed that the noise sources are spread out uniformly over the roadway, and a little mathematics would quickly yield an estimate of the average noise levels.

The material presented in the introductory part of this chapter borrows heavily from NCHRP Report 117 because the computational processes described in that handbook lend themselves to illustration of some of the basic principles of highway noise. There are other prediction schemes, however, and they use much of the same data and methods of analysis. There are also differences between the prediction schemes. Some of these differences are simply matters of format and minor procedural variation, while some of them are more fundamental in nature and will be discussed in detail at the conclusion of this chapter.

Figure 4.1 shows the NCHRP Report 117 relationships between hourly automobile volume and speed, and the resulting noise level observed at a point 100 feet from a straight, flat and infinitely long roadway carrying the automobile traffic. The familiar 3 decibel increase in noise level per doubling

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**Highway Capacity Manual 1965*, Highway Research Board Special Report 87.

†Policy and Procedure Memorandum 90-2; Transmittal 279, Subject: Noise Standards and Procedures; U.S. Department of Transportation, Federal Highway Administration, 8 February 1973.

of the number of noise sources can be found in this graph by comparing, for example, the 61 dBA level corresponding to a volume of 1000 vehicles per hour and a speed of 40 mph, to the 64 dBA level corresponding to an automobile flow of the same speed but of twice the hourly volume. While this law will hold for L_{eq} or the "average" noise, it ceases to hold for L_{50} at the left side of the graph where hourly volumes are low and the statistical aspects of the noise source distributions become more and more important. The general rule still holds, however — for a fixed average vehicle speed, the greater the automobile volume, the higher the average noise level at the observation point 100 feet away.

Figure 4.1 also shows the relationship between the average automobile speed and the noise level observed at 100 feet. For any fixed automobile volume flow, the 100 foot noise level increases with increasing average vehicle speed. Knowing how strongly the speed of an automobile affects its noise emission level, we might have expected that result.

The relationship between the noise level observed 100 feet from a line of trucks and the hourly truck volume and average speed is shown in Figure 4.2. The truck noise level, like the auto noise level, increases with increasing vehicle volume (at the rate of three decibels per volume doubling in the high volume region of the graph). Notice, however, that for any fixed hourly truck volume, the noise level at 100 feet *decreases* as the average truck speed increases. This dependence on speed is quite different from that of automobile traffic and is accounted for by the combined effects of: 1) the assumption that the individual truck emission levels are independent of speed; and, 2) the fact that for constant truck volume, as the average speed increases, the truck density (number of trucks per mile, for example) decreases, i.e., the trucks become farther apart. The average noise level some distance from the road decreases because the now widely-spaced trucks simply appear to be fewer in number. If the reader will refer to homework problems Number 1 and 2 in Chapter 2, he will recall that for a lane of traffic carrying 1200 uniformly spaced vehicles per hour, the number of vehicles per one-mile length was 40 when the average speed was 30 mph. When the average vehicle speed was increased to 60 mph, the number of vehicles per one-mile length was found to be only 20. Problem 3, parts c and d, demonstrated that the "average" sound level at an observation point some distance from the highway should be lower for the more widely spaced line of vehicles.

It is important to remember that the sound level produced by an individual truck is assumed, under this method of analysis, to be independent of speed. Of course, for any fixed volume, the automobile spacing also increases as the speed increases; but, the noise emission levels produced by individual automobiles increase so sharply with increasing vehicle speed that the reduction in noise due to the greater vehicle separation is more than balanced by the higher emission levels, thus the noise level versus speed relationship for automobile traffic shown in Figure 4.1.

A word of caution should perhaps be interjected at this point regarding the limitation of the above two graphs to highway situations where the traffic is essentially freely flowing. Of course, there are many situations where the traffic flow is intermittent, where cars and trucks operate in accelerating and decelerating modes, or where the principal sound source is an intermittent line of low speed, low volume trucks climbing a steep ramp grade. Simple and reliable noise prediction schemes for such complicated situations are not available. Some guidelines for making noise predictions for ramp traffic will be presented later in this chapter. But for the present, in order to build steadily an understanding of the principles of traffic noise, the discussions will be limited to noise prediction methods for steady, moderately high volume automobile and truck traffic.

4.1.2 Roadway Characteristics

The traffic noise level observed at some point distant from the highway depends upon the summed effects of a number of characteristics of the source and propagation path. Every characteristic describing the roadway actually manifests itself as a characteristic of either the source, or the propagation path, e.g., an upward grade of 5% increases the noise emission level of the truck; a depressed roadway embankment interrupts the path of sound propagation. Nevertheless, some of these characteristics can be more conveniently defined in terms of the roadway geometry and surface. Hence, part of the input data necessary to determine the traffic noise level has been classified as roadway characteristics.

An obvious characteristic of the roadway is its alignment. No highway is infinitely long and straight. A useful highway noise prediction scheme must take into account the fact that a highway that curves away from the observer, also places the sound sources farther from the observer than would a straight highway. The sound level contribution of each of these many sources could be treated separately and then added together at the observation point; however, an easier method, to be discussed later, is available consisting of breaking a curved road into a few short segments of straight roads for which the sound level contribution can be computed quickly.

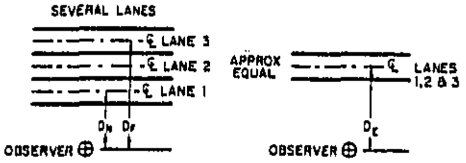
So far, the discussion has been limited to highways having only one lane of traffic, although such simple problems would only rarely arise in practice. One method of accounting for more than one traffic lane would be to analyze the sound level contribution of each lane separately and then add them together at the observation point.

Indeed, under certain circumstances, and with certain prediction models, this method is required to yield the accurate results desired.

For many situations a simplification can be made without a significant sacrifice in accuracy. The simplification involves finding the location of an imaginary single lane, that, given the total traffic volume for the highway, would yield, at the observation point, the same sound level as the actual several lane geometry. This "equivalent lane" is always located within the bounds of the several lanes, but never exactly at the centerline. The distance from the observation point to the equivalent lane is called the "single-lane-equivalent-distance", D_E, and is computed as follows:

$$D_E = \sqrt{D_N D_F}$$

where D_N and D_F are the distances from the observer to the centerlines of the near lane and far lane respectively as shown in the following sketch.



AT A DISTANCE $D_E = \sqrt{D_N \cdot D_F}$

SKETCH 4.1

For example, consider an observation point at a distance of 100 feet from the near lane, and 200 feet from the far lane of an eight lane highway. Then

$$D_N = 100 \text{ feet}, \; D_F = 200 \text{ feet}$$

$$D_E = \sqrt{D_N D_F} = \sqrt{100 \times 200} = 141 \text{ feet}$$

Now, instead of computing the noise level from each lane ranging from 100 to 200 feet away, the distance to the single-lane-equivalent is assumed to be 141 feet, and the traffic on all eight lanes is assumed to be located, without change in speed or operations, on the single-lane-equivalent.

Similar computations have been made for a wide range of geometries, and the results have been plotted in Figure 4.3. To illustrate the use of this graph, for the above example, having an observer-near lane distance, D_N, of 100 feet, and a 100 foot-wide highway, the equivalent lane distance, D_E, read from the vertical axis of Figure 4.3, is about 140 feet.

The type of road surface is another characteristic of the roadway that affects the generation of noise, and hence, the noise level observed at some distant point. The noise level computed by a standard noise prediction method can be simply adjusted upward or downward according to the type of road surface as defined in Chapter 2 on page 2-3.

Although it is convenient to account for variations in road surface by simply adjusting to total computed noise level accordingly, some judgments should be exercised in applying the tabulated adjustments. The adjustments should be applied uniformly to automobile noise; for trucks, however, because the exhaust noise is usually the controlling factor, the type of road surface generally does not significantly affect the noise levels produced by trucks. Occasionally, when the surface is very rough, and the vehicle speeds are above 60 mph or so, the addition of 5 decibels to truck noise is justifiable. The negative adjustment for smooth pavement should not be applied to truck noise.

Trucks laboring on gradients generally have slightly increased noise levels. The increased power demands on the engine are reflected in the higher noise levels radiated from the engine casing and exhaust stack. The gradient adjustments used in one traffic noise prediction scheme were tabulated in Chapter 2 on page 2-4.

These adjustments are to be applied directly to the computed truck noise levels. No adjustment is believed to be necessary for the automobile traffic. Note that all adjustments are positive, i.e., increases in noise level. Where a two-direction road segment is on a gradient, the adjustment can be applied equally to both sides of the highway without regard to whether the near truck lane is an up-grade or a down-grade. No adjustment should be made for an isolated, one-directional, down-grade road segment. The reader is invited to review Chapter 2 regarding these surface and gradient adjustments.

4.1.3 Propagation Path Characteristics

Given any combination of source characteristics and roadway characteristics, the noise level observed at a point some distance from the highway is strongly influenced by the propagation path the generated sound must take to reach the observer.

The most obvious characteristic of the propagation path is the distance between the noise source and the point of observation. For a true, continuous line source of sound, and where there is clear line of sight from the observer to all parts of the line, the sound level decreases as the sound propagates away from the source at the rate

$-10 \operatorname{Log}_{10} \frac{D}{D_0}$, or 3 decibels per doubling of

of distance, where D_o is some reference distance and D is the distance to the observation point in question. Practically, highway traffic is not quite a true line source, and there is rarely clear line of sight to every part of the road. Relationships developed from an experimental investigation and an emperically derived model of traffic noise resulted in the noise level vs. distance curves presented in NCHRP Report 117 which show the noise reduction with distance to be somewhat greater than 3 decibels per distance doubling for highway traffic situations where nearly clear line-of-sight is had from the observer to most of the highway.

The above relationships apply only to cases in which the highway can be considered infinitely long, straight, and flat. In practical situations, accounting must be taken of the distance relationships between the observer and a roadway of complicated geometry. The specific computational procedures for the more complex analyses are embodied in the individual prediction scheme and will be discussed in context.

There are certain other characteristics of the propagation path, however, which can be discussed at this point in rather general terms. These characteristics are responsible for sound attenuation factors which serve to reduce the highway noise level at a point of observation by an amount in excess of that due simply to distance. The clearest example of such a characteristic is a wall or berm that breaks the line of sight from an observer to the road. Shielding of the noise source can be a very effective method of decreasing the noise level at some point of interest. The shielding need not strictly take the form of a wall, but could be due to roadway cuts, scattered houses, and maybe even trees and ground cover. The first requirement of an effective noise shield or sound attenuating device is that it lie along the path of sound propagation between the sound source and the observer. More will be said about these topics later in this chapter and also in Chapter 5.

Other, less obvious noise attenuation mechanisms include molecular absorption of sound energy in the air and meteorological effects. Air absorption was discussed in Chapter 1 and has been shown to be important only at distances of over 1000 feet or so. Meteorological effects such as variations in temperature, wind and humidity were also discussed in Chapter 1, and under the right conditions can substantially reduce the sound level reaching the observer, but, cannot significantly increase the amount of noise propagated over the moderate distances of interest here. Wind and temperature gradients however, cannot be depended upon on a regular basis to reduce the highway traffic noise levels, and for purposes of traffic noise predictions are generally ignored. This simplification results in predicted noise levels that are the highest levels expected to occur. On days when the meteorological conditions are adverse to the propagation of sound, the observed noise levels will be lower than those predicted. The effects of air absorption and the average effects of humidity are taken into account in a general way through the distance adjustments.

4.1.4 Statistical Descriptors of Traffic Noise

In the first part of this chapter, an attempt has been made to bridge the gap between the noise emission levels produced by individual cars and trucks, and the noise level produced at some distant point by a collection of vehicles on a highway. The presentation of material has been general, with the purpose being to convey to the reader a certain understanding of the principles of traffic noise and an intuition in how to analyse highway noise problems.

In order to present this overview, most of the discussion has been directed toward the traffic noise parameters determining the energy mean level, or the "average" noise level. But very near the traffic lanes, or when the traffic density is low, the fluctuations in the traffic noise level are large and the rules governing the "average" noise level are not so successfully applied to the more precise statistical descriptors of traffic noise.

Since the Design Noise Levels defined by PPM 90-2 are in terms of the 10 percentile level, the computation procedures must result in a prediction of the traffic noise also in terms of this statistical descriptor. Before studying the details of the prediction methods, several concepts involving the meaning of the 10 percentile level should be reviewed.

The 10 percentile level, L_{10}, is simply the noise level that is exceeded only 10% of the time. The time period in question can be any length. For example, the noise environment that a particular L_{10} describes could include seasonal trends in noise level, day-to-day variations, hour-to-hour and moment-to-moment fluctuations. Such an L_{10} could be determined simply by monitoring the noise level at some point over the period of a year. But predicting the L_{10} for a one-year period would require a great deal of information and a large number of calculations. Moreover, there is not much information available on how people might react to various 10 percentile levels integrated over a year's time. A better use of such extensive noise monitoring data would be to help us select the most meaningful time of day and time of year to make our L_{10} measurements.

The 10 percentile level becomes a more convenient and useful tool for evaluating highway noise if the time period of investigation is a small part of a day. If the time period is short enough, the traffic parameters of volume and speed can be considered to be constant over the period, and the variations in level that the corresponding L_{10} describes are those moment-to-moment fluctuations in level observed as various vehicles pass the observation point. On the other hand, the time period should not be so short that the L_{10} describes the passage of a single vehicle.

The fact that *hourly* traffic volumes are cited in PPM 90-2 for use in the computation of traffic noise levels is really a matter of convenience. One hour appears to be sufficiently short that the traffic volumes are fairly constant over the period and yet sufficiently long that a statistically large number of the moment-to-moment fluctuations are sampled. More importantly, the traffic data is normally available by the hour. The L_{10} corresponding to a particular hourly traffic volume and speed may be taken as representing the level exceeded for 10 percent of any period of time within that hour.

4.2 COMPUTATION OF TRAFFIC NOISE USING THE NCHRP 117 HANDBOOK METHOD

General considerations in the prediction of highway traffic noise have been discussed above. The purpose of this section is to instruct the reader in the use of one particular method of predicting highway traffic noise — that of NCHRP Report 117.

The entire prediction method is based upon the principle of adjustment. The 50 percentile level is established for a reference distance 100 feet from the near lane of an infinitely long, straight, flat roadway. Adjustments are then made to this reference level to account for other distances, roadway geometry, road surface characteristics, and shielding. Since the end result is to be in terms of the 10 percentile level, an appropriate adjustment is also made to the computed 50 percentile level.

In the next few paragraphs, these adjustment procedures are illustrated by example. All the tables and graphs in NCHRP Report 117 needed for the computations are included at the back of this chapter for convenience.

4.2.1 Reference Conditions

The first step in the prediction method is to find the 100 foot L_{50} reference noise level from Figures 4.1 and 4.1. The graphs have been discussed in general terms earlier in this chapter. However, an example at this time would serve to illustrate their use.

Suppose the traffic situation to be investigated consists of an hourly volume of 7200 vehicles with 7 percent trucks, or 6696 automobiles and 504 trucks, traveling at an average speed of 50 mph.

From Figure 4.1, the reference noise level at a point 100 feet from the highway due to 6696 automobiles at 50 mph is 71 dBA L_{50}.

From Figure 4.2, the reference noise level at a point 100 feet from the highway due to 504 trucks at 50 mph is 74 dBA L_{50}.

Of course, the total sound from the highway is the decibel sum of automobile level and the truck level. However, some adjustments to the reference levels will be applied to the truck level in amounts different from those applied to the automobile level. The engineer should get accustomed to keeping the car level separate from the truck level until the final computation. The 100 foot reference levels are usually not very interesting anyway. Usually one would like to know the noise level at some particular point of interest, or perhaps construct a graph of noise level versus distance.

4.2.2 Adjustments

a) Distance Adjustment. The noise level at any distance from a highway can be found simply by making a distance adjustment to the 100 foot reference level as defined by Figure 4.4. The standard distance adjustment is made to the 50 percentile noise level and follows the form

$-15 \text{ Log}_{10} (D/D_0)$, corresponding to a decrease in noise level of 4-½ decibels for a doubling of distance. There are several curves on this graph, however; and to determine the distance adjustment, one must know the distance from the observation point to the center line of the near lane and the width of the entire highway.

Suppose the highway has three lanes each direction with the directions separated by a 25 foot-wide median strip; and there are two points of interest — one at a position 100 feet from the near lane and one at a position 500 feet from the near lane. In Figure 4.4, the proper adjustments for this example can be determined using the curve labeled 100 (8), meaning a highway width of 100 feet which is approximately equivalent to eight travel lanes. (Note that it is the actual highway width that determines the proper curve, not the actual number of travel lanes, which in this example is six.) The adjustment for the 100 foot observer-near lane is minus two decibels. For a distance of 500 feet the distance adjustment is approximately minus 10 decibels. So far, the computations can be summarized as shown in Exhibit 4.1.

EXHIBIT 4.1

DISTANCE, WIDTH ADJUSTMENT, dBA

Item	100 feet Distance		500 feet Distance	
	A	T	A	T
L_{50} reference at 100 feet	71	74	71	74
Distance, width adjust	-2	-2	-10	-10
L_{50} at observer	69	72	61	64

The distance adjustment is applied equally to autos and trucks.

Note that the predicted 100 foot noise level is lower than the 100 foot reference level by two decibels. This difference is due to the fact that the traffic is not all concentrated on the near lane as assumed for the reference level computation, but rather spread over a highway width of 100 feet. Figure 4.4 contains *both* the distance adjustment and the single-lane-equivalent distance adjustment.

b) Single-Lane-Equivalent Distance. The six lanes could be replaced by a single lane yielding the same acoustic result, provided the single lane is located at a distance from the observer called the single-lane-equivalent distance, a distance somewhat greater than the observer-near lane distance. Since the single-lane-equivalent distance is required for the computation of some of the adjustments, it will be found for this example road using Figure 4.3. For an observer-near lane distance of 100 feet, the single-lane-equivalent distance, D_E, for a 100-foot wide highway is approximately 140 feet as computed in Section 4.1.2. For an observer-near lane distance of 500 feet, the single-lane-equivalent distance, D_E, is approximately 500 feet.

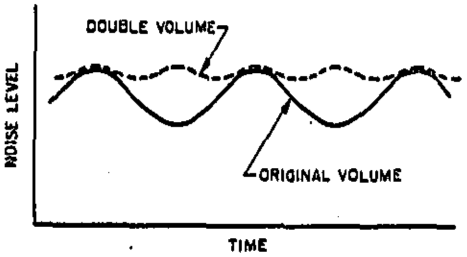
Actually, the equivalent lane distance for the latter case can be computed to be 547 feet. The resolution of Figure 4.3 simply does not permit reading the graph to this degree of accuracy. Fortunately, for a 100 foot-wide highway, any observer-near lane distance of 500 feet or more is satisfactorily close to the corresponding single-lane-equivalent distance that the difference can be ignored. In general, whatever resolution Figure 4.3 provides is close enough.

c) L_{10} Adjustments. So far, the L_{50} noise level for the example problem has been computed for observer-near lane distances of 100 feet and 500 feet. But what is really required is the 10 percentile noise level, or L_{10}. Since the L_{10} is exceeded only 10 percent of the time as opposed to 50 percent of the time for L_{50}, an upward adjustment of the L_{50} can be expected to yield L_{10}. How much of an upward adjustment is required depends on three parameters only:

a. The hourly vehicle volume, V.
b. The average vehicle speed, S.
c. The single-lane-equivalent distance, D_E.

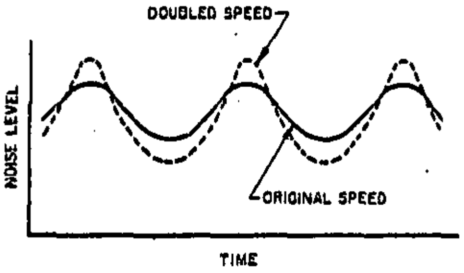
A little discussion on how the adjustment L_{10}-L_{50} depends on these three parameters can perhaps give the reader an intuitive feel for how the L_{10} should differ among various highway situations. Remember that while L_{50} is something like the "average" noise, the L_{10} puts a little more emphasis on the noise peaks that occur as vehicles pass the observation point. To a degree, the difference between L_{10} and L_{50}, L_{10}-L_{50}, is a measure of the size of the fluctuations in the noise level.

Imagine yourself standing quite near a moderately trafficked road. The L_{50} is determined in part by the noise levels of the individual vehicles passing, and in part by the sum of the noise levels of all the other distant vehicles on the road. The L_{10} is more influenced by the noise peaks of immediate vehicle pass-bys. Now, if the vehicle volume should double without affecting any other parameter, the "average" noise and the L_{50} would increase accordingly by several decibels. But the peaks would not change significantly; and some of the previous periods of relative quiet would now be filled with the noises of the additional vehicles as shown in Sketch 4.2. The fluctuations would not be as large. Hence, the adjustment, L_{10}-L_{50} decreases with increasing volume.



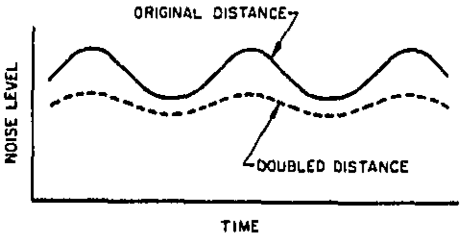
SKETCH 4.2

Imagine the original traffic situation again. Now imagine that the volume is unchanged while speed is doubled. This time the peaks may increase because of the speed increase; but the "average" noise would not increase so much because the vehicles would be more widely spaced creating deeper valleys of relative quiet, as shown in Sketch 4.3. The fluctuations would be larger. Hence, the adjustment, L_{10}-L_{50} increases with increasing speed.



SKETCH 4.3

Imagine the original situation again. Now imagine that the distance from the highway to the observation point is doubled. This time all the noise levels would be reduced; but, the peaks would appear to rise and fall so slowly that they would overlap more as shown in Sketch 4.4. In fact, at a great enough distance, the peaks would be indistinguishable from the background traffic noise. Fluctuations would be smaller. Hence, the adjustment, L_{10}-L_{50}, decreases with increasing distance.



SKETCH 4.4

To summarize, the adjustment L_{10}-L_{50} can be related inversely to the single parameter $\frac{VD_E}{S}$ shown in Figure 4.5, where:

V = hourly vehicle volume.

D_E = single-lane-equivalent distance, in feet.

S = average vehicle speed, in miles per hour.

The use of Figure 4.5 to find the L_{10}-L_{50} adjustment can be illustrated by continuing the example problem left in the previous section. The relevant data was as follows:

hourly vehicle volume, V = 6696 autos and 504 trucks

average vehicle speed, S = 50 mph

single-lane-equivalent distance D_E:

for 100 foot near-lane dist., D_E = 140 feet

for 500 foot near-lane dist., D_E = 500 feet

Then for the 100-foot near-lane distance, $\frac{VD_E}{S}$ equals 18,700 for autos with corresponding L_{10}-L_{50} = 2 decibels, and equals 1,410 for trucks with corresponding L_{10}-L_{50} = 6 decibels.

It is extremely important to notice that the L_{10}-L_{50} adjustment is computed separately for autos and trucks. If the total vehicle volume were erroneously used in this computation, the trucks, which are normally responsible for the greatest fluctuations in noise level, would appear to be high in volume resulting in smaller fluctuations, and, hence, a small L_{10}-L_{50} adjustment — less than 2 decibels in this example.

Similar computations for the observer position 500 feet from the highway results in an L_{10}-L_{50} adjustment of slightly more than one decibel for autos, and approximately 3 decibels for trucks.

The example computations so far can be summarized in Exhibit 4.2.

EXHIBIT 4.2

L_{10}-L_{50} ADJUSTMENT, dBA

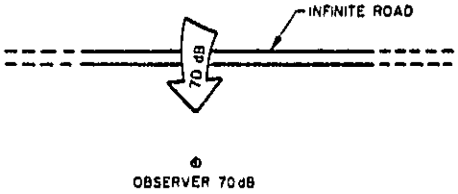
Item	100 feet Distance		500 feet Distance	
	A	T	A	T
L_{50} reference at 100 feet	71	74	71	74
Distance, width adjust	-2	-2	-10	-10
L_{50} at observer	69	72	61	64
L_{10}-L_{50} adjustment	+2	+4	+1½	+3
L_{10} at observer, by veh. type	71	76	62½	67
L_{10} at observer, summed	79		68½	

The bottom line has finally combined the auto levels with the truck level to obtain a single noise level of 79 dBA L_{10} for a point 100 feet from this highway. And a single noise level of 68½ dBA L_{10} is obtained for a point 500 feet from the highway. The only place it is truely safe to combine the auto levels with the truck levels is after all adjustments have been made. The levels were combined in accordance with the simple rules for combining the levels of two sources given in Table 1.1. Notice that some of the figures in this exhibit have been computed to one-half decibel accuracy. It may be meaningful to compute individual adjustments to a one-half decibel accuracy to avoid a cummulative error in summing several adjustments. However, little significance should be assigned to half-decibel refinements in the final answer.

There is one other item regarding this adjustment that should be discussed before moving on to the next topic. Figure 4.5 has been modified from the original NCHRP 117 graph to extrapolate the curve to lower values of the parameter $\frac{VD_E}{S}$. Many situations may arise in making highway noise predictions where this parameter for trucks is quite small. For example, for a point 25 feet from a local highway where the hourly truck volume is only 40 at a speed of 50 mph, the parameter $\frac{VD_E}{S}$ would be only 20. Figure 4.5 shows that the adjustment does not increase without bound for lower and lower values of $\frac{VD_E}{S}$, but rather, levels off quickly to a maximum of 13 decibels.

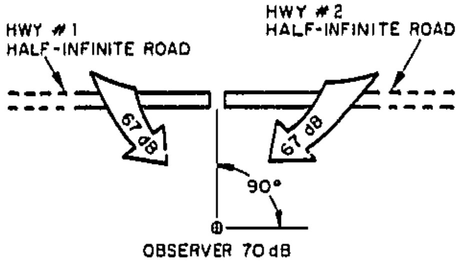
d) Road Segment Adjustment. What good is it to have learned to predict the L_{10} at some distance from an infinitely long, straight and level highway when no such highways exist? There are two answers to this question. Firstly, many highways are sufficiently long, straight and level that they may be assumed to be so without significant error. Secondly, simple adjustments can be made to the infinite highway results to yield a solution for a finite road segment having similar geometry and traffic.

While the adjustment method strictly applies to the mean energy level or "average" noise, in most practical situations it also applies to L_{50} and L_{10} with only minor error. Perhaps the best way to explain the logic behind the method is by example. Suppose the noise level at some distance from the infinite highway shown in Sketch 4.5 were 70 decibels.



SKETCH 4.5

Now the single highway could be considered to be two highways, each starting at the middle and extending infinitely outward as shown in Sketch 4.6.

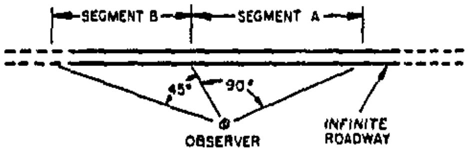


SKETCH 4.6

Of course, the two highways produce equal amounts of noise – – exactly half that of the original highway. From Chapter 1 it was learned that halving the noise sources should reduce the noise level by about 3 decibels, or that two equal noise sources produce a combined level that is higher than the level of either by 3 dB. Hence, it is obvious that each half of the infinite road must contribute 3 dB less noise to the observation point than the whole, or 67 decibels.

A mathematical investigation of the noise level contributions of road segments would show that the segment contribution is not strictly related to the length of the segment, *but solely to the angle subtended by the road segment*, with the vertex of the angle at the observation point. For example, the angle subtended by the original infinite highway was 180 degrees. The angle subtended by either half-infinite highways is 90 degrees. The adjustment from the infinite highway noise level to the half-infinite highway noise level can be expressed $10 \text{ Log}\left(\frac{90°}{180°}\right) = -3$ dB.

The following sketch illustrates two more examples of the relationship.



SKETCH 4.7

The adjustment for segment A is $10 \text{ Log}\left(\frac{90°}{180°}\right) = -3$ dB. The adjustment for segment B is $10 \text{ Log}\left(\frac{45°}{180°}\right) = -6$ dB.

In general, the rule for adjusting from infinite highways to highway segments can be written:

$$\text{Adjustment, dB} = 10 \text{ Log}\left(\frac{\theta}{180°}\right).$$

where θ is the angle in degrees, subtended by the highway segment.

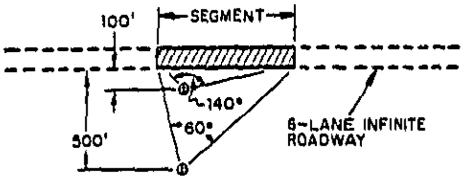
Clearly the angle θ could intercept any segment on the highway whatever. A corollary of the rule could be stated, "segments of a straight road make equal contributions to a common observation point at the vertices of the angles subtended by the segment when the subtended angles are equal." For example, if a certain segment along a road contributes 64 dB to the total noise level at some observation point, then any other segment subtending an equal angle would also contribute 64 dB to that point.

The foregoing remarks on road segments are all embodied in the Figures 4.6 and 4.7 borrowed from NCHRP Report 117. Consider Figure 4.7 first for finite road segments. The adjustment for a 90° segment is shown to be -3 dB. For a 45° segment the adjustment is -6 dB. For an 18° segment, the adjustment is -10 dB. Figure 4.7 is simply a graphic form of the adjustment rule discussed above.

But just as the rule applies to the general case of either finite or semi-finite road segments, so does Figure 4.7. In fact, Figure 4.6 for the special case of semi-finite roads is not needed. A brief introduction to its use will, nevertheless, be presented for the sake of completeness and because it has had wide distribution in NCHRP Report 117.

The confusion in using this graph arises in trying to determine whether the size of the angle θ is positive or negative. All will be clear in the use of this graph if the NCHRP Report 117 illustration shown in Figure 4.6 is replaced by the alternate illustration for the angle ϕ, and if the angles for θ on the abscissa of the graph are replaced by the bold lettered angles for ϕ. Now the graph corresponds exactly to the graph in Figure 4.7 and to the adjustment rule. For example, when the angle ϕ is 90° the adjustment is -3 dB. For an included angle ϕ of 18°, the adjustment is -10 dB.

As an illustration of the method for computing the sound level contributions of road segments, the example problem left off in the preceeding section will be continued. Let the geometry now be described as shown in Sketch 4.8.



SKETCH 4.8

From Figure 4.7, the adjustment for the 140° angle at the observer at 100 feet can be found to be -1 dB. For the observer at 500 feet the adjustment is -5 dB.

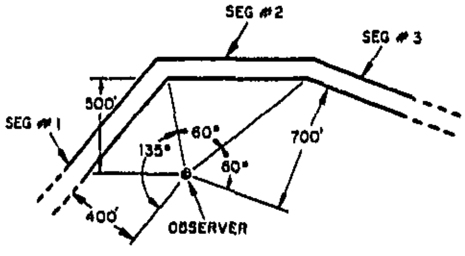
The computations for the example problem of determining the L_{10} noise levels from a road segment are summarized in Exhibit 4.3.

EXHIBIT 4.3

FINITE SEGMENT ADJUSTMENT, dBA

Item	100 feet Distance		500 feet Distance	
	A	T	A	T
L_{50} reference at 100 feet	71	74	71	74
Distance, width adjust	-2	-2	-10	-10
L_{10}-L_{50} adjustment	+2	+6	+1½	+3
L_{10} reference at observer	71	78	62½	67
Segment adjustment	-1	-1	-5	-5
L_{10} at observer, by veh. type	70	77	57½	62
L_{10} at observer, summed	78		63½	

In most practical highway noise problems, the highway is best described as made up of several highway segments. The noise level contributions are computed separately for each segment and are then added according to the rules of decibel addition to yield the noise level due to the traffic on the entire road. As a final example of the method, suppose that the highway segment shown in Sketch 4.8 is merely the center segment of the curved highway shown divided into three straight line segments in Sketch 4.9. All segments have the same traffic conditions.



SKETCH 4.9

The reader should make the required computations himself for this example case, assuming a roadway width of 100 feet and hourly traffic volumes of 6696 autos and 504 trucks moving at an average speed of 50 mph. Computational results can be compared with those shown in Exhibit 4.4.

EXHIBIT 4.4

SUMMATION OF SEGMENT CONTRIBUTIONS, dBA

Item	Seg. No.1		Seg. No.2		Seg. No.3	
	A	T	A	T	A	T
L_{50} reference at 100 feet	71	74	71	74	71	74
Distance, width adjust	-8½	-8½	-10	-10	-12½	-12½
L_{10}-L_{50} adjustment	+1½	+3½	+1½	+3	+1½	+3
L_{10} reference at observer	64	69	62½	67	60	64½
Segment adjustment	-1	-1	-5	-5	-5	-5
L_{10} at observer, by veh. type	63	68	57½	62	55	59½
L_{10} at observer, summed	69		63½		62	
L_{10} at observer, seg. total	71					

Notice that the 69 dBA contribution from segment 1 is within 2 decibels of the total 72 dBA for the entire road. Analysis by segment not only tells the engineer the total noise level at the observer; but, it tells him where noise control measures would have the most beneficial effect.

Notice also that the segment adjustment for segment number 1 was only -1 dB, i.e., the 69 dBA contributions of the segment is only 1 decibel less than the 70 dBA contributions from an infinite road under similar conditions. In practice, many cases exist where, although a road is not infinitely long, straight and flat, it can be treated as such with only a small error in the computed noise levels. In general, for practical purposes, a road segment can be considered an infinitely long highway if it extends in each direction a distance of at least four times the observer-near lane distance.

e) Other Adjustments. The basic computations discussed in the previous sections describe adequately the noise levels generated by smoothly flowing traffic on level roadways of normal surface material. In section 4.1.2 it was pointed out that the noise level produced may be altered by roadway gradients and by especially rough or smooth surface materials. The resulting change in the noise level observed at some distant point can be accounted for by a simple adjustment to the basic computations.

For vehicles traveling on very rough or very smooth pavement, the basic noise level computations are adjusted upward or downward, as the case may be, by 5 decibels in accordance with Table 4.1. Remember that only rarely should such an adjustment be applied to truck noise, and then only upward for trucks traveling at speeds above 60 mph and when the pavement is particularly rough. For the great majority of new surfaces, no adjustment is warranted. Occasionally, an old surface, worn badly by studded tires, or an intentionally grooved surface is encountered for which a 5 decibel positive adjustment is justified. Less frequently, a very smooth-coated surface warrants a 5 decibel negative adjustment. Such smooth surface roads, however, are rare because of their inherent low friction characteristics.

The positive adjustments to account for the increased noise of trucks on gradients are shown in Table 4.2. Remember that these adjustments are made only to truck noise levels, and are never negative, i.e., there is no adjustment for a downhill gradient. In most situations, where the two-directional lanes appear together on a gradient, the adjustment may be applied equally to both sides of the highway without regard to whether the near lane is an up-gradient or a down-gradient.

Consider roadway segment 2 of the example in the preceeding section to be on a 5 percent gradient, and to have a very smooth pavement surface. Adding 5 decibels to the truck noise levels; and subtracting 5 decibels from the auto noise levels results in the table of computations shown in Exhibit 4.5.

EXHIBIT 4.5

GRADIENT AND SURFACE ADJUSTMENTS, dBA AT 500 FEET

Item	Seg. No.2	
	A	T
L_{50} reference at 100 feet	71	74
Distance, width adjust	-10	-10
L_{10}-L_{50} adjustment	+1½	+3
L_{10} reference at observer	62½	67
Segment adjustment	-5	-5
Gradient	0	+5
Road surface	-5	0
L_{10} at observer, by veh. type	52½	65
L_{10} at observer, summed	66	

4.2.3 Simple Noise Contours

Very often it is informative to represent the noise levels over a broad area by noise level contours, or lines of equal noise level. Usually when the computational results are displayed in contour form, it is not expected that the contour lines are precisely accurate at every point, but that they are approximately accurate everywhere and show the general "shape" of the noise environment. When the noise level at a particular point is desired very accurately, it should be calculated for that point explicitly. Thus, generation of the contour lines involves a certain amount of estimating and smoothing.

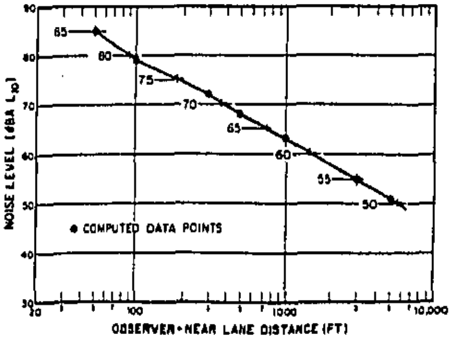
The first step in developing noise contours about a road is to draw a graph of noise level versus distance from the road. The L_{10} noise levels at distances of 100 feet and 500 feet were calculated for the example infinite highway discussed throughout this chapter and were summarized in tabular form in section 4.2.4. Suppose the computations were expanded to include several other distances with results shown in Exhibit 4.6.

EXHIBIT 4.6

NOISE LEVEL VS. DISTANCE

Distance from Near Lane, ft	50	100	300	500	1000	3000	5000
Noise level, dBA L_{10}	85	79	72	68	63	55	51

The reader should verify these results by computation. These values are then plotted on a semi-log graph paper with noise level in dBA L_{10} on the ordinate and log of the near-lane distance on the abscissa as shown in Sketch 4.10.



SKETCH 4.10

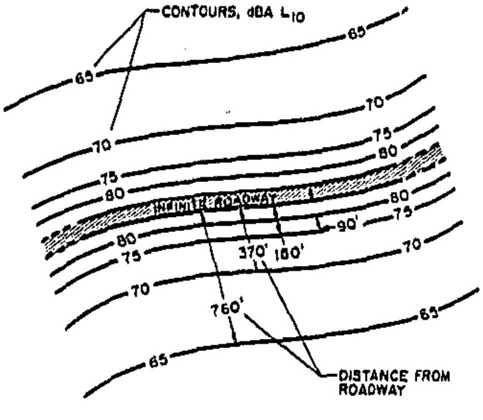
Contours can be drawn in 1, 2, 5 or 10 decibel intervals, or any other interval that seems appropriate. A common interval for highway traffic noise is 5 decibels. From Sketch 4.10 the table in Exhibit 4.7 can be constructed.

EXHIBIT 4.7

dBA L_{10} NOISE CONTOURS

Contour Line dBA L_{10}	85	80	75	70	65	60	55	50
Near lane distance, ft	50	90	180	370	760	1480	3000	5600

With the data in this table, noise level contours in 5 decibel intervals can be drawn around the highway as shown in Sketch 4.11.



SKETCH 4.11

For gently curving roads like the one shown in Sketch 4.11, the contour line can simply be drawn parallel to the road at the appropriate distance. Where the road curves sharply, noise levels at several specific points should be computed by summing the segment contributions as described in section 4.2.5. The noise contours should then be adjusted accordingly. Of course, the greater the number of specific points computed, the more accurate will be the contour line adjustments.

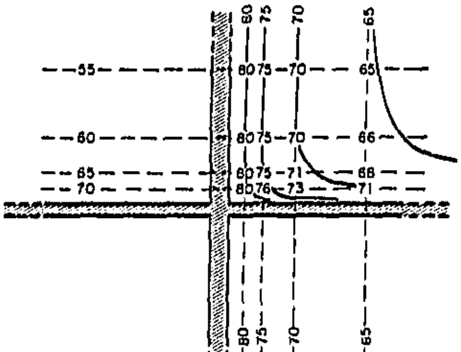
After the engineer has had some experience in contour drawing, he will learn how to best make adjustments to contour lines to accommodate various roadway geometries. Perhaps another simple example will speed somewhat the development of a little intuition in contour drawing. Suppose that two roads intersect at right angles in such a way that the traffic flow on each is continuous and uninterrupted. Suppose also that the noise level contours along each road individually have been calculated with the following results:

EXHIBIT 4.8

INTERSECTING ROAD CONTOURS

Noise Contour dBA L_{10}	Near Lane Distance, Feet	
	Roadway No. 1	Roadway No. 2
85	50	
80	90	25
75	180	50
70	370	90
65	760	180
60	1480	370
55	3000	760
50	5600	1490

Now the noise contours for the two roads together can be constructed as shown in Sketch 4.12.



SKETCH 4.12

The contour lines for each road have been drawn as though the other were not there. The combined levels at the intersection points of the two sets of contour lines have been computed by the simple decibel addition method shown in Table 1.1. For example, the combined level where the 65 dBA contour intersects the 70 dBA contour is actually 71 dBA. The 70 dBA contour line is drawn through all points of 70 dBA. Considerable visual interpolation is required; but the resulting set of noise contours shown here for only one quadrant can be quite informative and a real visual aid to understanding the noise environment at the intersection. If more accurate contours had been desired, we could have developed them by starting with contours for each road in 1 decibel intervals. Much less visual interpolation would have been required. More will be said about contour drawing in later sections of this chapter.

4.2.4 Barrier Attenuation

The subject of barrier attenuation was discussed in general terms in Chapter 2 and will be discussed again in detail in Chapter 5. The only purpose in mentioning the subject in this section is to acquaint the reader with how the noise reduction computations for barriers are integrated into the total NCHRP Report 117 method for highway traffic noise computation.

The amount of noise reduction achieved by a barrier wall, berm, depressed roadway or other form of noise shield is dependent on what angle of diffraction the sound must pass through in traveling from noise source to receiver. Thus, the noise reduction is dependent upon the interrelationships of the source and receiver locations, and the barrier height, length, and location. In Figure 4.8, the relationship between these parameters and the noise reduction achieved is shown for an infinitely long, straight, and level noise barrier at a constant distance from an infinitely long, straight and level road. For example, suppose such a pair of roadway and noise barrier existed such that:

EXHIBIT 4.9

Observer - Near Lane Distance, D_N = 500 feet
Equivalent Lane - Barrier Distance, D_R = 100 feet
Observer - Barrier Distance, D_B = 450 feet
Barrier Height, H = 15 feet

$H^2/D_B = 0.5$ and $H^2/D_R = 2.3$

For these two parameters, Figure 4.8 indicates a noise reduction of 15 dBA.

A few comments of clarification regarding the use of Figure 4.8 should be made here before continuing the example. The barrier section drawing accompanying the graph in Figure 4.8 is a little misleading. While the noise source is properly shown at pavement level for automobile traffic, the observer is usually not at ground level, but at 5 feet or more above the ground, depending on the terrain. Sometimes the observer is even at an upper story window of a building. The point is, the height "H" shown in Figure 4.8 is not the height of the barrier above the pavement, but rather the perpendicular penetration (or "effective height") of the barrier above the line-of-sight from source to observer as was shown in Sketch 1.4 on page 1-15.

With the line-of-sight connecting the pavement surface to the observer, the graph shown in Figure 4.8 yields the noise reduction achieved by the barrier for automobile noise. To account for the fact that the acoustic center of a line of trucks is not at pavement level, but several feet in the air, NCHRP Report 117 recommends that the noise reduction computed using Figure 4.8 be decreased by 5 decibels when applied to the truck noise. Hence, the noise reduction due to this example noise shield would be 15 decibels for cars and 10 decibels for trucks.

If a noise barrier of these dimensions were placed 50 feet from the example 6 lane highway used in this chapter for illustration of procedures, the noise level computations for a point 500 feet distant would be as follows:

EXHIBIT 4.10

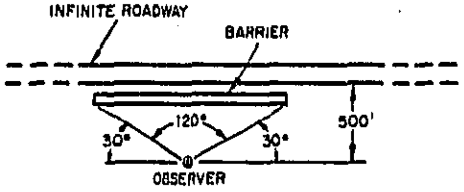
BARRIER COMPUTATIONS, dBA

	No Barrier		With Barrier	
Item	A	T	A	T
L_{50} reference at 100 feet	71	74	71	74
Distance, width adjust	-10	-10	-10	-10
L_{10}-L_{50} adjustment	+1½	+3	+1½	+3
L_{10} reference at observer	62½	67	62½	67
Segment adjustment	—	—	—	—
Barrier adjustment	0	0	-15	-10
L_{10} at observer, by veh. type	62½	67	47½	57
L_{10} at observer, summed	68½		57½	
Net Noise Reduction	11			

Note that the actual noise reduction worth of the barrier is neither 15 nor 10 decibels, but 11 decibels. Not until all computations are completed and the auto and truck contributions are added can the actual noise reduction for any particular traffic volume, speed and mix be determined.

Another important point to notice is the relative domination of the traffic noise by the trucks. In view of the importance of the truck noise, care should be taken to take accurate accounting of the influence of the truck source height on the noise reduction provided by barriers and shields. Simply subtracting 5 decibels from the automobile noise reduction is only accurate within a limited range of traffic conditions. A more general and more accurate approach to noise reduction computations is contained in Chapter 5 of this text.

So far, the computations for noise reduction have assumed that the noise shield is infinitely long yielding a noise reduction of 11 decibels. For practical noise shields of less than infinite length, the noise reduction can be far less impressive. Suppose the length of the barrier in the previous example is as shown in Sketch 4.13.



SKETCH 4.13

This road without a noise barrier produced 68½ dBA L_{10} at the 500 foot observation point, and with an infinitely long noise barrier produced 57½ dBA L_{10}. The road could now be broken into three segments - two 30° segments of a 68½ dBA road and one 120° segment of a 57½ dBA road. From Figure 4.7 the segment adjustment for a 30° subtended angle is -8 decibels. For a 120° segment the adjustment is about-1 decibel. Presented in tabular form, the computations for the summed noise level of the three segments would be:

EXHIBIT 4.11

INFINITE ROADWAY WITH FINITE BARRIER, dBA

Item	Observer at 500 Feet		
	30° Seg.	120° Seg.	30° Seg.
L_{10} reference at observer	68½	68½	68½
Segment adjustment	-8	-1	-8
Barrier adjustment	0	-11	0
L_{10} at observer	60½	56½	60½
L_{10} at observer, summed	64½		

Without the barrier, the noise level 500 feet from this infinite road was found to be 68½ dBA L_{10}. With an 11 decibel barrier subtending an angle of 120° the noise level was found to be 64½ dBA L_{10} - a noise reduction of, not 11 decibels, but only 4 decibels. Clearly, the length of a barrier is a very important noise reduction parameter.

The purpose of the foregoing exercise, however, was to introduce the reader to the concept of finite length barriers using the basic rules of decibel addition and segment adjustments. Fortunately, such computational processes do not have to be worked out separately for each problem. The computations for a range of barrier situations have been worked out for NCHRP Report 117 and are presented here as Table 4.3 where α is the angle subtended by the barrier, and β is the angle subtended by the road (β=180° for an infinite road). In the example above, the ratio α/β would be 0.66 or approximately 0.7. For the 11 decibel infinite barrier noise reduction, the corresponding finite barrier noise reduction read from Table 4.3 would be 4 decibels as computed earlier by the long method. A 15 decibel barrier that shields the observer from one-half the road (α/β = 0.5), would achieve a three decibel reduction in total noise from the infinite road as expected.

The angle β does not have to be 180° as for an infinite road. If the angle β, subtended by a road segment less than 180° (e.g., a 120° segment), the ratio α/β determines the shielding adjustment that should be applied to the noise level contribution of that road segment.

Noise reduction computational methods for depressed roadways, elevated roadways and other variations of the noise barrier will be discussed in detail in Chapter 5.

4.2.5 Check List for Handbook Computations

A suggested form for Traffic Noise Computation Tally is shown in Figure 4.9. This form does not provide work space for computations, but rather provides a storage place for the traffic data and for the computational results in an organized fashion. The four column headings on this form have been left blank because they could refer to any of several variables of interest, e.g., four different observer distances, four different road segments, four different highway elevations, etc. The only common restrictions of the four problems are that they must have the same traffic and highway width. The reasons for having four columns on the tally are simply that it is often convenient to have more than one on a sheet; and no more

EXHIBIT 4.12   Sheet 1 of 1

TRAFFIC NOISE COMPUTATION TALLY
NOISE LEVEL, dBA

Project ROUTE 532, DOGPATCH Engineer JRS

Segment POST 34 TO 35 - MAP 1301 Date 1 APRIL 1973

Autos/hr. 6696 Trucks/hr. 504 Miles/hr. 50

Highway Width 100 feet. Observer AS INDICATED

Comments ILLUSTRATE USE FOR SAME ROAD - DIFFERENT DISTANCES

	OBSERVER DISTANCE =	#1 100'		#2 500'					
	Item	A	T	A	T	A	T	A	T
L_{50} reference at 100 feet		71	74	71	74				
	Distance, width adjustment	-2	-2	-10	-10				
	L_{10}-L_{50} adjustment	+2	+6	+1½	+3				
L_{10} reference at observer		71	78	62½	67				
	Segment adjustment	-1	-1	-5	-5				
	Barrier adjustment	-15	-10	-10	-5				
Miscellaneous Adjustments	Gradient	0	+3	0	+3				
	Road surface	-5	0	-5	0				
	Foliage	0	0	-5	-5				
	Rows of houses	0	0	-4	-4				
L_{10} at observer, by veh. type		50	70	33½	51				
L_{10} at observer, summed		70		51					

EXHIBIT 4.13 Sheet 1 of 1

TRAFFIC NOISE COMPUTATION TALLY
NOISE LEVEL, dBA

Project ROUTE 532, DOGPATCH Engineer JRS

Segment POST 34 TO 38 – MAP 1301 Date 1 APRIL 1973

Autos/hr. 6696 Trucks/hr. 504 Miles/hr. 50

Highway Width 100 feet. Observer #2 AT 500'

Comments ILLUSTRATE SUMMATION OF SEGMENT CONTRIBUTIONS

		SEG #1		SEG #2		SEG #3			
Item		A	T	A	T	A	T	A	T
L_{50} reference at 100 feet		71	74	71	74	71	74		
	Distance, width adjustment	-8½	-8½	-10	-10	-12½	-12½		
	L_{10}-L_{50} adjustment	+1½	+3½	+1½	+3	+1½	+3		
L_{10} reference at observer		64	69	62½	67	60	64½		
	Segment adjustment	-1	-1	-5	-5	-5	-5		
	Barrier adjustment	0	0	-10	-5	0	0		
Miscellaneous Adjustments	Gradient	0	0	0	+3	0	+3		
	Road surface	-5	0	-5	0	-5	0		
	Foliage	0	0	-5	-5	-5	-5		
	Rows of houses	0	0	-4	-4	-10	-10		
L_{10} at observer, by veh. type		58	68	33½	51	35	47½		
L_{10} at observer, summed		68		51		47½			
L_{10} AT OBSERVER, SEGMENT TOTAL		68							

than four would fit. Exhibits 4.12 and 4.13 show the form filled out for the examples discussed in earlier sections of this chapter. Two different uses of the form are illustrated. Note that all addition within a column is simple algebraic addition. Adding the results of one column to another must be performed according to decibel addition. Where the noise contributions from several segments are added, the blank space at the bottom line of the tally sheet can be used for the summed, segment total as shown in Exhibit 4.13.

4.3 COMPUTATION OF TRAFFIC NOISE USING THE COMPUTER PROGRAM OF THE TRANSPORTATION SYSTEMS CENTER

There are many computational schemes available for the prediction of traffic noise; the method of NCHRP 117 is but one of them. Another method, and very useful method, is the computer program of the Transportation Systems Center of the Federal Highway Administration. In general, the computer program applies to the same highway traffic situations, and has the same limitations as the method of NCHRP Report 117.

1. The procedures consider only freely-flowing highway traffic. Stop-and-go traffic, and the effects of vehicle acceleration and braking are not included in the model.
2. The procedures assume a uniform standard atmosphere. Effects of wind and temperature gradients are ignored.
3. The procedures consider all noise sources to radiate sound equally in all directions.

The main advantages of the computer program method are that it can consider very many, and very complex, situations quickly and accurately. The program performs the statistical computations efficiently and leads directly to the answer in dBA L_{10}. A disadvantage of the computer method is that meaningful answers to complex problems often require copious quantities of input data. The computational results are no better than input data upon which the program operates. And even for very simple problems, preparing the computer program input data, then waiting for the results, can be a nuisance.

In order to provide a simple and direct method of predicting the traffic noise level for simple situations, the Transportation Systems Center used the computer program to develop a nomograph.

4.3.1 Nomograph Method for Highway Noise Prediction

This "Nomograph for Approximate Prediction of Highway Noise Levels" can be found in Report No. DOT-TSC-FHWA-72-1, Manual for Highway Noise Prediction, and is shown here in Figure 4.10. Strict application of this nomograph is limited to continuous, freely flowing traffic on a single infinitely long, unshielded, straight and level roadway.

The use of the nomograph may be explained through the following example shown in Exhibit 4.14 for an observer 500 feet from an infinite highway carrying 2400 vehicles per hour with 5% trucks traveling at a speed of 60 mph:

1. Draw a straight line from the left pivot point on the nomograph through the "5%" truck point on the "60 mph" line. Extend the straight line to the Turning Line A. In this example, the intersection is marked "A1".
2. Draw a second straight line from the intersection point A1 to 2400 veh/hr. on the vehicle volume line and note the intersection, B1, of this line with the vertical line B.
3. Draw a third line from point B1 to 500 feet on the "Distance to Observer" line. The intersection of this third line with the vertical line between marks the predicted A-weighted, 10-percentile noise level. For this example problem, the predicted noise level is 71 dBA L_{10}.

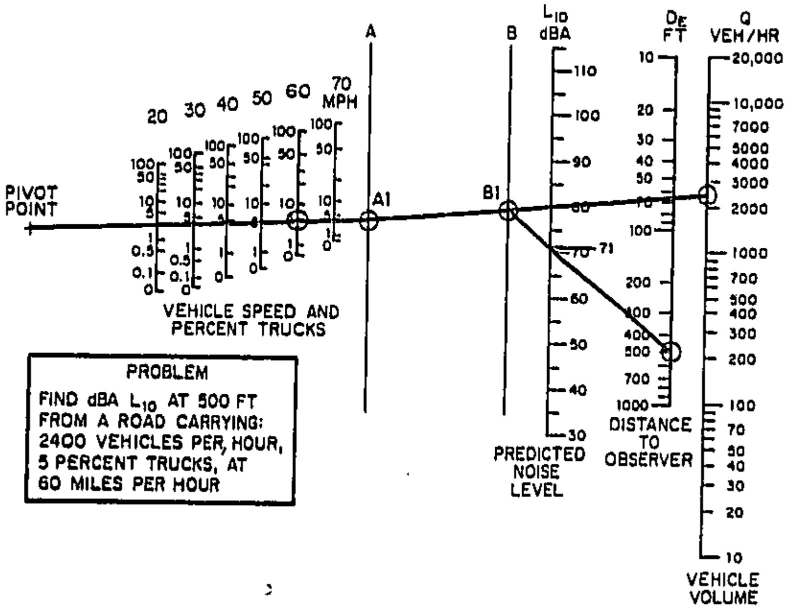
The nomograph method is particularly convenient in developing noise contours, since the distance corresponding to any desired noise level can be found simply by pivoting this third line about the point B1. For this example, noise contour line distances corresponding to 5 decibel steps would be:

contour line, dBA L_{10}	85	80	75	70
distance, feet	22	65	190	590

The reader is reminded that results of this nomograph method apply only to infinitely long straight and flat highways and should be used only for first approximations of the noise level predictions. For the idealized conditions for which this method was intended, however, the nomograph estimates noise levels typically higher than, but within 2 dBA of those levels calculated by the computer program.

EXHIBIT 4.14

NOMOGRAPH EXAMPLE PROBLEM
CARS AND TRUCKS TOGETHER

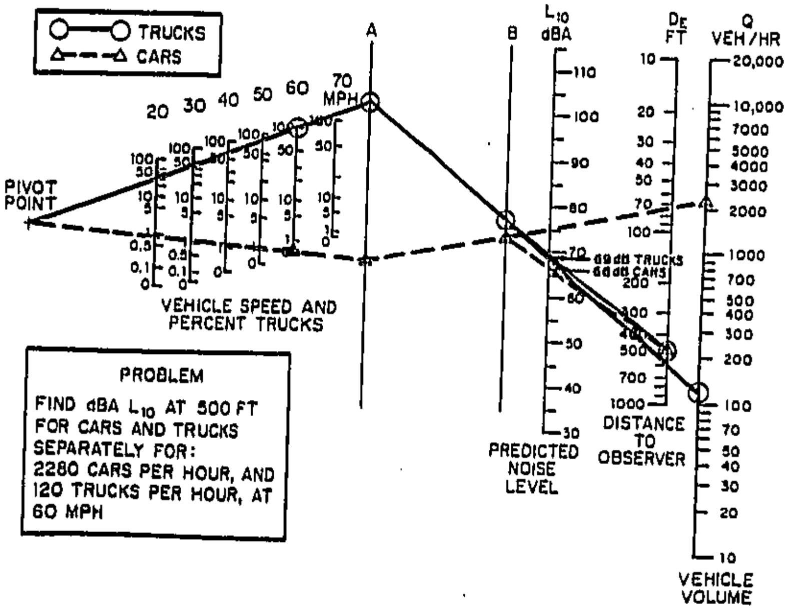


PROBLEM

FIND dBA L_{10} AT 500 FT FROM A ROAD CARRYING: 2400 VEHICLES PER HOUR, 5 PERCENT TRUCKS, AT 60 MILES PER HOUR

EXHIBIT 4.15

NOMOGRAPH EXAMPLE PROBLEM
CARS AND TRUCKS SEPARATELY



PROBLEM

FIND dBA L_{10} AT 500 FT FOR CARS AND TRUCKS SEPARATELY FOR: 2280 CARS PER HOUR, AND 120 TRUCKS PER HOUR, AT 60 MPH

The nomograph is more flexible that it appears. It is quite possible and useful to separate cars and trucks in the use of this nomograph just as was done in using the NCHRP Report 117 method. For example, the 2400 vehicles/hr. with 5% trucks could just as easily have been written 2280 cars per hour and 120 trucks per hour. To find the 60 mph truck noise contribution at 500 feet, in this example, simply use the 60 mph line at 100% trucks to find point A1. Connect A1 to 120 vehicles per hour to find B1. And connect B1 to 500 feet to find the truck, A-weighted, 10 percentile noise levels. This process and its counterpart for finding the automobile contribution to the 500 foot noise level is shown in Exhibit 4.15 yielding 69 dBA L_{10} for trucks and 66 dBA L_{10} for cars. Note that the truck noise level and the car noise level can be added logarithmically to yield the 71 dBA L_{10} combined level computed first in Exhibit 4.14.

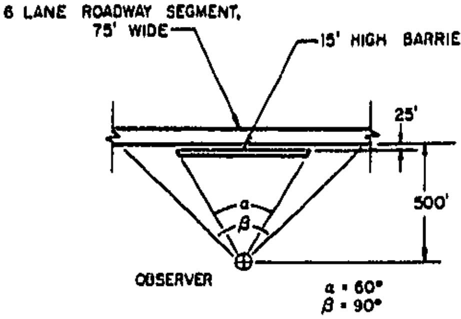
But the point of computing the truck noise contribution separately from the car noise contribution is that now, separated, the levels can be adjusted for barrier effects, gradients and road surface effects, etc., which treat car noise and truck noise differently. The separated car levels and truck levels may be entered into the Traffic Noise Computation Tally, Fig. 4.9, at line 4, "L_{10} Reference at Observer", adjusted as appropriate according to the methods of 4.2.2, and added logarithmically just as was done for the NCHRP Report 117 method. Only the steps of calculating the L_{50} 100-foot reference level and the L_{10} - L_{50} adjustment have been omitted from the computation.

How is the roadway width accounted for in using the nomograph method? The "Distance to Observer" line in the nomograph always refers to the equivalent lane distance, D_E, which can either be found from Figure 4.3 or calculated by the relation

$$D_E = \sqrt{D_N D_F}$$

where D_N and D_F are the distances from the observer to the centerlines of the near lane and far lane, respectively.

As an illustration of the method, consider the problem shown in Sketch 4.14 for a traffic volume of 2400 vehicles per hour with 5 percent trucks and an average vehicle speed of 60 mph. The objective is to determine the L_{10} noise level at the 500-foot observation point due to the traffic on this 90° road segment.



SKETCH 4.14

Enter the traffic and roadway data into the Traffic Noise Computation Tally sheet as shown in Exhibit 4.16.

Determine from the nomograph the L_{10} reference levels, for cars and trucks separately, for an infinite roadway carrying the given traffic. The distance is the single lane equivalent distance, 535 feet. Then, from the segment adjustment rule,

$$\text{Adjustment, dB} = 10 \log \frac{\beta}{180} = 10 \log \frac{90}{180} = -3\text{dB}$$

The reference levels are reduced by 3 dB for the unshielded segment of roadway.

Determination of the barrier adjustment requires two steps - one to determine the basic effectiveness or worth, of a 15 foot high barrier, and one to account for the fact that the ends of the roadway segment are not completely shielded by the barrier.

Assume that the observer height is 5 feet above the pavement level; then, a computation for the "effective height", H, for a barrier 15 feet above pavement level, 50 feet from the single lane equivalent and 475 feet from the observer would yield $H \approx 14.5$ feet. From Figure 4.8, the effectiveness of this barrier, roadway, observer geometry is 15 dB noise reduction for cars, and 10 dB noise reduction for trucks. Note that the distance of the barrier from the single lane equivalent is

$$D_R = \sqrt{D_N D_F} = \sqrt{25 \times 100} = 50 \text{ feet}$$

and does not involve the observer or the single lane equivalent distance to the observer.

From Table 4.3, the adjustments for a 15 dB car/10 dB truck barrier that shields only 60° of a 90° road segment are -5 decibels

EXHIBIT 4.16 Sheet 1 of 1

TRAFFIC NOISE COMPUTATION TALLY
NOISE LEVEL, dBA

Project EXAMPLE BARRIER PROBLEM Engineer JRS

Segment — Date 1 APRIL 1973

Autos/hr. 2280 Trucks/hr. 120 Miles/hr. 60

Highway Width 100 feet. Observer AT 500'

Comments SEE SKETCH 4.14

		500' DISTANCE							
Item		A	T	A	T	A	T	A	T
L_{50} reference at 100 feet									
	Distance, width adjustment								
	L_{10}-L_{50} adjustment								
L_{10} reference at observer		66	69						
	Segment adjustment	-3	-3						
	Barrier adjustment	-5	-4						
Miscellaneous Adjustments	Gradient								
	Road surface								
	Foliage								
	Rows of houses								
L_{10} at observer, by veh. type		58	62						
L_{10} at observer, summed		63½							

for cars and -4 decibels for trucks. Exhibit 4.16 shows the segment adjustments and the barrier adjustments entered in the tally sheet, and the summed result of 63½ dBA L_{10} at the observer.

Generally, when the nomograph method is used, the gradient adjustment and the adjustment for accelerating trucks are assumed to be zero. The reason for this simplification stems from the mean noise emission level assumed in the computer program for highway trucks. Recall from Chapter 2 that NCHRP Report 117 truck noise emission levels are assumed to be uniformly 82 dBA under normal operating conditions and 5 decibels higher for accelerating trucks. The TSC computer program mean truck emission level is assumed to be 87 dBA under all operating conditions. It is probable that this 87 dBA emission level is higher than the levels typical of trucks in low speed cruise conditions, but is about right for trucks operating under the wide throttle conditions typical of accelerations, climbing gradients, and high speed highway cruise. Therefore, no further adjustment is made to the highway truck-noise levels to account for gradients and accelerations.

4.3.2 Method for Computerized Prediction of Highway Noise

The TSC highway noise computer program, known as the Traffic Noise Prediction Model MOD 2, was designed to run on the IBM 7094 computer at TSC in the batch mode. The program is written in the FORTRAN IV language and can be used directly on most computer systems, and modified to be used in an interactive mode. In the present format, inputs are provided through punched cards, and outputs are provided through a line printer. The details of the organization of the computer program itself, main program, subroutines, and card listings can be found in Report No. DOT-TSC-FHWA-72-1, "Manual for Highway Noise Prediction (Appendix B)".

The main body of the above report is a user's manual for the computer program, while the "Appendix A" reviews the basic acoustic concepts and mathematical expressions embodied in the computational procedures. The user's manual is complete with sample cases and must be studied carefully by each new user. The discussion of the computer program method in the present section will be limited to a summary and clarification of the instructions, a few precautions to take, and suggested methods for problem analysis.

The input data is divided into five major classifications as follows:

1. Program initialization parameters
2. Road and vehicle parameters
3. Barrier parameters
4. Ground cover parameters
5. Receiver parameters

All data must be entered in the form of punched card.

The program initialization parameters must appear, one to a card, in the first of each series of problems and generally remain unchanged throughout an entire study.

a. Receiver height adjustment - With a single initialization parameter, the coordinates at all the receivers may be adjusted vertically upward by the number of feet specified. For example, if the input card data specifies all receivers at ground level, a simple receiver height adjustment at the beginning of the input data could move all receivers to ear level or second story window level.

b. Number of frequency bands - The program is capable of performing the noise level computations for eight octave bands of frequency, or for only one band, 500 Hz, which approximates closely the net behavior of the eight octave bands. Generally, the single frequency band computations are sufficiently accurate.

c. The standard deviation of noise levels of passenger cars - The standard deviation of automobile 50 foot emission levels has been set at 2.5 dB and should not be changed (see Chapter 2).

d. Source height adjustment for passenger cars - The height of the automobile noise source is usually at the pavement level where the tires interact with the road. This parameter should be left zero.

e. Standard deviation of noise levels of highway trucks - The standard deviation of highway truck 50 foot emission levels has been set at 3.5 dB and should not be changed (see Chapter 2).

f. Source height adjustment for highway trucks - The vehicle location data is defined by the roadway input data. To account for the fact that the effective truck noise source is really several feet above the road surface, a single height adjustment is entered at the beginning of the program. The effective height of a truck noise source in this program has been set at 8 feet and should not be changed (see Chapter 2).

g. Three other initialization parameters are available but not required. The parameters define the source characteristics of a third type of vehicle as yet undefined. The third vehicle was originally intended to be a "new" or future vehicle, but can be any vehicle for which an emission level, standard deviation and source height can be defined or estimated.

The remaining input data is unique to each problem and is also entered in the form of punched cards. In the following paragraphs, the data format and requirements are summarized.

Associated with each roadway must be the appropriate traffic data consisting of four quantities - the hourly automobile volume, average automobile speed, hourly truck volume and average truck speed.

The roadway data is entèred by the Cartesian (x,y,z) coordinates, in feet, of points on the roadway surface. It requires at least two points to define a roadway. If the roadway changes grade or is curved, it is divided into straight-line segments, each segment defined by its two end points. If traffic enters or leaves a road, or if the vehicle speed changes, a new roadway must be defined, each roadway having constant traffic volume and speed. How many roadways and roadway segments are required to describe accurately the noise level at a receiver depends upon the geometry. For a receiver located far from a multi-lane highway without ramps, consideration of a single roadway is sufficient, with that single roadway assigned the total traffic flow of the multi-lane highway. For receiver locations close to the highway, each traffic lane might be described as an individual roadway. Ramps also are treated as separate roadways.

Noise barrier data is entered in the same way as roadway data, by the Cartesian coordinates in feet of points on the top contour of the barrier. No sound is assumed to penetrate below the barrier contour.

Barrier top contours that are curved in plane or varying in slope are approximated by straight line barrier segments. Barriers may be designated either reflective or absorptive to sound. The sound energy incident on a reflective barrier directly from the source is assumed to be entirely reflected in the direction a light ray would be reflected by a mirror. Second reflections are ignored. All sound energy incident on an absorptive barrier is assumed to disappear. Vertical cuts and constructed barrier walls, and building facades are examples of reflective barriers. Sloping earth berms, hills or other obstacles that reflect sound either weakly or toward the sky can be considered absorptive barriers.

High grass, shrubbery and trees are considered noise attenuating ground cover in this program and can be entered as plane, rectangular patches. The location and limits of a patch are defined by the Cartesian coordinates of the end points of the centerline and the width of the patch, all units in feet. In general, the program significantly overstates the noise reduction due to ground cover and its use is discouraged except in the case of tall and very dense trees and folliage completely blocking the line of sight to the roadway.

The points at which the noise levels would like to be known are called the receivers and are also entered by their Cartesian coordinates in feet. A receiver cannot be located on a road, nor on, over, or under the top line of a barrier, nor on a ground cover strip. In each case, the distance from that receiver to the roadway, barrier, or ground strip would be zero; and the computer cannot handle a zero distance.

The output data printed is more than is needed for most problems. For each receiver, the following computed noise level results are printed:

1. Octave band levels, reduced according to the A-weighted filter network, of the mean sound energy level reaching the receiver point.
2. The A-weighted energy mean level, $L_E(A)$.
3. The noise pollution level, L_{NP}, of the A-weighted sound level.
4. The A-weighted 90 percentile level, L_{90}.
5. The A-weighted 50 percentile level, L_{50}.
6. The A-weighted 10 percentile level, L_{10}.

Usually, only the 10 percentile level, L_{10}, and occasionally the noise pollution level, L_{NP}, are needed in describing the noise environment near highways; and the other four output data can be ignored. In further discussions of the computer program results, only the L_{10} and the L_{NP} will be considered.

Before continuing with suggested guidelines for problem analysis and some examples, a few suggestions and precautions in the use of the program are offered.

1. The program cannot be expected to relieve the engineer of the burden of thinking. Judgement is still required.

2. The complexity of each highway situation should be reduced to simple terms when possible to limit the amount of input data and computational time required. To a first approximation, the computation time used is proportional to the product of the number of roadways, the number of barriers and the number of receivers. Do not have more roadways nor roadway segments than necessary to satisfactorily describe the source geometry. Limit the barriers to those that will have a significant effect on the receivers of interest. Rely on your understanding of noise propagation and noise contour shapes to reduce the number of receivers to a reasonable few.

3. When the distances from the highway to the receivers are small compared to the highway length, the study area and roadway should be broken up into segments, each segment to be run on the computer as a separate problem. This procedure saves greatly on computation time.

4. Prepare the input data carefully and meticulously. The output data is no better than the input, and mistakes are hard to find and sometimes go unnoticed.

5. In some cases, errors involving input data that is incompatible with the program are detected by the computer. Error messages are printed in the following cases:

   a. A barrier intersects a roadway

   b. The center line of a ground strip intersects a roadway.

   c. The number of reflections from reflective barriers exceeds the upper limit.

6. Frequent errors not diagnosed by the computer include:

   a. A receiver located on or very near a barrier, road, or ground strip.

   b. Failure to notice that the program does not recognize shielding for an elevated roadway unless the roadway edge is entered as a barrier.

   c. Failure to extend the roadway input data to a distance well beyond the study area.

4.3.3 Suggested Guidelines for Problem Analysis

Every engineer, as he gains more experience with the use of the handbook and computer methods for noise computation, will develop his own system for analysing highway noise problems. Some suggestions are offered here, however, as guidelines to problem analysis that may speed the learning process and encourage a uniform and organized approach.

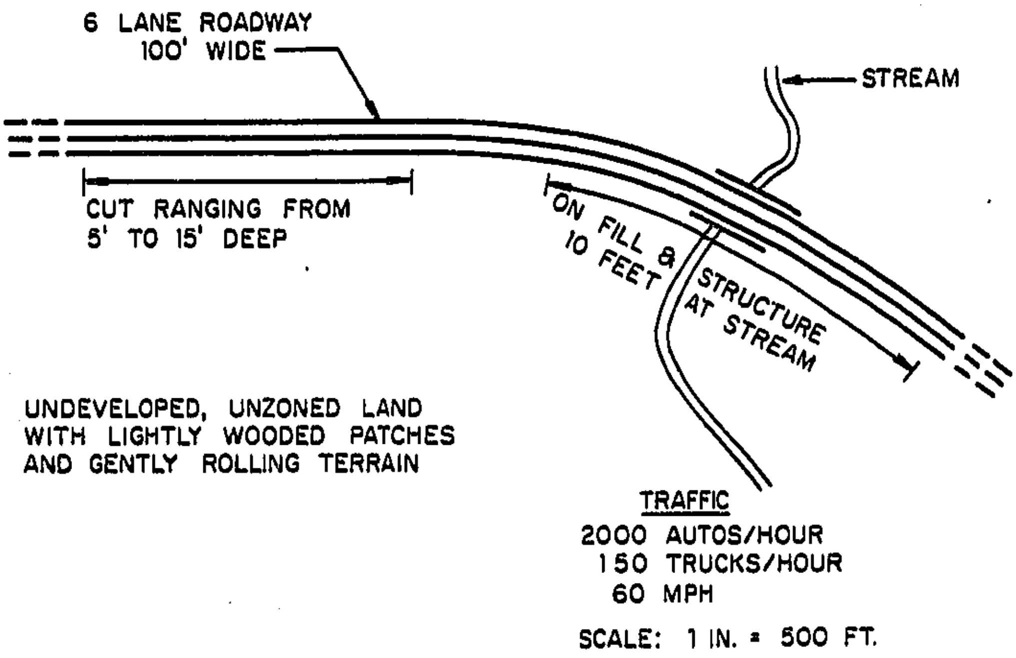
Example - For most highway problems a map of suitable scale can be found that describes the road and the study area, e.g., an aerial photograph or planimetrics. A simplified example of such a map is shown in Sketch 4.15. Suppose this segment of a 6 lane road runs through fairly open countryside. The terrain is gently rolling, while the road is comparatively flat, running through a modest cut at one end, and on fill and structure over a small stream valley at the other end.

What data should be prepared for the computer in order to predict the noise produced by traffic on the road? How detailed should the input data be. How many receiver points should be designated?

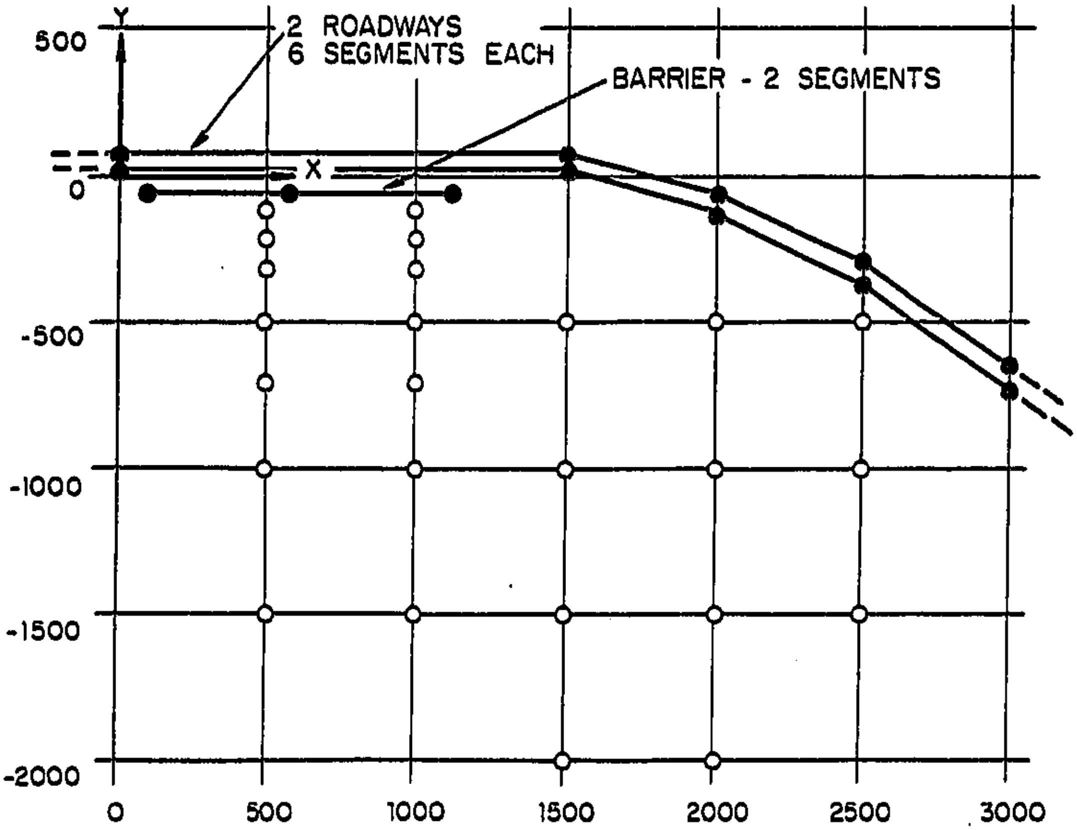
Suppose that we are not interested in the precise noise prediction for any one point; but, rather, since it is open country, we would like to know the general shape and location of the 75, 70, and 65 dBA L_{10} noise contours.

By a quick calculation with the nomograph, assuming all the traffic to be concentrated on a single lane, infinitely long and straight, the 75, 70 and 65 decibel contours can be found to fall at distances from the road of approximately 200, 600 and 1800 feet. Hence, receivers should be located at various distances between, say, 100 feet and 2000 feet.

Sketch 4.16 shows a schematic of the road and the locations of possible choices of input data points for the roadway, barrier and receivers. A coordinate system is located in the map (its particular location is only a matter of convenience) and grid lines are drawn and labeled in feet. The six-lane highway is approximated by only two roadways located in the center lanes of the two directions. At distances greater than 200 feet, all six lanes would be separated only if special precision were



SKETCH 4.15
MAP OF COUNTRY ROAD PROBLEM



SCALE 1 IN. = 500 FT.

● ROADWAY AND BARRIER INPUT DATA POINTS
○ RECEIVER INPUT DATA POINTS

SKETCH 4.16
INPUT DATA FOR COUNTRY ROAD PROBLEM

required in the computational results. The curvature of the road is approximated by several straight line segments.

Similarly, the cut barrier is approximated by only two segments, where the cut is about 5 feet deep at the ends and 15 feet deep near the center. For contour lines 200 feet or so from the road, 10' high fill segments can be assumed to be on grade having negligible barrier effect.

Receiver points are more densely populated in regions where the contour line locations are somewhat difficult to predict. In other areas only a few receiver points are required. The results of the computer program should not be expected to draw the noise contour lines for us, but rather to guide us in developing the approximate shapes and distances of the contours. Of course, the input data points for this problem were selected with the objective in mind to develop rough noise contours for this highway situation. If precise contour locations were desired, the required precision and quantity of input data would increase accordingly.

All the data input points shown are entered on punched cards by x,y,z coordinates. Don't forget that the road does not end at $x = 0$ and $x = 3000$ feet. A usual method of including the effects of distant traffic, beyond the study area, is to enter an additional flat and straight road segment at each end of the roadway shown, extending a distance some 4 or 5 times the distance from the road to the farthest receiver location. The exact location of the point defining the far end of this segment is not important and is usually estimated.

Example - A four-lane highway with the two directions dividing to two, two-lane roads separated by about 240 feet is shown in Sketch 4.17. Part of the roadway is elevated 30 feet. A community is located some 350 feet to the south; and an industrial complex is located 200 feet from one of the divided highway segments. A railroad spur, slightly elevated on fill, separates the highway from the industrial complex. The objective is to compute the highway traffic noise levels along the highway.

An efficient method of analysis is to first use the nomograph method to determine the study areas of special concern, and to help reduce the amount and complexity of input data. For example, a quick calculation indicates that the 75 dBA L_{10} contour, for an unshielded infinite highway with the traffic given in this example, lies about 200 feet from the road - not quite to the industrial complex. It is hardly worth a detailed study of the contours in this area. Hence, the possible shielding effects of the railroad spur will be ignored; and few receiver locations will be needed.

The nomograph also indicates, however, that the 70 dBA L_{10} line would be about 500 to 600 feet from an infinite highway; and might extend into the residential development. This area should be studied in some detail.

Sketch 4.18 shows a schematic reduction of the problem to a level that can be handled by the nomograph method. The roadway has been divided into 4 straight line segments. The earth mound top contour has been approximated by a single straight line. The noise contours shown were estimated from the results of nomograph computations based on this schematic problem map. It is clear from this estimated noise contour map where the receiver locations should be concentrated and what level of detail should be incorporated in the roadway data.

Sketch 4.19 shows a possible selection of roadway, barrier, and receiver points. The computed dBA L_{10} noise levels for these receivers are also shown along with estimates of the 75, 70 and 65 dBA L_{10} noise contours. Compare these contours with those originally estimated based on the nomograph method.

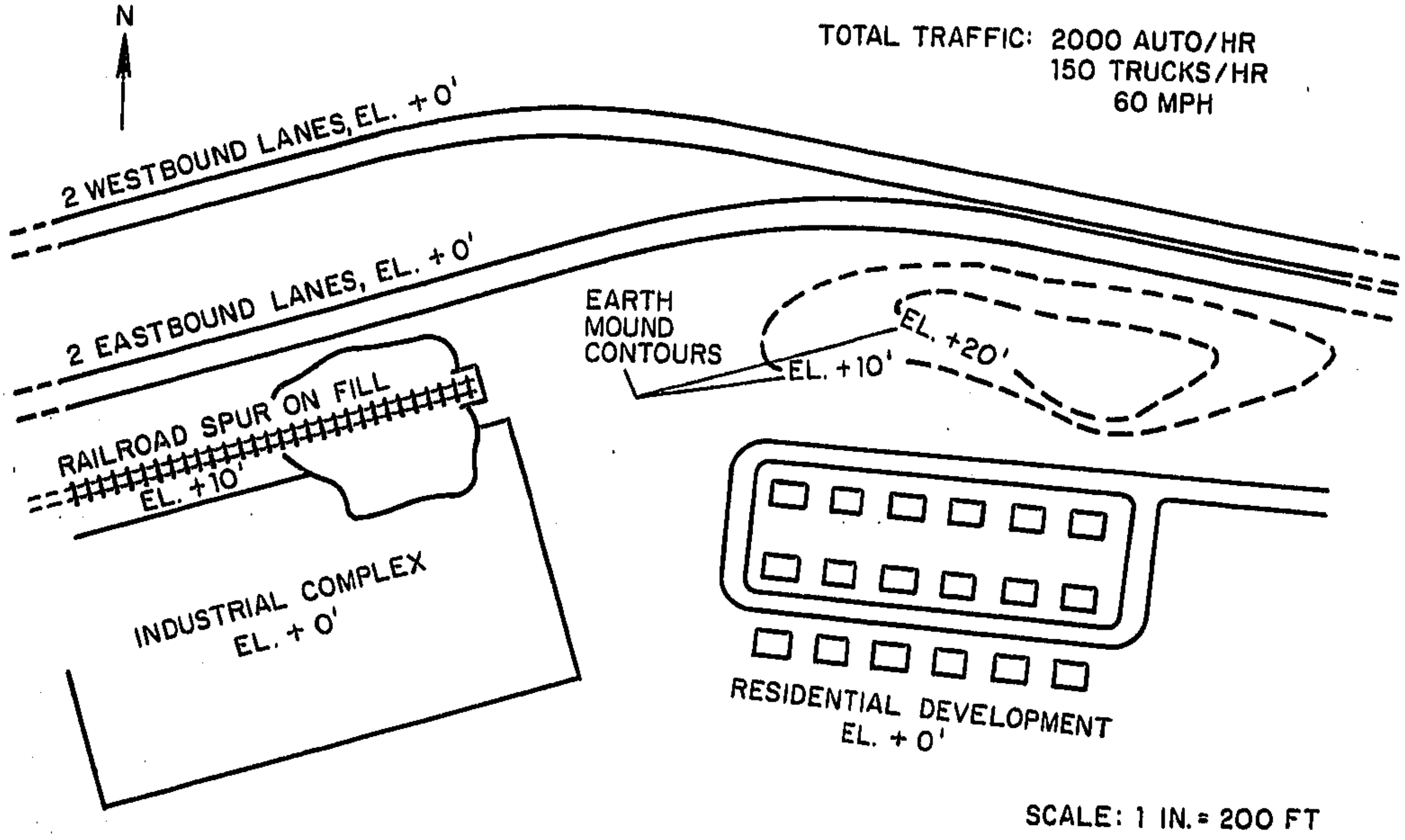
The point of this example has been to demonstrate the utility of first analyzing a problem roughly by the nomograph method. The input data to the computer can then be greatly reduced in quantity with the more strategic selection of meaningful data points.

4.4 SPECIAL CONSIDERATIONS IN TRAFFIC NOISE PREDICTION

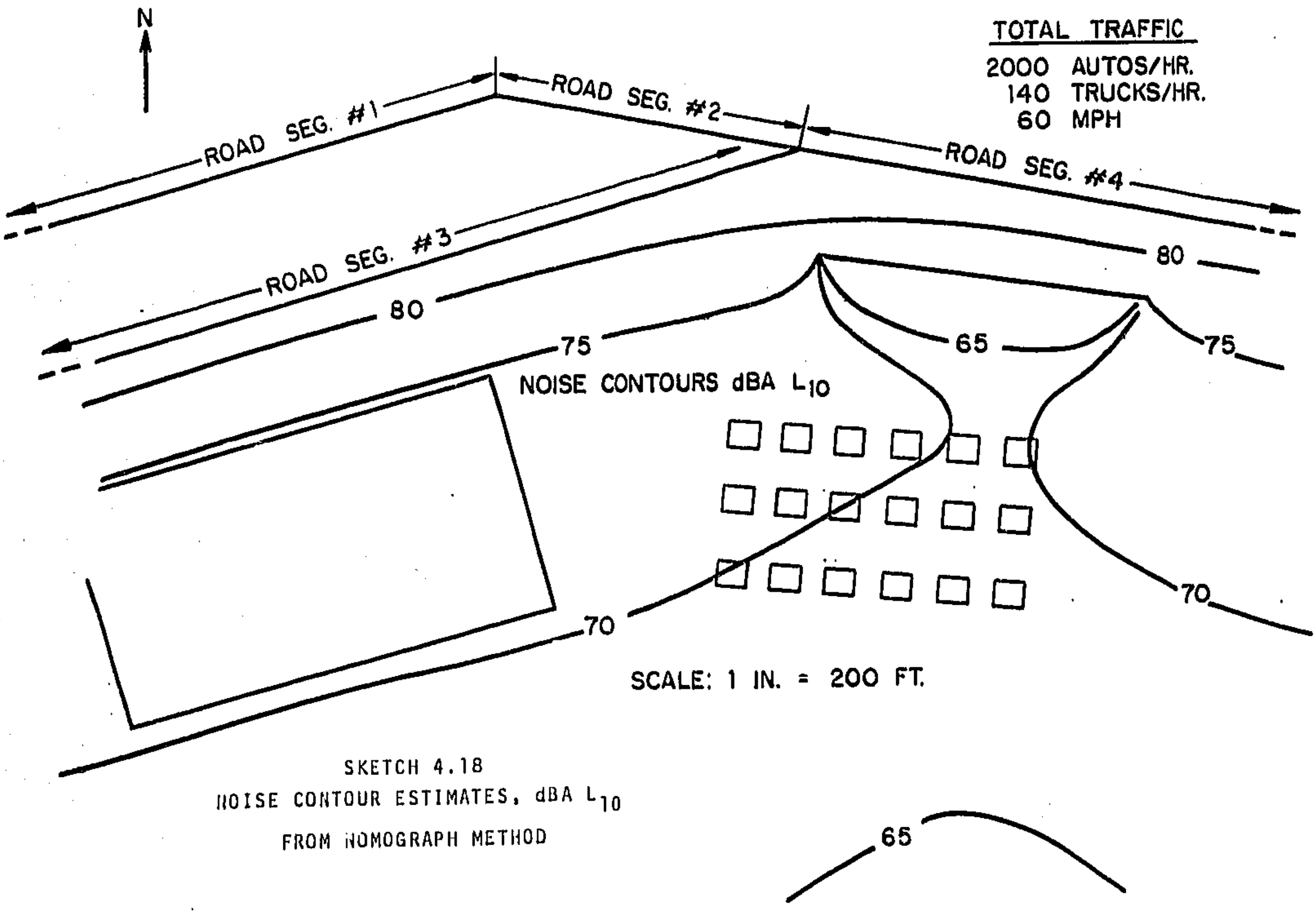
The prediction methods presented so far have been straightforward, for the most part, with little deviation from the instructions given in NCHRP Report 117 and the TSC Manual for Highway Noise Prediction. A few points need a little qualification, however, and others require expansion in order to apply to the broader range of highway noise problems encountered in practice.

4.4.1 Propagation of Sound over Large Distances

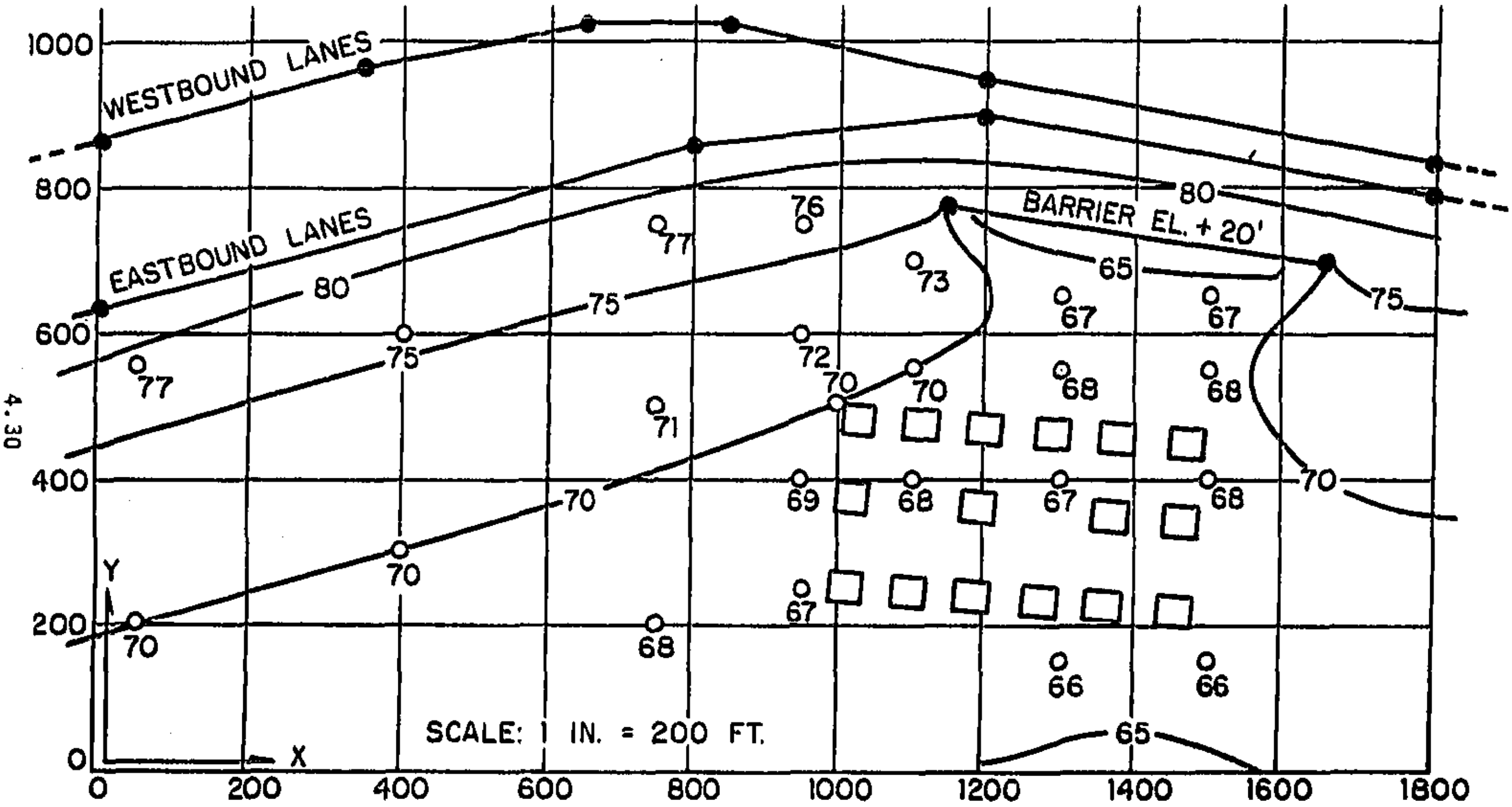
Equipped with the handbook and computer methods available, the engineer is usually able to make meaningful traffic noise level predictions at points within 500 or 600 feet of the highway. At these relatively small distances, local disturbances in the sound field caused by a few scattered buildings here and there, trees, rolling terrain, etc., can be ignored and the overall description of the traffic induced noise environment is still pretty accurate. At large distances, however, say over 1000 feet, the presently available computation methods simply cannot account for, in a reliable way, the cumulative effects of build-



SKETCH 4.17
MAP OF DIVIDED HIGHWAY PROBLEM



SKETCH 4.18
NOISE CONTOUR ESTIMATES, dBA L_{10}
FROM NOMOGRAPH METHOD



● ROADWAY AND BARRIER INPUT DATA POINTS

○ RECEIVER LOCATION

71 COMPUTED NOISE LEVELS, dBA L_{10}

—75— NOISE CONTOURS, dBA L_{10}

SKETCH 4.19

COMPUTER INPUT/OUTPUT AND FINAL NOISE CONTOURS ings, trees, and terrain. Also the humidity, and wind and temperature gradients affect, quite markedly, the propagation of sound over large distances. It cannot be claimed the predicted noise levels at distances over 1000 feet are more meaningful than simply guidelines to expected noise levels.

An idea of the uncertainty in predicted noise levels at large distances can be found by comparing levels predicted by the NCHRP Report 117 method with those predicted by the nomograph at 1000 feet. For example, at 100 feet from a single lane roadway carrying 1000 cars per hour at 60 mph, the nomograph and the NCHRP Report 117 method each predict 65 dBA L_{10}. But at 1000 feet, the nomograph predicts 55 dBA L_{10}.

The reason for this difference involves the assumed rate of decrease in noise level with increase in distance. The NCHRP Report 117 method assumes that the L_{10} noise levels drop off at a rate typically ranging between 4½ and 6 decibels per doubling of distance from the source. The nomograph (and computer program) have an L_{10} rate of decrease slightly greater than 3 decibels per doubling of distance. Which is the more accurate rate of decrease depends upon the highway situation.

The mathematical model upon which the computer program is based assumes that the road is at grade level, is infinitely long, straight, and flat, and the surrounding terrain is also flat. Under these conditions, the line of vehicles does, indeed, act nearly like a true line source; and the 3 decibel per doubling rate of decrease is as it should be for "average" noise from a line source. Any buildings or variations in terrain that may act as noise barriers, and trees and ground cover that may affect the propagation of sound, must be put into the computer program explicitly as input data if accurate computational results are to be obtained for points far from a highway.

The 4½ dBA L_{50} noise reduction per distance doubling embodied in the NCHRP Report 117 method was originally introduced as a result of a computer simulation model of highway traffic noise. A series of measurements was obtained to compare with the simulation results. The distance dependence characteristics in the two cases were found to agree very closely. Consideration of the field test location geometries suggested the possibility that, in many practical situations, the length of roadway that effectively contributes to the noise levels observed at a particular point is not infinite; but, rather the extremities of the roadway are shielded somewhat from the observer by terrain, trees and other foliage, and miscellaneous buildings and structures.

A recent series of highway noise measurements has indicated that noise propagating near the surface of grassy terrain (e.g., 5 feet high, or so) decreases with distance at a higher rate than noise propagating high above the surface. This propagation characteristic is shown clearly by the vertical plane noise contour lines displayed in Figure 5.27, "Increase in Noise Level with Increasing Receiver Height", found in Chapter 5. It is thus appropriate to expect that, for many highway situations typically encountered in practice, the noise levels should fall off at a rate substantially greater than 3 decibels per distance doubling, especially for receivers near ground level.

There are no clear cut rules for determining which rate of noise reduction (which method of analysis) should be applied to a particular problem. Some guidelines are offered as follows:

1. If there is clear, unobstructed line-of-sight to all parts of a highway for distances, both directions, of more than 5 times the observer-highway distance, use the three decibels per distance doubling rate embodied in the TSC nomograph and computer methods. If there is clear line-of-sight, as above, except for a limited number of well defined, solid obstructions to the propagation path, use the three decibel rate; but consider each obstruction as a noise barrier, and compute its effect on the noise propagated to the observation point. This method should generally be applied to elevated receiver locations at second story window height or so.
2. If the line-of-sight to the highway is only partially blocked by rolling terrain, scattered buildings, and perhaps somewhat spare vegetation, use the reduction with distance rate assumed in the NCHRP Report 117 method. This situation almost always applies to distances of over 1000 feet, not only because of partial shielding, but also because of meteorological effects that tend to reduce the sound propagated over large distances. In addition to the assumed average shielding effects inherent in the 4½ to 6 decibel rate, conspicuous barriers to the highway noise should be considered explicitly in this method also.

At very large distances the rate of noise decrease with increasing distance is accelerated in all prediction methods because of the effects of atmospheric sound absorption.

A noise reduction of five decibels was suggested in Chapter 1 for a one hundred foot depth of dense forest having trees extending at least 15 feet above the line-of-sight between the highway traffic noise sources and the observer, provided there is abundant foliage above and underbrush or ground cover below. For an additional depth of woods of 100 feet or more, an additional 5 dBA attenuation can be assumed; but the total attenuation claimed for all such plantings should not exceed 10 decibels. Appropriate reductions of the predicted noise levels at specific observer locations can be made as was shown in Exhibits 4.13 and 4.14 when the location is shielded by a substantial forested area.. Or the noise contour lines can be adjusted to show the forest noise reduction in the same way they were drawn to show the effects of barriers in Sketch 4.19. Usually, explicit noise reduction values are not assigned to sparse woodlands, occasional trees, shrubs and ground cover. On the average, over large distances, the effects of these items are accounted for in the NCHRP Report 117 rate of noise reduction per distance doubling.

Likewise, well defined rows of houses having 50%, or less, open space between houses may produce significant reduction in noise level to the areas on the side of the houses opposite the highway. In Chapter 1, the reduction estimates recommended for the first row of houses were: 3 dBA for one row of buildings occupying 40% to 60% of the length of the row; 5 dBA for one row of buildings occupying 70% to 90% of the length. More rows equally densely packed may be assigned comparable noise reductions up to a maximum of 10 decibels reduction for the combined effect of multiple rows. Single large buildings can be considered individually as noise barriers; and, scattered houses and small buildings are usually ignored, or taken into account implicitly in the NCHRP Report 117 rate of noise reduction with distance doubling. Again, the shielding adjustment can be made for any observation point by entering the value in the tally sheet; or noise contours can be appropriately adjusted to yield a better visualization of the shielding effects.

4.4.2 Interchange and Ramp Traffic Noise

Not every highway noise problem involves continuous, freely flowing traffic. In many cases the severest noise problems occur at the interchanges and ramps to expressways. The high noise levels associated with vehicle accelerations, and the close proximity of the ramp traffic to houses and other buildings located along local crossroads and feeder streets can often more than compensate for the comparatively low ramp volume. Unfortunately, the available computational methods for determining the L_{10} noise level for low volume traffic are of uncertain accuracy. Very little field verification data for low traffic volume noise has been available.

In the final step in the L_{10} computation, the TSC computer program assumes that the time distribution of noise level at any point from a highway is Gaussian. For a randomly distributed, high volume of traffic, this assumption is probably nearly true; however, for sparse traffic the distribution is far from Gaussian. The volume line in the TSC traffic prediction nomograph shown in Figure 4.10 has been extrapolated downward to 10 vehicles per hour. The nomograph will now yield the same results as the computer program. The predicted levels for these low traffic volumes, however, will in many situations be higher than should realistically be expected.

The L_{10}-L_{50} adjustment parameter, $\frac{VD}{S}$, in the NCHRP Report 117 method has also been extrapolated downward to permit the computation of levels at points near sparse traffic. This extrapolated curve, shown in Figure 4.5, was generated from the theoretical model of Johnson and Saunders* for the 10 percentile level produced by a regular array of moving vehicles. At high volumes this model is not expected to be very accurate because of the periodic overlap of source influence. At large values of the parameter VD/S, the design curve in Figure 4.5 departs considerably from the Johnson and Saunders theory. However, at low values of VD/S, where the sources appear to be widely spaced, there is no appreciable overlap of source influence and the regular array theory should closely approximate the results for a random distribution of vehicles as well. In the limit, as the vehicle spacing approaches infinity, the L_{10}-L_{50} adjustment approaches the maximum of 13 decibels. Thus the L_{10}-L_{50} curve quickly levels off as VD/S drops below 200 and reaches an upper limit of 13 decibels. An even simpler model of the L_{10} noise level of a single vehicle pass-by (a regular array of vehicles of infinite spacing) limits the L_{10}-L_{50} adjustment to a maximum of 14 decibels. Hence the Johnson and Saunders theory is thought to represent a satisfactory description of the adjustment, L_{10}-L_{50}, at points near low traffic volume roads.

A quick comparison between the results of the nomograph method and the NCHRP Report 117 method can be made by the following example: Suppose there are 20 trucks per hour traveling at a speed of 40 mph on a single lane ramp. What would be the L_{10}

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* "The Evaluation of Noise from Freely Flowing Road Traffic". D.R. Johnson and E.G. Saunders, J. Sound and Vibration, Vol. 7, No. 2 pp 287 - 309 (1968).

noise level at 100 feet? The Figure 4.10 nomograph yields the solution 70 dBA L_{10}. From the Figure 4.5 extrapolation of the NCHRP Report 117 method, the computed parameter $VD/S = 50$ indicates an L_{10} noise level of 62 dBA. Not all the 8 decibel discrepancy here is due to the computational method. Recall that the average truck noise emission level for the TSC program is 5 decibels higher than the level used in the NCHRP Report 117 method. Thus, allowing for this difference in assumed source level, the nomograph and NCHRP Report 117 methods differ by perhaps only three decibels for this example. For smaller values of the parameter VD/S, the discrepancy increases because of the Gaussian distribution assumption inherent in the computer program mathematics. The objective of this little exercise is not so much to compare the results of one method with those of another, but rather, to point out that under certain conditions where the receiver is near a road of low vehicle volume, the TSC computer method and nomograph may tend to overstate the noise level. The problem is, of course, minimal when a sufficiently high volume of automobile traffic dominates the noise environment.

One last item should be discussed regarding the computation of noise from low traffic volume roadways - the "Michigan Noise Predictor Computer Program". The complete prediction method of NCHRP Report 117 has been computer programmed by the Michigan Department of State Highways. Given the traffic data and geometry data as required for hand computations by the NCHRP Report 117 method, the computer program can perform the table search, data storage, and summation functions quickly and accurately to determine the resulting L_{50} and L_{10} noise levels at a particular receiver location. Because the program was designed for use on a time-share computer terminal, the results of modified input data to the program can be rapidly generated, permitting the efficient investigation of the effects of various alternate highway and barrier designs.

Two precautions regarding the program should be mentioned:

1. Like any other computer program, this one requires that the user understand the basic physical principles involved in the computations. Since the program is based on the computational methods employed by NCHRP Report 117, the user should have a working understanding of that document.

2. Since the NCHRP Report 117 graph for determining the adjustment $L_{10}-L_{50}$ does not accommodate values of the parameter VD/S below 200, a substitution method was devised to enable the computer program to handle such situations. This method consists of substituting 15 automobiles for each truck when VD/S is less than 200, and recomputing the predicted noise level for a new augmented volume consisting entirely of automobiles. This method will not, in general, yield an accurate prediction of the truck contribution to the noise levels at the observer location in question. The computation will satisfactorily describe the total noise environment at that point only when the automobile volume is sufficiently high as to render the truck noise contribution negligible. The situation can be remedied by modifying the computer program to calculate the $L_{10}-L_{50}$ adjustment for VD/S less than 200 from the Johnson and Saunders relation:

$$L_{10}-L_{50}=10\ \text{Log}\left[\frac{\cosh\ (1.19 \times 10^{-3}\rho D)}{\cosh\ (1.19\times10^{-3}\rho D)-0.951}\right]$$

In the meantime, hand computations can be made using the graph shown for $L_{10}-L_{50}$ in Figure 4.5.

There are yet three other special considerations in determining the noise levels near ramps and interchanges. To facilitate discussion of these three considerations, imagine that an interchange can be broken down into three roadway categories:

1. Roadway segments on which the traffic is neither accelerating, nor climbing up a gradient, e.g. feeder roads, distributor roads, and off-ramps where vehicle speed is nearly constant;

2. Roadway segments where traffic is climbing up a gradient, but not accelerating, e.g., category 1 above, but the road is also on a gradient;

3. Roadway segments on which the traffic is accelerating to attain the final highway speed, e.g., on-ramps for autos, and perhaps the first mile or so of the highway downstream of the ramp for trucks.

The first of these segments can be treated in the usual way using as traffic data the estimated volume and average speed of vehicles on the ramp segment. The computations for the second segment type are also performed in the usual way with the exception that an adjustment is added to the truck levels in accordance with Table 4.2 to account for the increased noise levels produced by trucks on a gradient. This gradient adjustment, however, should only be added to the levels computed by the NCHRP Report 117 method where standard highway trucks are assumed to have an average noise emission level of 82 dBA. Recall from Chapter 2 that the average truck noise emission level used in the TSC computer method is 87 dBA under all operating conditions. This emission level is typical of highway trucks at high cruising speeds where the throttle is in the nearly wide-open position for much of the time. But, it is also typical of diesel trucks under certain lower speed conditions when the throttle is opened wide for gradient segments and for acceleration. Thus the gradient adjustments and the acceleration adjustment are already embodied in the 87 dBA emission level assumed for the TSC computer program trucks. Additional upward adjustments for gradients would result in corresponding overstatements of the resulting noise levels.

For noise computations involving acceleration roadways, a slight modification of the standard computation method is required to account for a roadway segment that does not have a uniform traffic speed throughout. All the computational methods discussed so far have the common requirement that the traffic on any one segment must have a constant traffic volume and speed over the entire length of the segment. For a segment on which the speed varies, the question becomes, "which speed should be used in the computations?" If a low speed is chosen, the vehicles will appear to be closely spaced over the entire length of the acceleration roadway, resulting in an artificially high noise level. On the other hand, the choice of a high speed would result in too low a predicted noise level.

A compromise solution that leads to a simple result is to assume that each vehicle accelerates according to a constant power relationship. The average speed over the length of the acceleration roadway would then be 2/3 the final speed where the ramp entrance speed is zero. Compared with the final highway speed, this average speed results in a reduced vehicle spacing that increases the truck noise level by two decibels. Thus, to compute the noise level due to trucks on an acceleration roadway, simply add two decibels to the levels computed for the specified ramp truck volume and the final highway speed. If using the NCHRP Report 117 method, also add 5 decibels more to the computed level to account for the increased source noise levels corresponding to accelerating trucks. Only the two-decibel, average spacing adjustment should be made to the TSC computer method results for trucks. Generally, these adjustments should apply to a mile long stretch downstream from the ramp entrance if the expressway is flat, straight, and wide. If the trucks are accelerating up a gradient, all the adjustments are the same; but the acceleration segment to which they apply is extended in accordance with the guidelines offered in the Highway Capacity Manual, 1965.

For accelerating automobiles, the two-decibel reduced vehicle spacing adjustment, added to the 69 dBA noise emission level typical of accelerating automobiles, just about equals the 69 to 73 dBA noise emission level typical of automobiles traveling at 60 mph. Therefore, the levels due to accelerating automobiles on ramp segments are computed without adjustment, in the usual manner using the specified ramp automobile volume, but using the final highway speed.

The treatment of interchange and ramp traffic noise can be summarized as shown in Exhibit 4.17 below:

EXHIBIT 4.17

RAMP AND INTERCHANGE TRAFFIC NOISE

Segment Category	Traffic Data	Adjustment, dBA			
		NCHRP 117		TSC	
		A	T	A	T
#1) No gradient, no acceleration	Specified ramp volume and speed	0	0	0	0
#2) Up-gradient no acceleration	Specified ramp volume and speed	0	+2* to +5	0	0
#3) Accelerating traffic	Specified ramp volume and *final* highway speed	0	+7	0	+2

*Depending on % gradient, see Table 4.2

When using the TSC computer program method, the effects of accelerating vehicles can more accurately be taken into account by dividing the acceleration roadway into smaller segments each assigned an appropriate speed.

4.4.3 Summary of Differences between the NCHRP Report 117 and the TSC Methods.

Throughout Chapters 2 and 4, comparisons have been made between the NCHRP Report 117 and the TSC highway noise prediction methods. All major differences have been discussed. However, before concluding this chapter on the prediction of highway noise, perhaps it would be helpful to summarize these differences in method, results and application. Those items that are easily tabulated are shown below in Exhibit 4.18.

A few other earlier discussions of the two prediction methods, not so easily tabulated, should also be summarized here.

1. The TSC computer program calculations carry the traffic statistics all the way through the problem geometry with only minor simplification. The computations involving barrier noise reductions, and roadway segment contri-

butions are very accurate and useful. The program is especially handy in performing the complex geometry computations involved in predicting the noise from interchanges.

2. The NCHRP Report 117 truck emission levels are more applicable to lower speed highway situations or off-highway roads where the cruise condition is at somewhat less than full throttle. The flexibility permitted in the adjustments to source levels for gradients, accelerations, and surface materials is useful and should be employed wherever applicable.

   The TSC truck noise emission levels are likely to be more accurate in high speed highway situations, and other situations requiring high power, where trucks are operating at nearly wide-open throttle. The program can be simply modified to handle a broader range of situations encountered in practice, e.g., emission level adjustments, acceleration roadways, non-Gaussian treatment of low volume predictions.

3. The NCHRP Report 117 4½ to 6 decibel decrease in noise level with distance doubling is more useful when studying the ground level noise environment over a relatively large area of rolling terrain, ground cover, and scattered trees and buildings; and a noise level estimate in terms of a "local average" is sufficiently accurate.

   The TSC method 3+ decibel decrease in noise level with distance doubling is more accurate when, except for well-defined noise barriers, there is clear line of sight from the observer to all parts of the highway. This situation often occurs when the observer position is somewhat elevated, e.g., at the second story bedroom window.

With experience in the use of the prediction methods and a willingness to make some thoughtful judgements, the engineer will find that the two prediction methods are not so much in conflict as may have seemed at first encounter, but rather, together make a fairly complete and efficient set of highway traffic noise prediction and analysis tools.

EXHIBIT 4.18

SUMMARY OF DIFFERENCES BETWEEN PREDICTION METHODS

Item	NCHRP 117	TSC Method	Comments
Emission levels Trucks Autos	82 dBA 60 dBA @ 30 mph 71 dBA @ 70 mph	87 dBA 61 dBA @ 30 mph 75 dBA @ 70 mph	TSC level at observer correspondingly higher than NCHRP 117 levels
Decrease in noise level with increasing distance	4-1/2 to 6 decibels per distance doubling	3+ decibels per distance doubling	Significantly greater reduction over large distances with NCHRP 117
Low traffic volume extrapolation	Johnson & Saunders equation for regular array	Assumption of Gaussian distribution	For small values at VD/S, TSC slightly over-states the levels
Acceleration adjustment to truck emission levels	+5 dBA	None	Adjustment makes emission levels for for NCHRP 117 and TSC the same
Gradient adjustment to truck emission levels	+2 to +5 dBA depending on gradient	None	Adjustment brings NCHRP 117 and TSC emission levels in closer agreement
Surface adjustment for automobiles	-5 to +5 dBA depending on surface	None	Usually of minor importance
Barrier noise reduction for trucks	5 dBA less effective than for autos	Computation based on source and barrier geometry	NCHRP 117 method oversimplifies for high truck volumes

4.4.4 Urban Noise Complications

While the prediction methods for freely flowing highway traffic noise are fairly well developed, the noise emission and propagation characteristics for urban noise situations are complicated and have not yet been reduced to simple prediction methods.

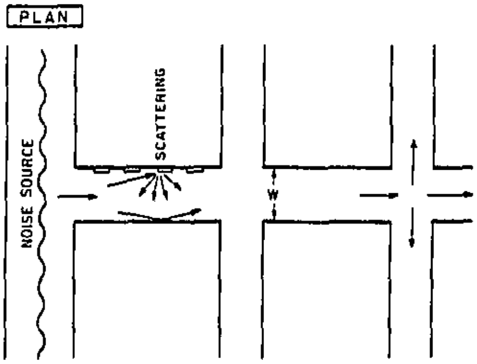
Typical urban traffic can not be described as freely flowing, but as stop-and-go traffic controlled by traffic signals and flow constrictions on congested city streets, bridges, tunnels and frontage roads. Reliable models of stop-and-go traffic, suitable for general application, have not been developed. The HUD Noise Assessment Guidelines* makes adjustment for points within 800 feet of stop-and-go traffic through a traffic multiplier approximately equivalent to adding 3 to 5 dBA to the freely flowing traffic noise prediction. At points where the noise level is dominated by accelerating traffic entering high-speed highway lanes, the ramp traffic model suggested in Section 4.4.2 of this text adds 2 or 7 decibels to the freely flowing traffic noise predictions depending on whether the TSC method or the NCHRP Report 117 method is used.

But measurements in New York City, made both very near, and far from traffic signals indicated that no adjustment should be made to freely flowing traffic noise to describe stop-and-go traffic noise. Although it is generally agreed that accelerating vehicles produce more noise than vehicles traveling at uniform speed, in the highly urbanized traffic situation only a fraction of the vehicles were accelerating at any point in time - some vehicles were idling, some were decelerating, and some were continuing at a uniform speed. For heavy trucks it was concluded that, on the average, the NCHRP Report 117 prediction method could be applied directly to the stop-and-go traffic situation assuming, for volume and speed, that the flow is uninterrupted by the traffic signal. For the traffic conditions measured, the automobile contribution to the noise level was insignificant. The number of medium sized trucks was so large, however, that they could neither be ignored, nor included in the standard "car" and "truck" classifications without significant error. A special prediction model was developed to include these medium sized trucks in the prediction method for stop-and-go traffic in New York City.

Could these results and models be applied directly to any other city? Perhaps the traffic types and patterns in some of the larger cities are sufficiently similar that the results would apply. Insufficient data is available at this time to allow a comparison. Certainly the methods do not apply to all cities.

There are other noises of city traffic that are not included in the available traffic noise prediction methods, e.g., idling traffic where noise is produced by traffic of zero speed, and rattles and horns which are not described by the prediction model, but nevertheless, contribute heavily to annoyance.

Describing the propagation of noise through cities is also a very complex problem. For example, the noise propagation down a side street could not be described as "free field" propagation. The rate of noise reduction with distance depends on the street width, on the number and size of sound reflecting and scattering surfaces along the propagation path, and on the amount of sound energy distributed to cross streets as shown in Sketch 4.20. Often the noise from the traffic activity on the side street dominates the noise propagating down the street from some other noise source, say an expressway or high traffic volume route. In such cases, the noise prediction requirements for a new highway may be simplified rather than complicated. If we need only concern ourselves with the impact of the new highway on the buildings that are very near the travel lanes and have clear line-of-sight to all the highway, the conditions are then satisfied for which the prediction methods are most accurate. The problem is well suited to solution by, for example, the TSC nomograph method for an infinitely long, level and straight highway.



SKETCH 4.20

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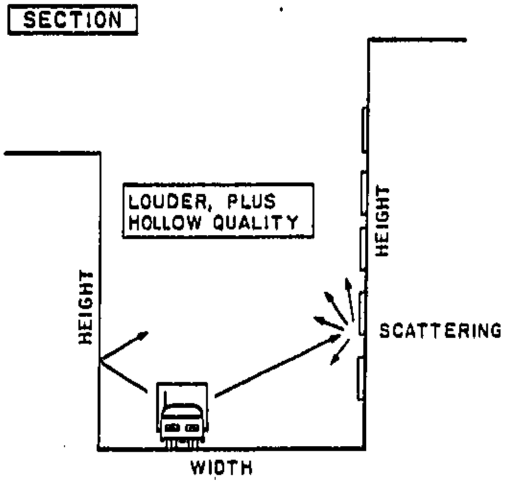
* See Noise Assessment Guidelines Technical Background, U.S. Dept. of Housing and Urban Development, Office of Research and Technology. Washington, D.C. 20410

Vertical propagation of noise to upper floors in multi-story buildings is particularly difficult to describe under the reverberant "canyon" conditions shown in Sketch 4.21. The noise level at the upper floors is not only increased because of the confined volume, but has a more diffuse sound. Even the standard vehicle emission levels are likely to be inappropriate for application to city street traffic because of the modified driver habits in confined and congested areas. Noise measurements made at second story height in narrow, confined streets, where a reverberant increase in sound level was expected showed no such increase over measurements made in broader streets.



SKETCH 4.21

As another complication, there is the opinion shared by many that the L_{10} traffic noise standards that apply to land uses along major highways are not as appropriate in highly urbanized environments where the distances are so small between dwellings and traffic lanes. For example, 10 trucks per hour traveling at 30 mph should produce an L_{10} of 73 dBA at a distance of 15 feet; but, every six minutes, on the average, the truck passby noise level raises to 92 dBA, almost 20 decibels higher than the L_{10}.

Other questions regarding noise standards arise in city environments. Often the existing noise level exceeds PPM 90-2's 70 dBA L_{10} design noise level. No amount of noise reduction planning for a new highway will serve to reduce the noise level below the design noise level. On the other hand, if the existing noise level is due to low speed trucks, e.g., on a frontage road, the reduction in vehicle engine and exhaust emission levels expected in future trucks may reduce the frontage road traffic noise to the point that the new, high-speed highway becomes the dominant source.

Criteria for allowable increase in noise level require a critical review before application to urban noise situations. What allowable increase in noise level is appropriate when the existing noise level is already as high as 70 dBA L_{10}?

Finally, as a point of interpretation of the PPM 90-2 design noise levels, protection of the highway's neighbors is the final objective. Self-serving interpretations to the detriment of the highway neighbors are artificial, and weaken the usefulness of efforts to assess and control traffic noise. It is conceded by all that many of our highway and urban noise problems are tough ones. But progress is being made by earnest professionals in many fields as more and more learn and use the fundamental concepts involved in highway noise.

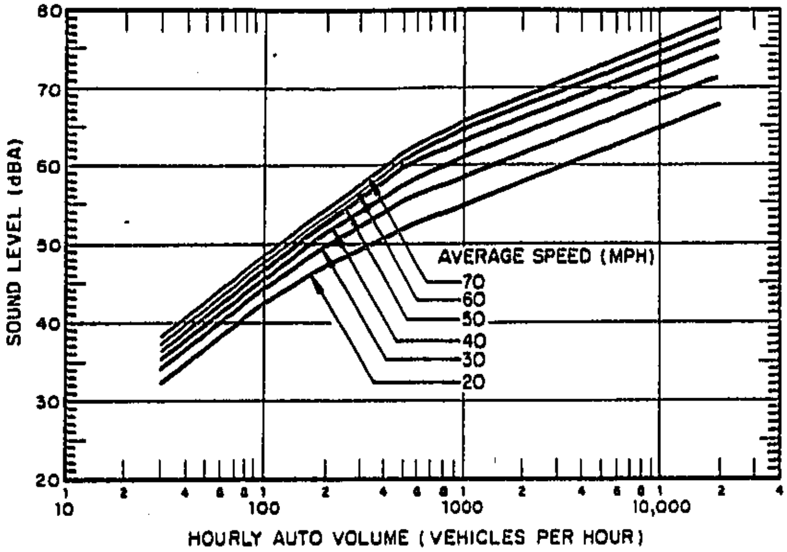


FIGURE 4.1
L_{50} SOUND LEVEL VS. AUTO VOLUME
AT 100-FOOT REFERENCE DISTANCE

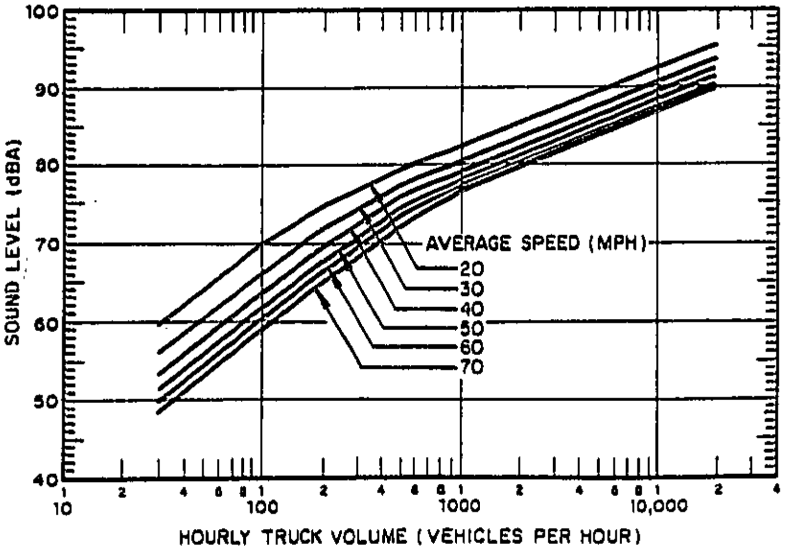


FIGURE 4.2
L_{50} SOUND LEVEL VS. TRUCK VOLUME
AT 100-FOOT REFERENCE DISTANCE

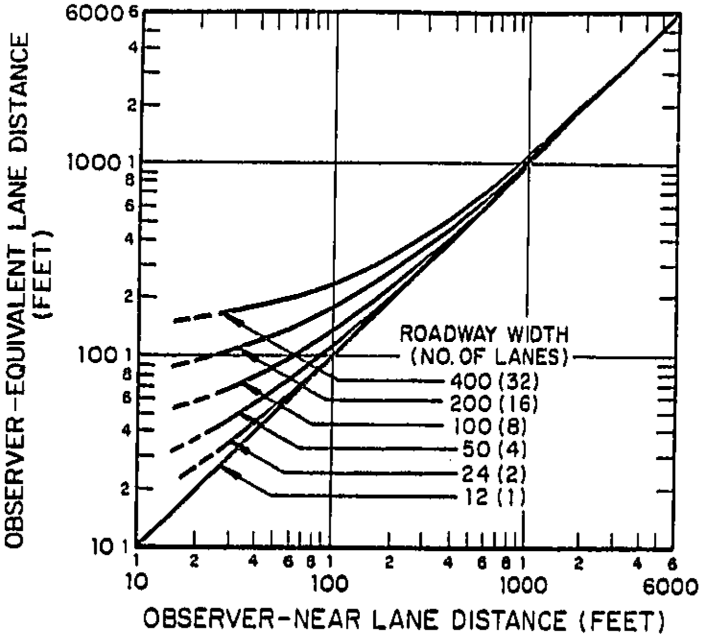


FIGURE 4.3
EQUIVALENT LANE DISTANCE VS. NEAR LANE DISTANCE

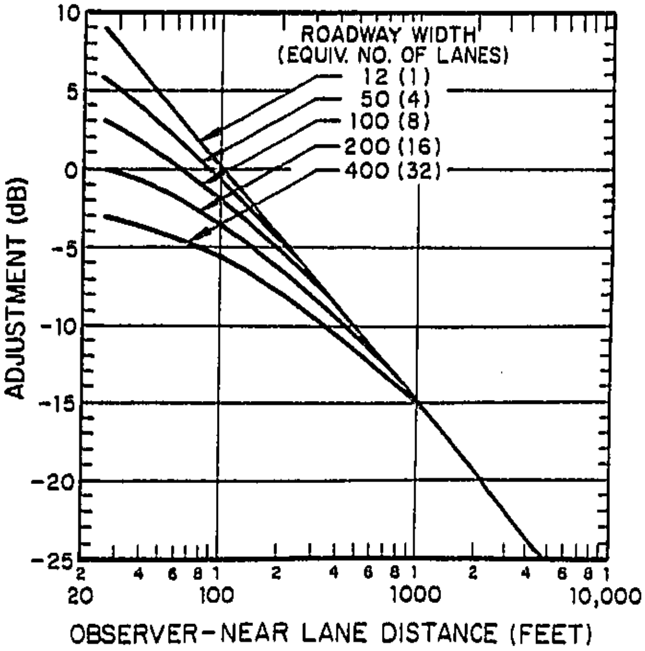


FIGURE 4.4
DISTANCE ADJUSTMENT TO 100-FOOT REFERENCE DISTANCE

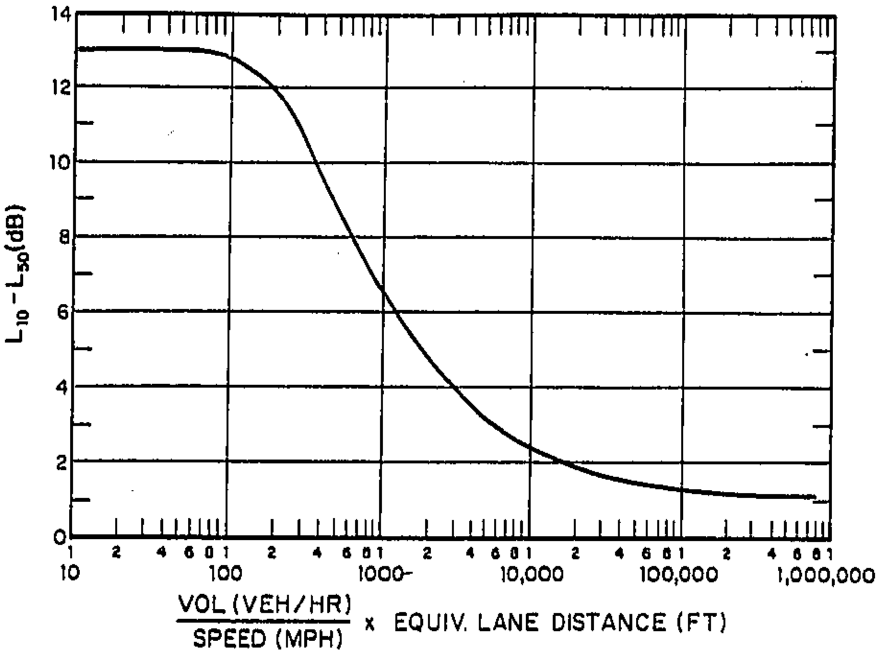
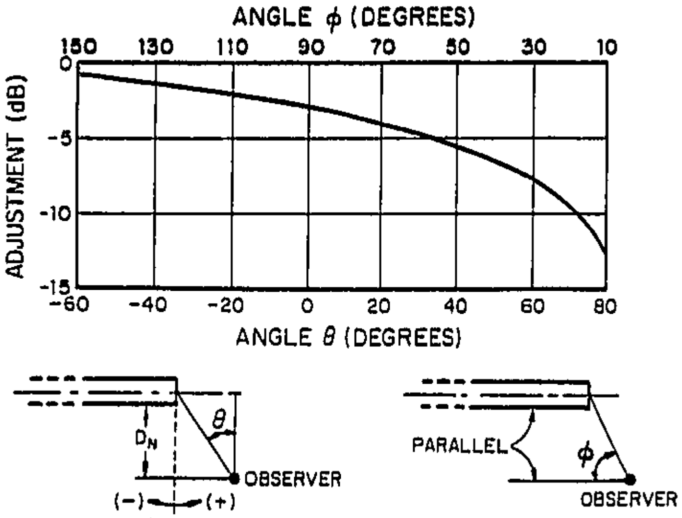


FIGURE 4.5
L_{10} - L_{50} ADJUSTMENT



NOTE: THE ANGLE θ CAN BE (+) OR (-)
DEPENDING IF IT IS MEASURED
TO THE RIGHT OR LEFT

FIGURE 4.6
SEMI-INFINITE ROADWAY ADJUSTMENT

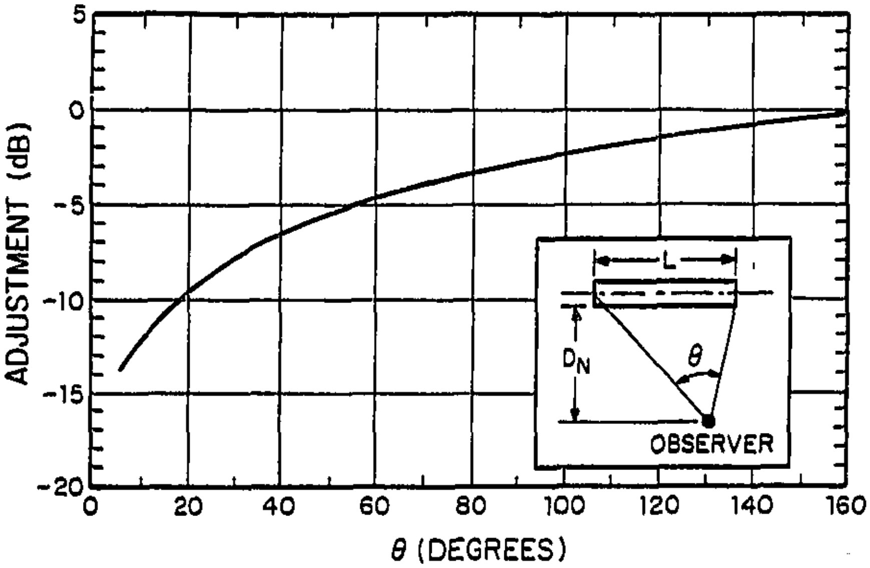


FIGURE 4.7
FINITE ROADWAY SEGMENT ADJUSTMENT

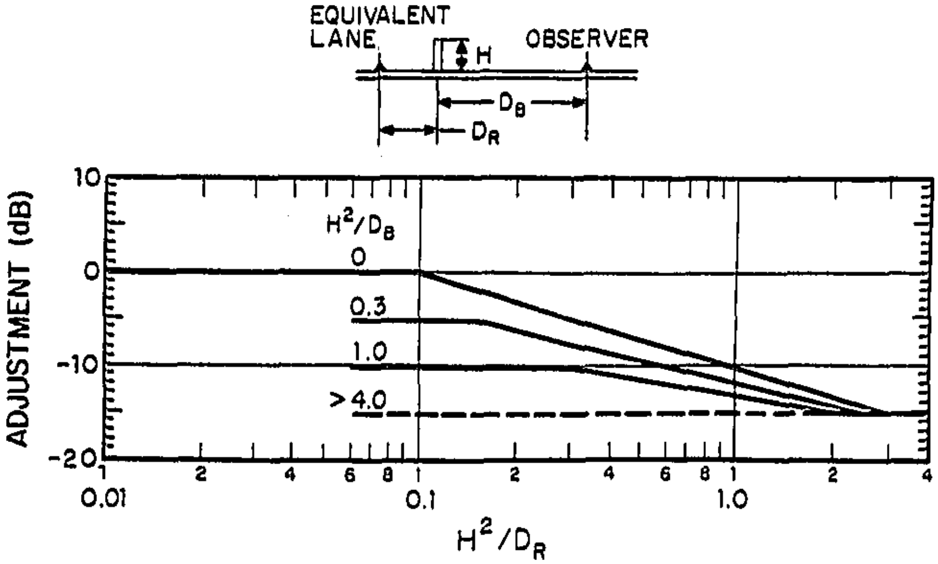


FIGURE 4.8
BARRIER ADJUSTMENT

FIGURE 4.9 Sheet___of____

TRAFFIC NOISE COMPUTATION TALLY
NOISE LEVEL, dBA

Project______________________________ Engineer____________

Segment______________________________ Date ____________

Autos/hr._____________Trucks/hr._________ Miles/hr._________

Highway Width_________feet. Observer_______________

Comments____

Item		A	T	A	T	A	T	A	T
L_{50} reference at 100 feet									
	Distance, width adjustment								
	L_{10}-L_{50} adjustment								
L_{10} reference at observer									
	Segment adjustment								
	Barrier adjustment								
	Miscellaneous Adjustments: Gradient								
	Road surface								
	Foliage								
	Rows of houses								
L_{10} at observer, by veh. type									
L_{10} at observer, summed									

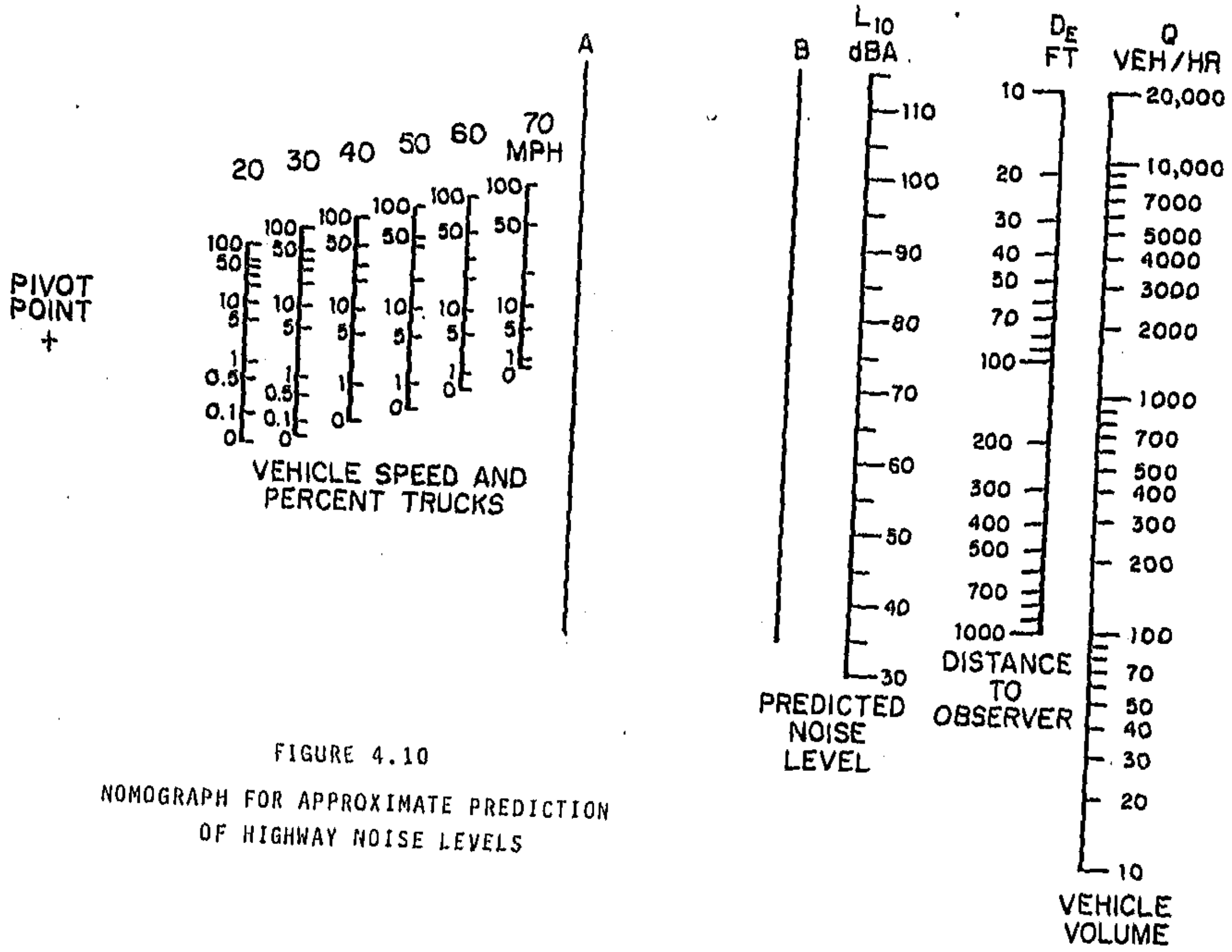


FIGURE 4.10

NOMOGRAPH FOR APPROXIMATE PREDICTION OF HIGHWAY NOISE LEVELS

TABLE 4.1
ADJUSTMENTS TO AUTOMOBILE NOISE LEVELS FOR ROAD SURFACE TYPE

Surface Type	Description	Adjustment (dB)
Smooth	Very smooth, seal-coated asphalt pavement	-5
Normal	Moderately rough asphalt and concrete surface	0
Rough	Rough asphalt pavement with large voids 1/2 in. or larger in diameter, grooved concrete	+5

TABLE 4.2
NOISE LEVEL ADJUSTMENTS FOR TRUCKS ON GRADIENTS

Gradient (%)	Adjustment (dB)
≤ 2	0*
3 to 4	+2
5 to 6	+3
≥ 7	+5

*The influence of gradients of 2% or less is considered to be negligible

TABLE 4.3
ADJUSTMENT TO NOISE LEVEL FOR FINITE BARRIERS, dBA

Infinite Barrier Performance	Ratio α/β										
	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
-5 dB	0	0	-1	-1	-1	-2	-2	-3	-4	-4	-5
-10 dB	0	0	-1	-1	-2	-3	-3	-4	-6	-7	-10
-15 dB	0	0	-1	-2	-2	-3	-4	-5	-7	-10	-15

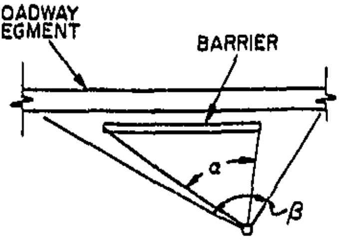


FIGURE 4.9 Sheet____of____

TRAFFIC NOISE COMPUTATION TALLY
NOISE LEVEL, dBA

Project______________________________ Engineer______________

Segment______________________________ Date ______________

Autos/hr.______________Trucks/hr.__________ Miles/hr.__________

Highway Width__________feet. Observer______________

Comments____

Item									
		A	T	A	T	A	T	A	T
L_{50} reference at 100 feet									
	Distance, width adjustment								
	L_{10}-L_{50} adjustment								
L_{10} reference at observer									
	Segment adjustment								
	Barrier adjustment								
Miscellaneous Adjustments	Gradient								
	Road surface								
	Foliage								
	Rows of houses								
L_{10} at observer, by veh. type									
L_{10} at observer, summed									

FIGURE 4.9 Sheet____of____

TRAFFIC NOISE COMPUTATION TALLY
NOISE LEVEL, dBA

Project________________________________ Engineer____________

Segment________________________________ Date ______________

Autos/hr.____________ Trucks/hr.__________ Miles/hr.__________

Highway Width_________ feet. Observer______________

Comments____

	Item	A	T	A	T	A	T	A	T
L_{50} reference at 100 feet									
	Distance, width adjustment								
	L_{10}-L_{50} adjustment								
L_{10} reference at observer									
	Segment adjustment								
	Barrier adjustment								
Miscellaneous Adjustments	Gradient								
	Road surface								
	Foliage								
	Rows of houses								
L_{10} at observer, by veh. type									
L_{10} at observer, summed									

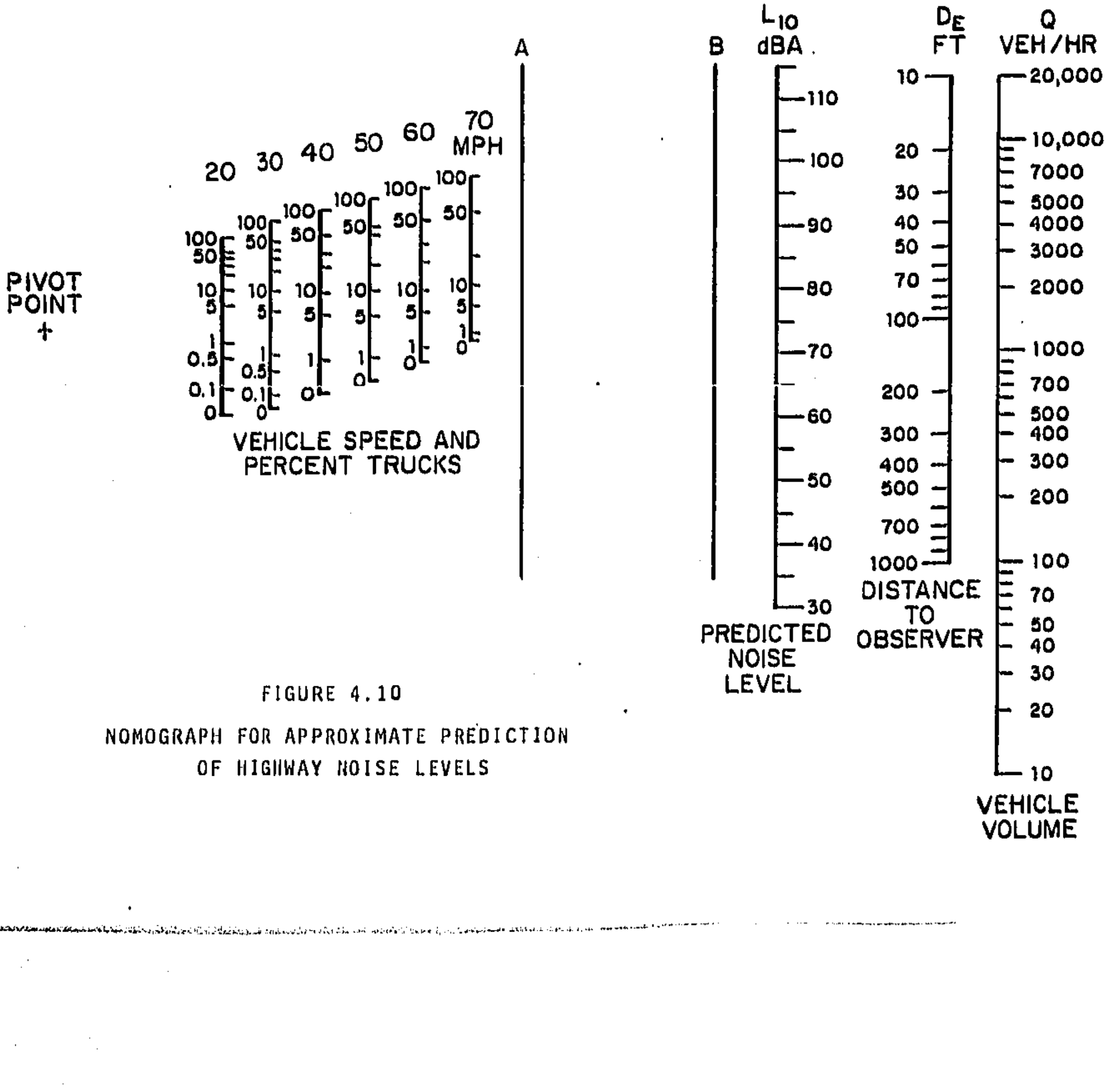


FIGURE 4.10

NOMOGRAPH FOR APPROXIMATE PREDICTION
OF HIGHWAY NOISE LEVELS

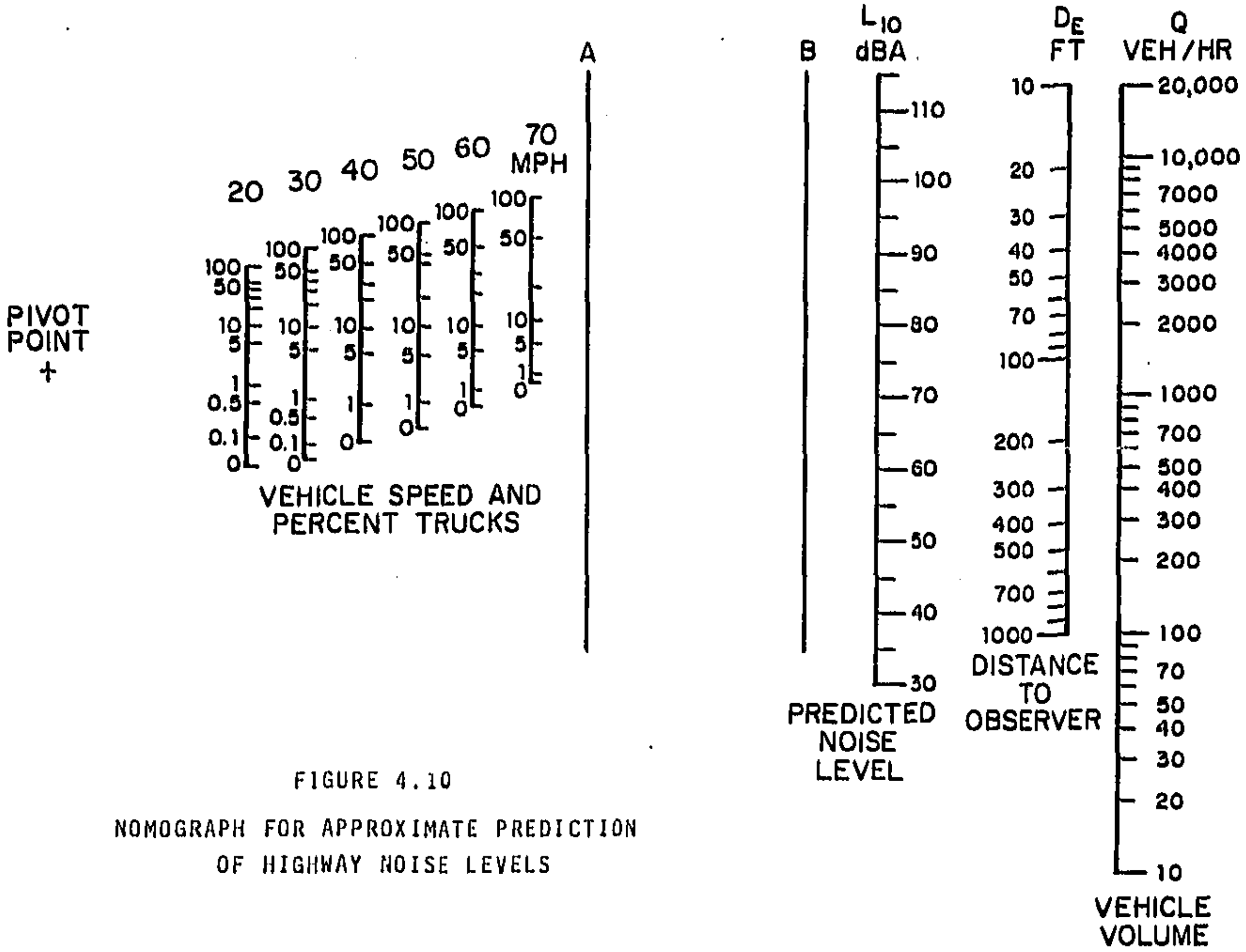
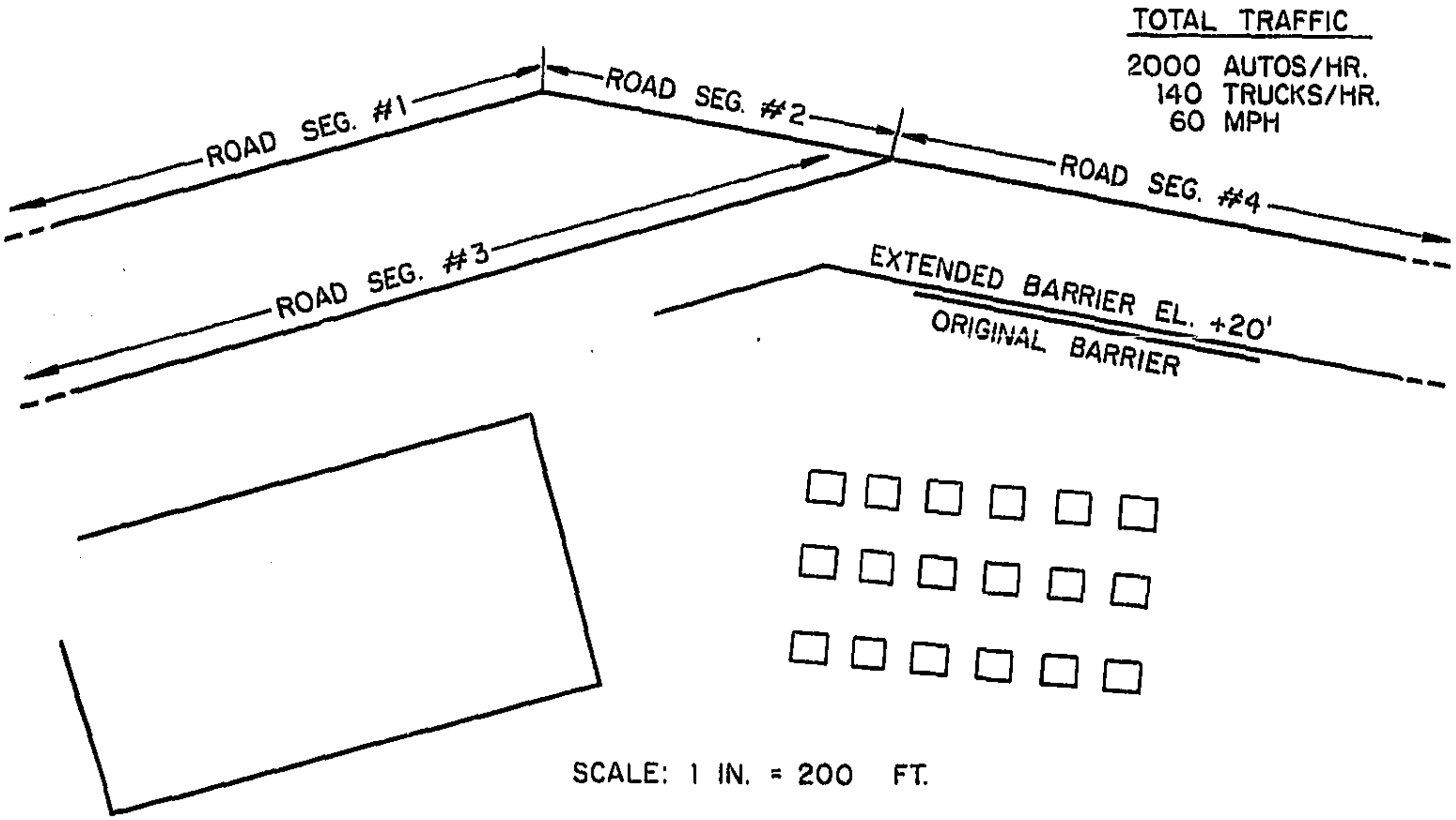


FIGURE 4.10

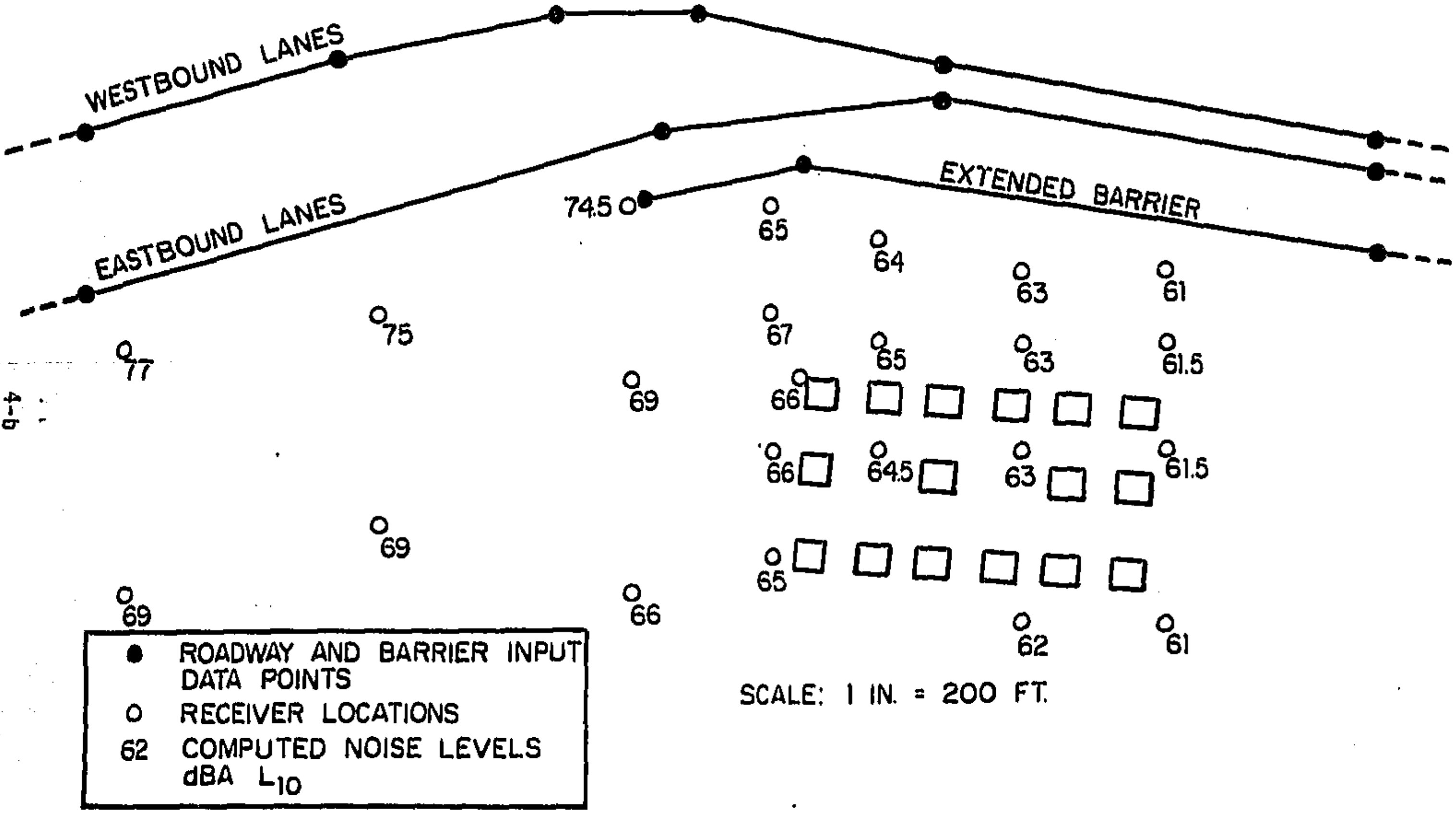
NOMOGRAPH FOR APPROXIMATE PREDICTION OF HIGHWAY NOISE LEVELS

EXTENDED BARRIER PROBLEM

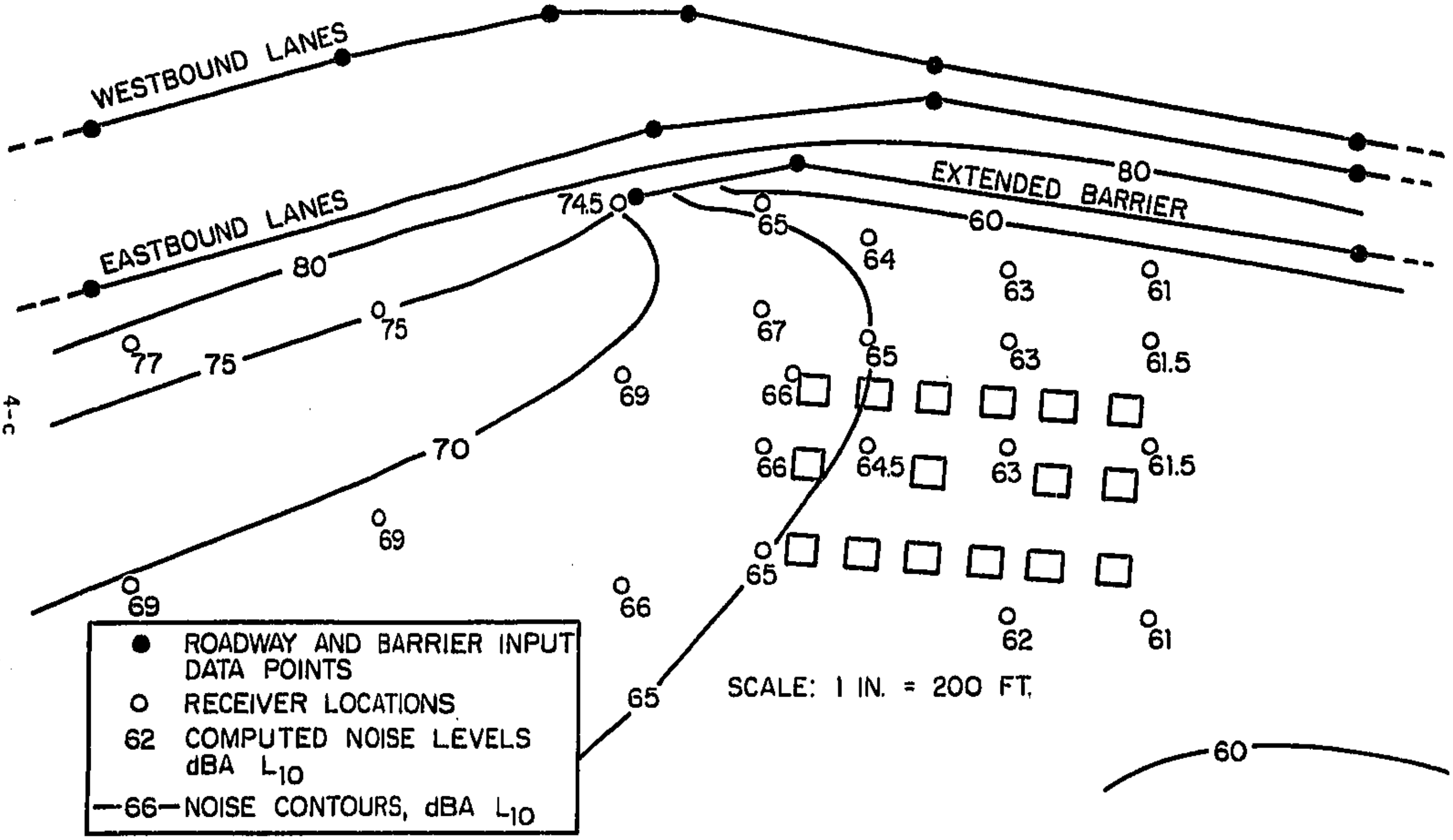


SCALE: 1 IN. = 200 FT.

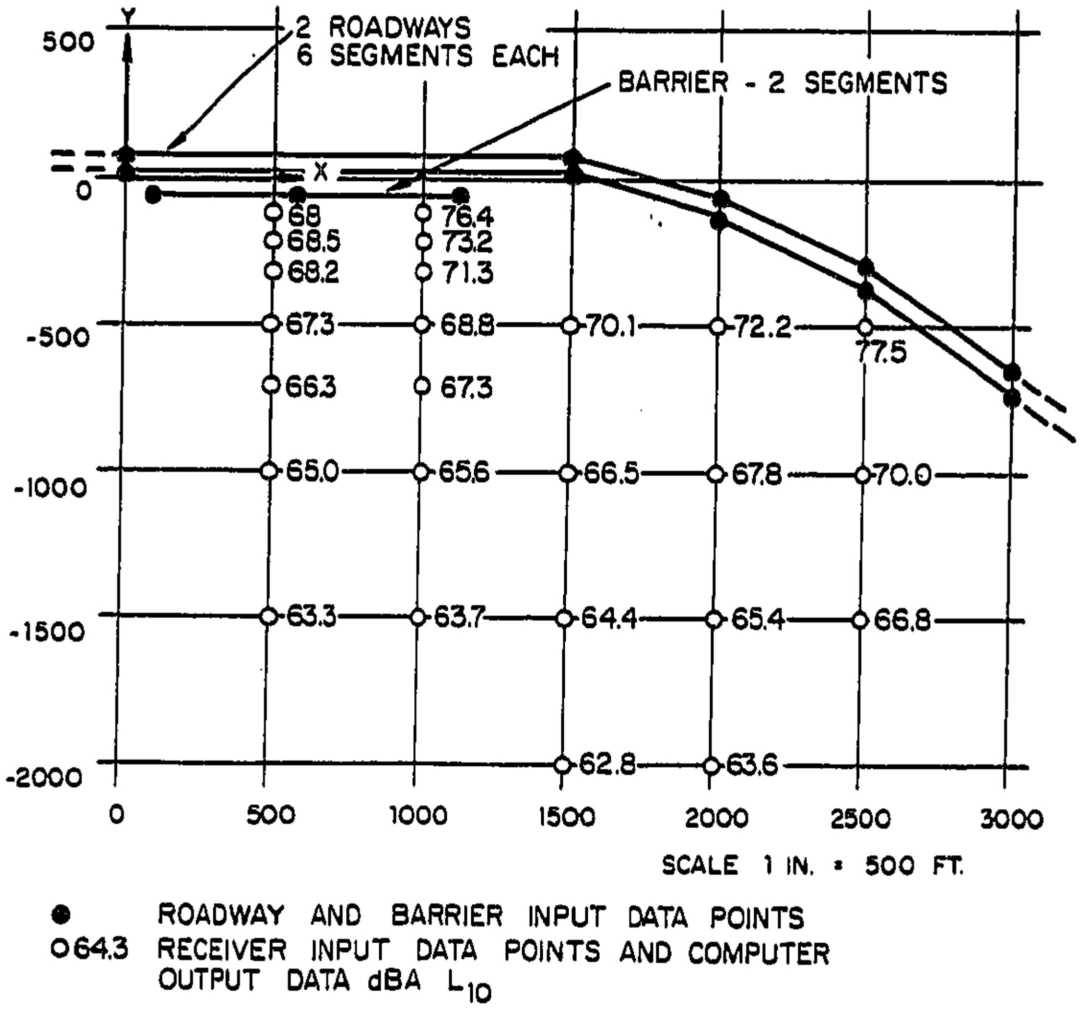
EXTENDED BARRIER PROBLEM COMPUTER OUTPUT DATA



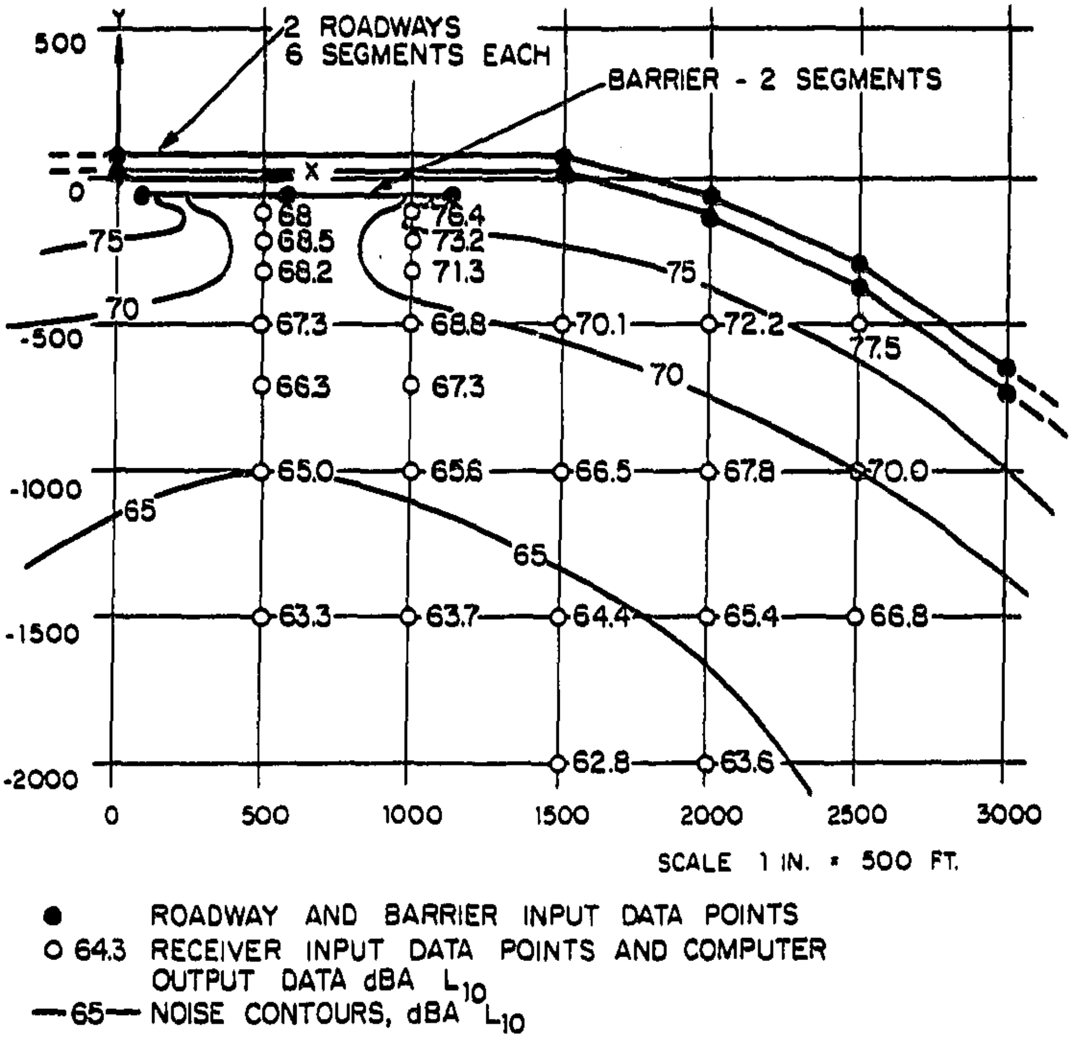
EXTENDED BARRIER PROBLEM NOISE CONTOUR LINES



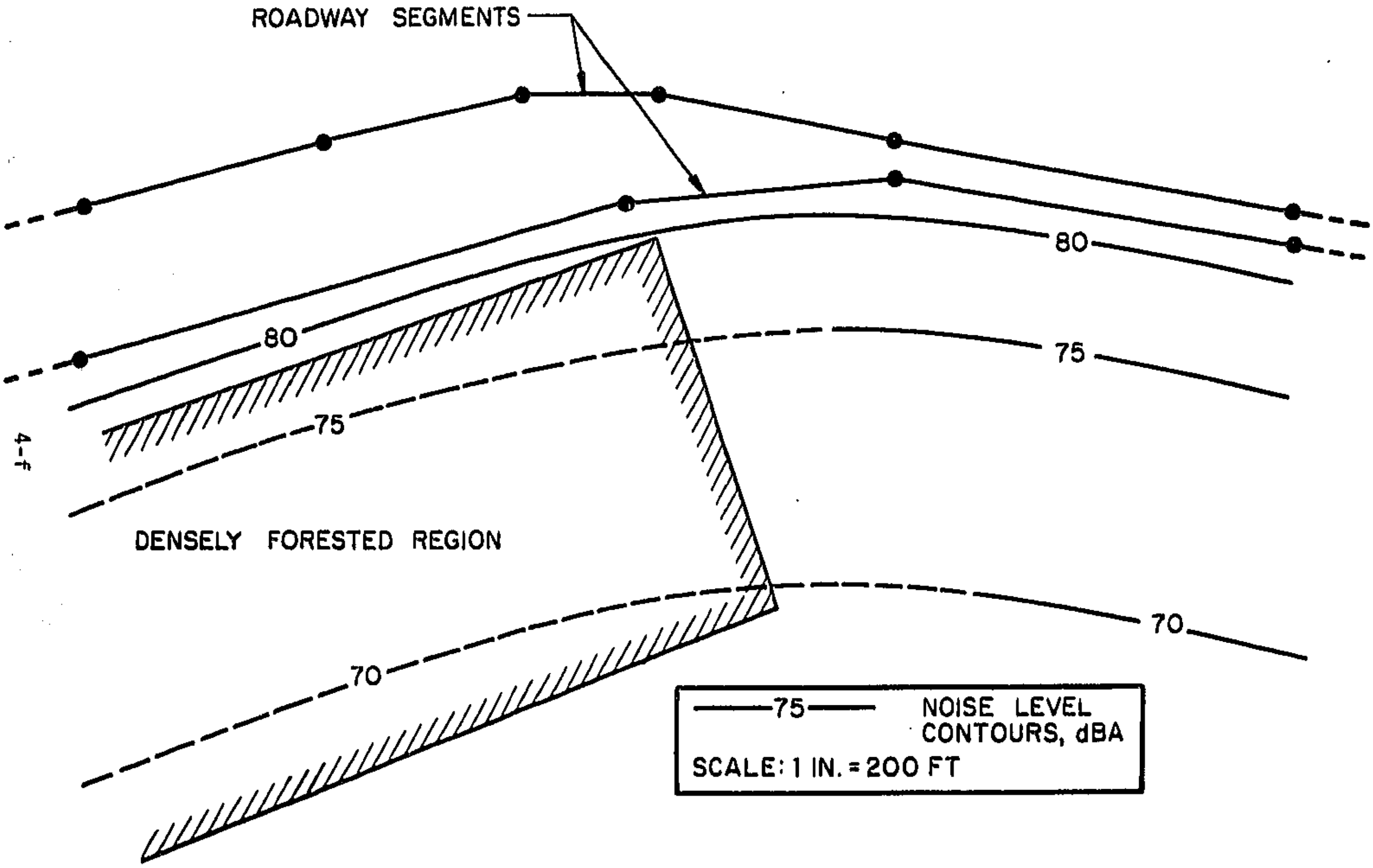
COMPUTER OUTPUT DATA FOR COUNTRY ROAD PROBLEM



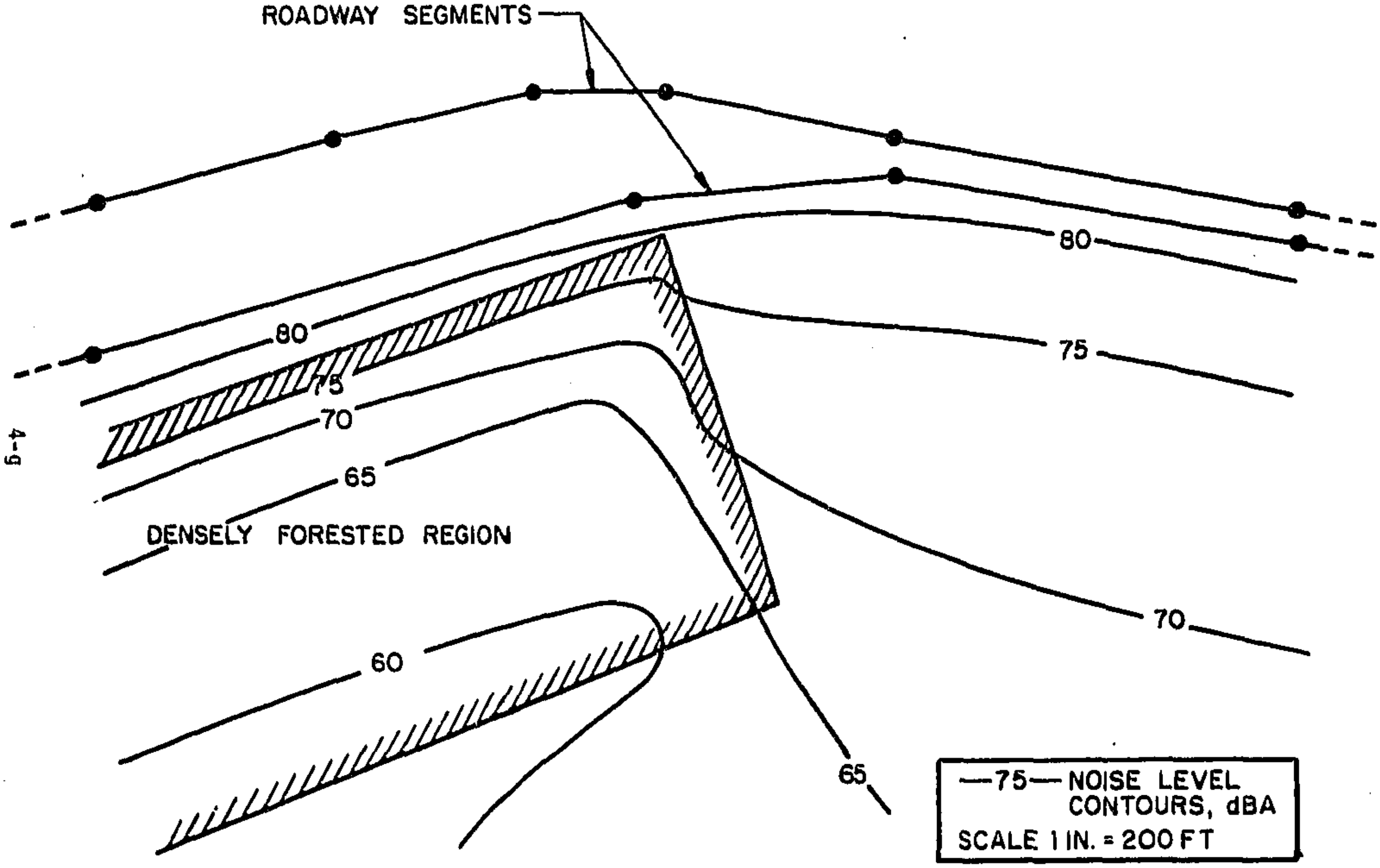
NOISE CONTOURS FOR COUNTRY ROAD PROBLEM



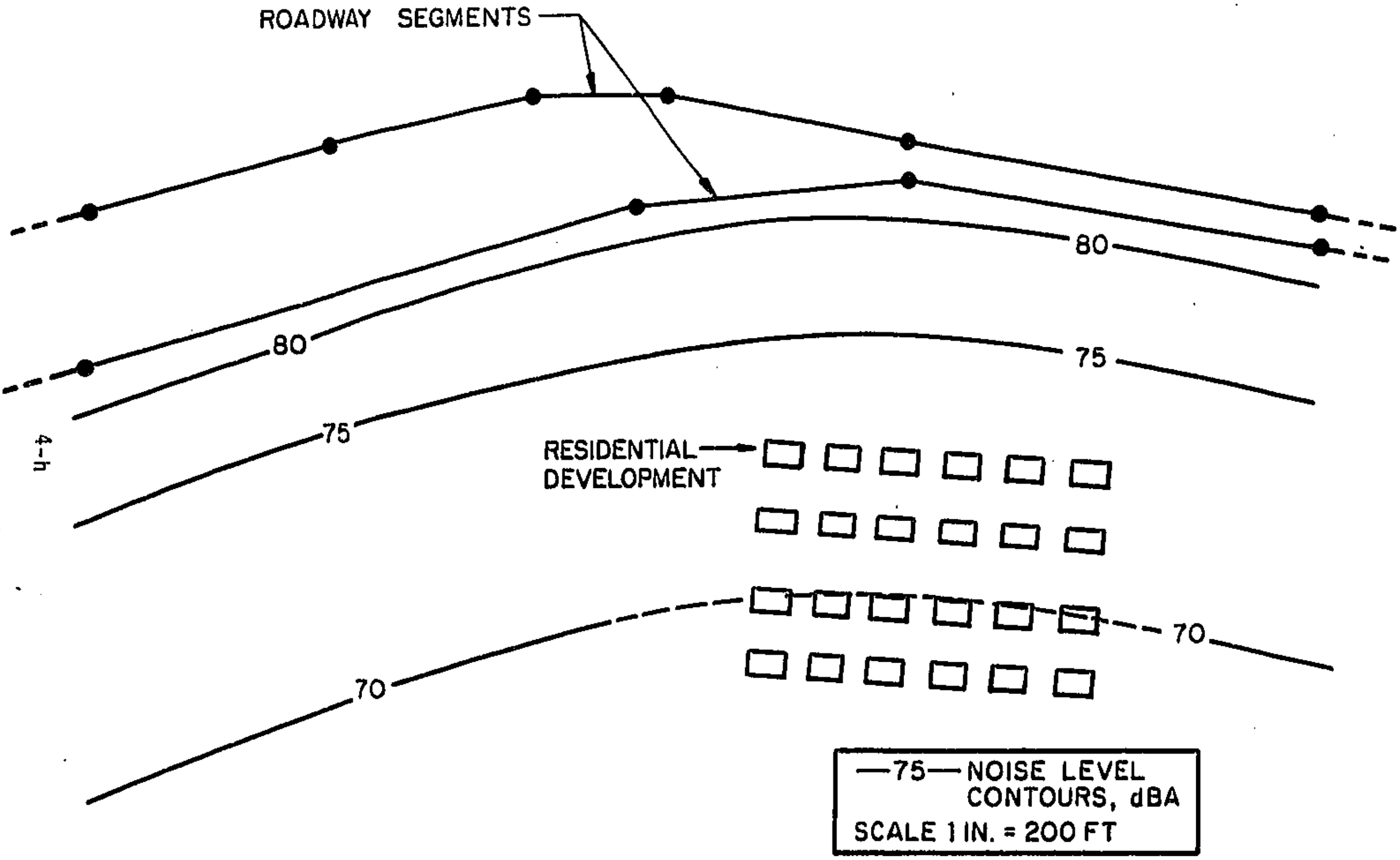
NOISE CONTOURS IN FORESTED REGION
UNADJUSTED



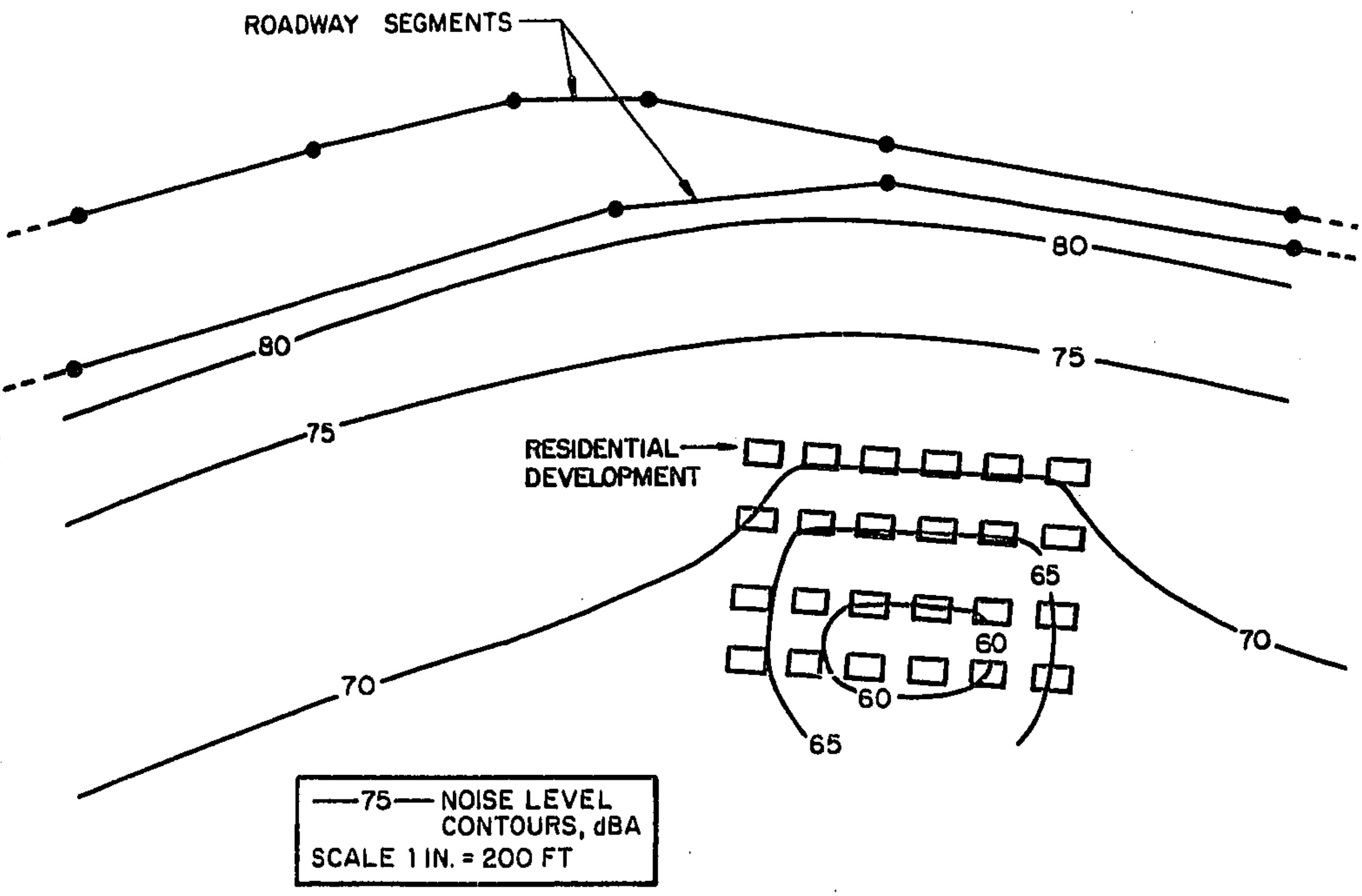
NOISE CONTOURS IN FORESTED REGION ADJUSTED



NOISE CONTOURS IN RESIDENTIAL DEVELOPMENT - UNADJUSTED



NOISE CONTOURS IN RESIDENTIAL DEVELOPMENT - ADJUSTED



CHAPTER 5

NOISE ABATEMENT

In Chapter 5, we discuss the several methods of traffic noise abatement available to the highway engineer, as design options. The design of roadside acoustic barriers is emphasized. A newly developed design tool for roadside barriers is presented and discussed. Examples are included that illustrate the power of this design tool in quickly predicting the reduction in both the L_{10} and the L_{NP} of highway traffic noise.

The other methods of noise abatement through highway design are reviewed, and various pitfalls in their use are discussed. In addition, anticipated reduction in individual vehicle noise is briefly reviewed.

5.1 BARRIER ATTENUATION OF TRAFFIC NOISE

5.1.1 Review of Some Basic Principles

The principles of barrier attenuation were discussed in Chapter 1. Several of these principles will be reviewed here, before the details of barrier attenuation calculations are presented.

A section through a roadside barrier is shown in Fig. 5.1. Noise emanating from the roadway on the left can follow four paths that are important for our purposes. These paths are shown in the figure.

- The traffic noise follows a direct path to receivers who can see the traffic well over the top of the barrier. The barrier does not block their line-of-sight (L/S) and therefore provides no attenuation. No matter how absorptive the barrier is, it cannot suck the sound downward and absorb it.

- The noise follows a diffracted path to receivers in the shadow zone of the barrier. The noise that passes just over the top edge of the barrier is diffracted (bent) down into the apparent shadow shown in the figure. The larger the angle of diffraction, the more the barrier attenuates the noise in this shadow zone. In other words, less energy is diffracted through large angles than is diffracted through smaller angles.

- In the shadow zone, the noise transmitted directly through the barrier may be significant in some cases. For example, for extremely large angles of diffraction, the diffracted noise may be less than the transmitted noise. In this case the transmitted noise is compromising the performance of the barrier, and it must be reduced - usually by constructing a heavier barrier. The allowable amount of transmitted noise depends upon the barrier attenuation desired. More will be said below about this transmitted noise.

- The final path shown in Fig. 5.1 is the reflected path. After reflection, the noise is of concern only to a receiver on the opposite side of the roadway, across from the barrier. For this reason, acoustical absorption on the face of the barrier will reduce this reflected noise, but will not benefit any receivers in the shadow zone. Their noise is diffracting over the top of the barrier, unaffected by the absorption.

In summary, a receiver in the shadow zone hears the noise that has diffracted over the top of the barrier. The resulting noise level is less than it would be without the barrier; the net benefit is called the "barrier attenuation." If the barrier transmits an excessive amount of noise, this transmitted noise may "short-circuit" the barrier attenuation.

Another short-circuit path is shown in Fig. 5.2, a plan view of the same barrier. The noise diffracted over the top of the barrier is reduced by the barrier attenuation. However, part of the roadway is unshielded by the barrier. The receiver can see the roadway beyond the ends of the barrier, up and down the corridor. If the barrier is not long enough, then this noise from around the ends may compromise, or short-circuit, the barrier attenuation. The required barrier length depends upon the net attenuation desired. When some 10 to 15 dBA attenuation is desired, roadside barriers must be very long, as indicated by the example in Chapter 1. Therefore, barriers must not only break the lines-of-sight to the nearest section of roadway, but also to the roadway far up and down the corridor.

One other general principle is worth reviewing at this point: the relation between noise attenuation expressed (1) in decibels, (2) in energy terms, and (3) in subjective loudness.

Table 5.1 summarizes the relationship between decibels, energy, and loudness. As indicated in the loudness column, a barrier attenuation of 3 dBA will be barely discerned by the receiver. To cut the loudness of the highway in half requires a reduction of 10 dBA - equivalent to eliminating 90 percent of the energy initially headed towards the receiver. As indicated above, this drastic reduction in energy requires very long barriers, as well as very high barriers.

Often this reduction is the practical limit in barrier design - a good rule of thumb to remember.

BARRIER ATTENUATION

5 dBA - SIMPLE
10 dBA - ATTAINABLE
15 dBA - VERY DIFFICULT
20 dBA - NEARLY IMPOSSIBLE

To achieve a 20 dBA reduction - thereby cutting the energy by 99% - requires enormous structures, supplemented by great ingenuity to prevent short-circuiting around this 99% "filter".

5.1.2 NCHRP Report 117 Barrier Procedure

To compute the barrier attenuation using NCHRP Report 117, the following procedure is followed:

First the roadway is broken into segments with uniform barrier characteristics, as illustrated in Figure 5.3. Then the segment contribution is computed for each of the segments individually, using the procedures described in Chapter 4. For the segment shielded by the barrier, the segment contribution is reduced by the barrier attenuation. The complete routine is performed twice, once for automobiles and once for trucks. Finally, the segment contributions, for both autos and trucks, are combined by dB-addition to yield the net noise at the observer. Then a comparison of the shielded with the unshielded noise indicates the net barrier attenuation. For the case of Figure 5.3, the 120-degree segment would control the noise at the observer, without the barrier. With the barrier, it is likely that the noise would be controlled by the 30-degree segments, unless the barrier were very low. Then it might be controlled by the truck noise from the 120-degree segment. Only a separate calculation for automobiles and trucks can indicate the true relationship.

To compute the barrier attenuation of the 120-degree segment, the parameters shown in Figure 5.4 must be known. These are the same parameters discussed in general terms in Chapter 1. First the line-of-sight (L/S) between the noise source and the observer is drawn; then H equals the perpendicular break in this line-of-sight. As can be seen from the figure, H is not the barrier height. As a matter-of-fact, if the line-of-sight slants up or down from the source to the receiver, then this perpendicular break H also slants away from the vertical. Figure 5.8 below illustrates this slant geometry.

The source end of the L/S terminates at the pavement for automobile traffic and 8 feet above the pavement for truck traffic. At the receiver end, the L/S terminates at the receiver's ear height, which may be several stories above the ground for bedroom windows, etc. The figure drawn in Report 117 is quite misleading (Figure 5.5). The double line drawn between the equivalent lane and the observer in Figure 5.5 is the line-of-sight, not the ground plane. With this in mind, the two sets of parameters are the same.

An additional complication enters when the noise source consists of several lanes of traffic, and it is desired to combine all lanes into one equivalent lane. For such cases, the equivalent distance from barrier to source must be computed. The computation uses the same equation as the equivalent distance D_e from receiver to source, discussed above in Chapter 4. However, for the barrier attenuation calculation, it is the equivalent barrier-to-source distance that is computed. The computation is carried out in Example 4 below.

As a short-cut, Report 117 allows the barrier calculation to be made only for automobiles, with the trucks automatically assigned 5 dBA less attenuation. This 5 dBA truck correction is a rough average for many barrier situations, and was suggested in Report 117 for situations where truck noise does not dominate. Since we now are restricting our calculations to the ten-percentile level L_{10}, this 5 dBA adjustment should be restricted to highways with extremely low truck percentages, say below 1 percent. Rather than use this short-cut of Report 117, it is suggested that the barrier calculation be performed in full for the trucks (with their eight-foot source height) and then 5 dBA added, to approximate the automobile noise attenuation.

With this revised short-cut, the dominant truck noise is afforded the more accurate calculation. It is highly recommended, however, that the calculations be made separately for both autos and trucks, as described above, rather than relying upon either short-cut.

Another short-cut described in Report 117 involves the use of Figure 5.6 to avoid the initial break-up into segments. Whenever a barrier shields only a part of the roadway (non-infinite barrier), this figure can be used to correct the infinite barrier performance. In this manner, the noise coming around the ends of the barrier, from the unshielded segments of the roadway, is taken into account. For example, if the previous figure had indicated a 10 dBA barrier attenuation (infinite barrier), and the barrier subtended an angle of 120 degrees (out of the total 180-degree roadway) then the ratio of α to β would be 0.67. The table would then indicate that the finite barrier attenuation is 4 dBA.

5.1.3 Additional Barrier Research

Since the barrier attenuation curves of Figure 5.5 were drawn, much additional barrier research, both theoretical and experimental, has been undertaken. The theoretical research indicates several departures from the curves of Figure 5.5. First, in the region of low H^2/D, more attenuation is expected than shown in the figure. In fact, for $H = 0$, the diffraction theory predicts 5 dBA attenuation, rather than the 0 dBA attenuation shown. This additional work is included in the barrier calculations of Fig. 1.10 in Chapter 1. As is evident, there is a significant increase in complexity involved. For intermediate values of H^2/D, the theory has been extended to incorporate barrier attenuation from <u>line</u> sources. As shown in Chapter 1, the barrier attenuation for vehicles far down a roadway is less than for the closer-by vehicles, since both the barrier-to-source and the barrier-to-observer distances have increased. As a result, the net attenuation from a full line of noise sources is less than if they were all concentrated at the closest point of the roadway. This results in lower barrier attenuation for traffic noise than is shown in Figure 5.5.

Parallel to the theoretical work, much experimental work has been undertaken over the past several years, both on laboratory models and on full-scale field installations. All of this work confirms the most recent theory.

The barrier attenuation computations contained in the TSC computer program incorporate the results of this most recent theory and experimentation. As such, the TSC barrier attenuation is state of the art. In addition, the complex geometries involved in a complex barrier system design are properly treated by the computer program. Both roadways and barriers are divided fully into segments, the attenuation for each is calculated, and then the conglomeration is recombined properly (in a statistical sense) for the total noise level. This computer program provides the ultimate tool for evaluating a system of noise barriers, once designed. Unfortunately, the program is very expensive and time consuming to use as a <u>design tool</u>. Even when used during preliminary testing of a barrier design, the program provides no hint of the "weak links" in the design - it does not indicate the relative contribution of various segments, lanes, vehicles, or reflected noise to allow intelligent redesign of the barrier system. What is needed is a quick and inexpensive approximation to the computer program - one that indicates the relative contribution of the various components of the noise, in addition.

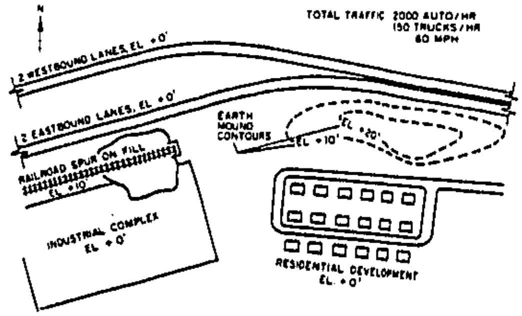
BARRIER PROCEDURES

	BENEFITS	DRAWBACKS
TSC	• STATE-OF-THE-ART	• EXPENSIVE • TIME CONSUMING • CANNOT INDICATE "WEAK LINKS"
REPORT 117	• HAND DONE	• LOW ACCURACY • COMPLEX
*NOMOGRAPH	• HAND DONE • GOOD DESIGN TOOL • APPROXIMATES TSC ACCURACY	• STRAIGHT ROADWAYS ONLY

5.1.4 Nomograph Barrier Procedure

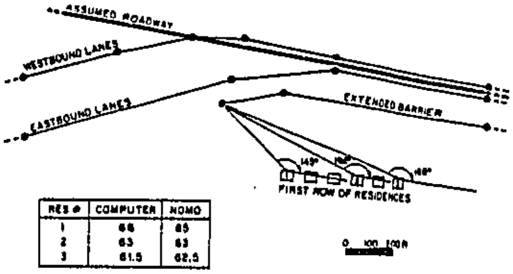
The calculation procedure described in the present chapter has been developed as a design tool, to enable quick barrier calculations approximating the TSC computer program. It is less precise than the computer program, but more convenient as a design tool. It is recommended as a substitute for the calculation procedure of NCHRP Report 117. It will be referred to as the "Nomograph Barrier Procedure".

This procedure assumes an infinite straight roadway, with a barrier of uniform height that parallels the roadway at a constant distance. It can generally be used with confidence when the geometry is <u>mostly</u> straight and parallel - as it usually appears to very close-by receivers. The barrier can be of finite length and the receiver can be located anywhere with respect to the barrier - he need not be centered on the barrier, for example. The problem can be treated in all its complexity, as seen in section: edges of elevated structures, lips of depressed sections, reflection from opposite retaining walls, complete breakdown by lane if desired, etc. Proper source heights are used throughout, in agreement with assumptions in the TSC computer program.



SKETCH 5.1

The barrier nomograph has been applied to one of the barriers from Chapter 4, to indicate the errors introduced for non-parallel geometries. The map of Sketch 5.1 is reproduced from Chapter 4. Sketches 5.2 and 5.3 indicate two possible nomograph solutions.



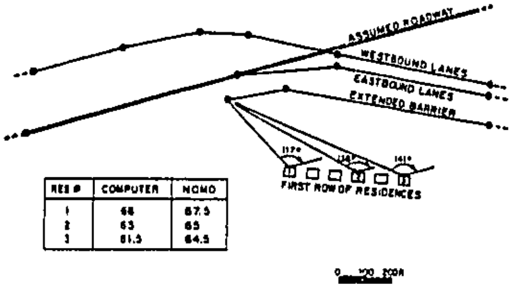
RES #	COMPUTER	NOMO
1	66	65
2	63	63
3	61.5	62.5

SKETCH 5.2

The two solutions have different assumed roadways, both infinite and straight. For each solution, the barrier is positioned parallel to the roadway, where the line-of-sight from the receiver crosses the actual barrier. A comparison of the nomograph solution with the computer solution indicates that even in this rather gross approximation, the error is not extreme.

Solution #1 duplicates the roadway-barrier relationship more exactly, and therefore provides a more accurate approximation well behind the barrier, where the noise level is controlled by sound diffracted over the barrier. Solution #2 duplicates more accurately the roadway, as seen around the left end of the barrier. This solution, therefore, provides a more accurate approximation towards the left, where the noise level is controlled by sound coming around the end.

As is apparent from these two nomograph barrier solutions, the requirements of straight roadways and parallel barriers need not be too stringently interpreted.



RES #	COMPUTER	NOMO
1	66	67.5
2	63	65
3	61.5	64.5

SKETCH 5.3

One additional note: As mentioned in Chapter 1, barriers of insufficient height can increase the annoyance potential of traffic noise. Such barriers reduce the steady noise of the automobiles without reducing the peak noise of the trucks. The increase in noise fluctuation can offset the reduction in the L_{10}, producing a worse condition than without the barrier. The Nomograph Barrier Procedure incorporates a check to determine whether or not the barrier system will have this effect.

NOMOGRAPH BARRIER PROCEDURE

ASSUMPTIONS	CAN HANDLE
• INFINITE STRAIGHT ROADWAY	• FINITE OR INFINITE BARRIERS
• BARRIER PARALLEL TO ROADWAY	• DEPRESSED & ELEVATED ROADWAYS
• BARRIER UNIFORM HEIGHT	• REFLECTIONS
	• BREAKDOWN BY LANE & VEHICLE TYPE
	• NOISE FLUCTUATIONS

An overview of the barrier nomograph is included as Figure 5.7. Just the salient features are included. The dark horizontal line across the bottom center is the line-of-sight (L/S) between the noise source and the receiver. The simplest line-of-sight is used - from the receiver perpendicular to the roadway. The top of the barrier penetrates into this line-of-sight, as shown by the wavy line. The relation between the source, the receiver, and the top of the barrier is drawn in this pictorial way to aid in the nomograph's use. The top of the barrier falls on a curve of constant attenuation. For example, if the barrier were moved closer to the left end of the L/S, it would not have to penetrate the L/S as much for the same attenuation.

The barrier position is read on the small nomograph at the bottom, under the L/S. The barrier's break in the L/S is read similarly at the left. The attenuation is read to the right. This attenuation is a function of the angle that the barrier makes at the receiver.

All of these quantities will be more clearly defined below. First, however, it is instructive to talk through the nomograph. The length of the L/S is used three times in the nomograph, to normalize all distances to the scale of the pictorial sketch. Starting at the bottom, a line is drawn from the L/S length, through the barrier position, to the turning line. The position is measured to either the source or the receiver, whichever is closer. After turning upward, this line sets the position of the barrier relative to the source and the receiver. Then starting at the left, a line is drawn from the L/S length through the barrier break-in-L/S to the turning line, and then horizontally into the attenuation curves. Where these two lines meet is the top of the barrier. It will lie on some particular barrier attenuation curve. This curve is followed upward to the right, then turned to the L/S length. From where this crosses the pivot line, a line is drawn to the right, reflected straight upwards from the proper angle line, to the barrier attenuation.

Notice that the nomograph can be used in other modes, to solve for the barrier position, or the barrier break-in-L/S, or the angle subtended - if the other factors are known. For example, if the attenuation and angle are known, the attenuation line is determined. Then the break-in-L/S can be found for any barrier position, or vice versa. As another example, if we wanted the same attenuation with a smaller angle, we would end up on a higher attenuation curve. If the barrier position remained unchanged, then the break would have to increase to reach this new curve.

At this point, let us define our parameters more carefully. Figure 5.8 shows a section view of a roadside barrier. The section is perpendicular to the roadway, in the normal manner. The line-of-sight (L/S) slants downward from the noise source to the receiver. The L/S length is this slant distance, not the horizontal distance. From the top of the barrier, a line is drawn perpendicular to the L/S. This is the break in the L/S, always perpendicular to the L/S. Finally the barrier position is measured along the L/S to the perpendicular break point. This, too, is a slant distance, not horizontal. It is measured to either the source or the receiver, whichever is closer. Note that the vertical and horizontal scales on all sectional drawings must be identical. Otherwise, slant distances cannot be measured.

BARRIER PARAMETERS

LENGTH OF L/S ≠ HORIZONTAL DISTANCE
BREAK IN L/S ≠ BARRIER HEIGHT

As further illustrations of the geometry involved, the parameters have also been drawn for depressed and elevated sections in Figs. 5.9 and 5.10.

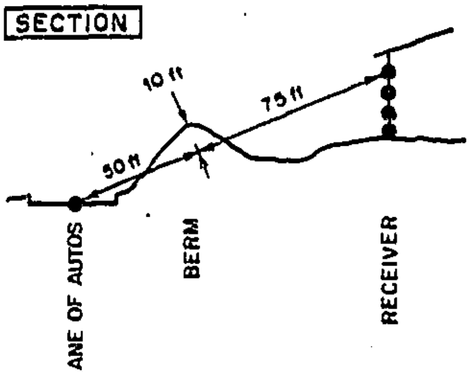
For any type of section, the receiver can be either left or right of the roadway, the L/S can slant either up or down. In all cases, the perpendicular break in the L/S is required, and the barrier position is measured to the closer end of the L/S.

The angle is defined in the plan view of Figure 5.11. It is the angle subtended at the receiver by the barrier. The receiver position relative to the barrier is not important. The receiver can be centered on the barrier, off-center, at the end of the barrier, or even beyond the end of the barrier. All cases are shown. Of course, if the receiver is at the end of the barrier or beyond, the largest angle possible is 90 degrees, and not much attenuation can be expected. All definitions of parameters have been condensed into Table 5.2 for convenience.

Example #1

At this point, the reader is asked to try a sample barrier problem with the fully detailed nomograph (Fig. 5.12) before a sample is talked through. It is hoped that the various scales are self-explanatory. In any case, the reader will benefit by resolving his own confusions with the nomograph before a full explanation is given. The example is simple: a single lane of automobiles, shown in Sketch 5.4.

The earth-berm barrier subtends an angle of 170 degrees at the receiver. Answer to sample problem: The barrier provides 11 dBA reduction from the automobile traffic to the fourth floor of the residence shown. Again, the reader is urged to attempt each example before following the explanatory discussion.



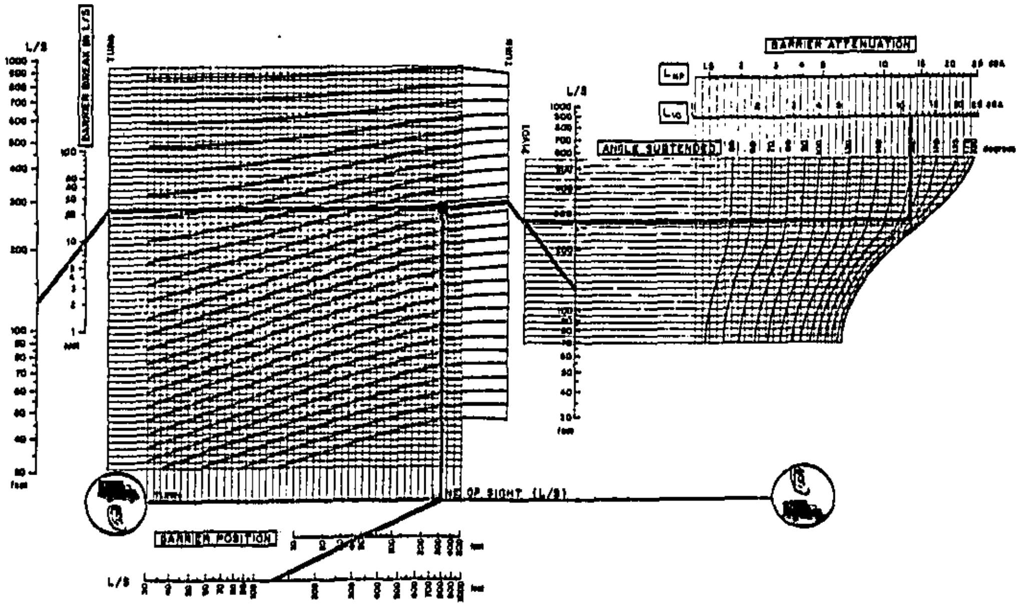
SKETCH 5.4

The completed barrier nomograph is included as Sketch 5.5.

Did you use the full L/S distance? Did you try to use the barrier-receiver distance for the barrier position? Notice that it is the longer of the two distances, so should not be used. Notice again that the barrier break in the L/S is the perpendicular break, not the vertical break. Notice also that this break is not the barrier height. The L/S is slanting upward towards the fourth-floor window; the break in L/S is less than the barrier height.

Please correct your nomograph if it is incorrect. Using the corrected nomograph, what is the barrier attenuation if the angle subtended is reduced to 160 degrees? Answer: 9½ dBA attenuation. With this smaller angle, what size barrier must be constructed to regain the original 11 dBA reduction? Answer: the new barrier must break the L/S by 20-25 feet.

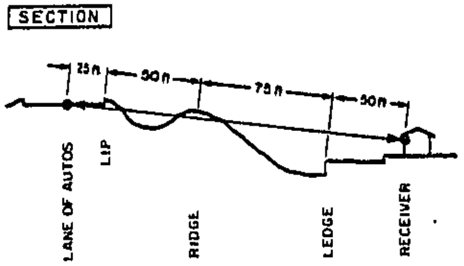
One further comment: note that both the position and break scales are logarithmic. This overemphasizes the barrier height and the distance of the barrier from the near end of the L/S. For this reason, the sketch on the nomograph is pictorial only. No attempt should be made to place the barrier top on the sketch by inspection only, from the section view. The small nomographs to the left and at the bottom must be used.



SKETCH 5.5

Example #2

Let us now work through an example knowing the barrier attenuation desired - 10 dBA. The section is shown in Sketch 5.6.

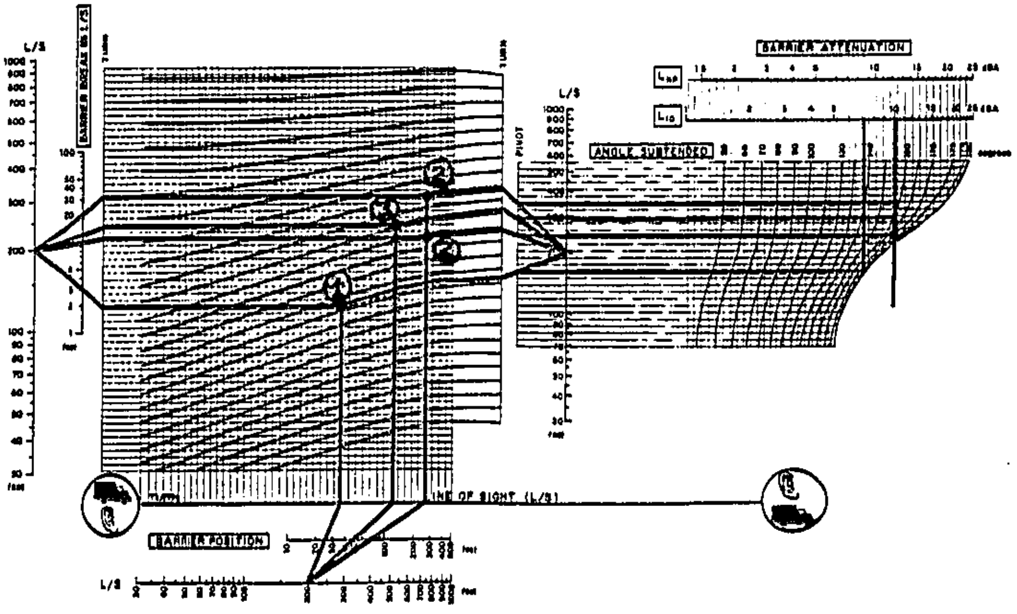


SKETCH 5.6

First, does the lip of the roadway itself provide enough attenuation? The nomograph is worked out (lines numbered "1") in Sketch 5.7.

Starting from the left, the roadway lip breaks the L/S by 3 feet (obviously measured on a larger scale drawing than the actual sketch). From 200 feet on the L/S scale, a line is therefore drawn through 3 feet on the break-in-L/S scale, to the turning line, and then horizontally to the right. Then starting over at the bottom, from 200 feet on the L/S scale, a line is drawn upward through the barrier position of 25 feet to the turning line, and then vertically upward until it crosses the first line drawn. This cross point is the top of the barrier. As can be seen, both its distance from the source and its break in L/S are exaggerated by the log scales.

From the top of the barrier, the attenuation curve is followed up to the right, then turned to pass through 200 feet on the L/S scale. Where this crosses the pivot line, proceed horizontally to the right. Since this roadside lip extends the full roadway distance in both directions, the barrier angle equals 180 degrees. Reflect the line from 180 degrees upwards to the L_{10} attenuation, 7 dBA. This is not enough attenuation.



SKETCH 5.7

As a second attempt, let us place a berm along the top of the ridge that already breaks the L/S slightly. How high must the berm be to achieve 10 dBA attenuation? The lines numbered "2" on the same nomograph(Sketch 5.7) trace through the reasoning in this case. The attenuation and the position are fixed; the break-in-L/S and the angle subtended are variable. Starting from an attenuation of 10 dBA, a line is dropped vertically. Then starting over at the bottom, from 200 feet on the L/S scale, a line is drawn up through 75 feet on the position scale, and then turned vertically into the attenuation curves. For different subtended angles, different height barriers are required. Two solutions are shown: a ten-foot break, subtending 170 degrees and a twenty-foot break subtending 155-160 degrees.

It is possible, of course, that for smaller angles (for example, 140 degrees) the desired attenuation cannot be achieved with any height barrier. In such situations, the noise coming around the end of the barrier exceeds the allowable noise, and even a tunnel section over that small angle would not achieve the desired attenuation.

As a third attempt, let us try to achieve 10 dBA attenuation with a barrier close to the residence. A likely position is at the ledge some 50 feet in front of the residence. The proper lines for such a barrier are numbered "3" on the nomograph. The position and attenuation are both known; the break-in-L/S and the angle subtended are variable. One solution is shown. A large angle (160 degrees) was chosen, since the barrier is close to the residence and the required length is therefore proportionately less; the required break is 13 feet for this angle.

The barrier design chosen depends upon the many non-acoustical constraints at this location. Perhaps extending the lip of the road upward on the side of the receiver is a desirable alternative. How high would the lip have to be? Answer: It would have to break the L/S by 5½ feet. The roadway lip on the opposite side of the roadway could not be raised also, or reflections from it would compromise the barrier's performance. More will be said about this complication below.

Two possible mistakes should be pointed out here: Once the top of the barrier is found on the nomograph, the user might be tempted to move horizontally towards the right, instead of following the attenuation lines upward to the right. If this is done, then the barrier position would have been ignored in the nomograph's use. Another mistake might occur in using the angle lines. Instead of reflecting vertically upward from the angle lines, the user might be tempted to hit an angle line, and then follow the line upwards to the right towards the barrier attenuation. If this is done, then only the angle has been taken into account; all other parameters would be ignored in the nomograph use. To avoid both mistakes, the user should consult the example at the lower right, until he is familiar with the nomograph.

Example #3

For Example #3, two additional complexities will be added: (1) trucks will be added to the automobiles, and (2) a worksheet (Worksheet 5.1) for combining multiple lanes and/or vehicle types will be introduced. The worksheet is included as Sketch 5.8, properly completed for the last example's ridge barrier:

NOISE SOURCE	NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
Trucks			
Autos	75.0	10.0	65.0
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
TOTAL	75.0	TOTAL	65.0

NET BARRIER ATTENUATION: 10 dBA for L_{10}

SKETCH 5.8

The no-barrier L_{10} has been arbitrarily filled in; the barrier attenuation is subtracted, resulting in the with-barrier L_{10} in the right-hand column. The two L_{10} columns are added by dB-addition at the bottom of the worksheet, and then subtracted to obtain the net barrier attenuation. It is hardly worth using the worksheet for this simple case.

The worksheet becomes more useful for Example #3, in which the lane of traffic includes both automobiles and trucks. At the risk of getting ahead, the completed worksheet for Example #3 is included as Sketch 5.9.

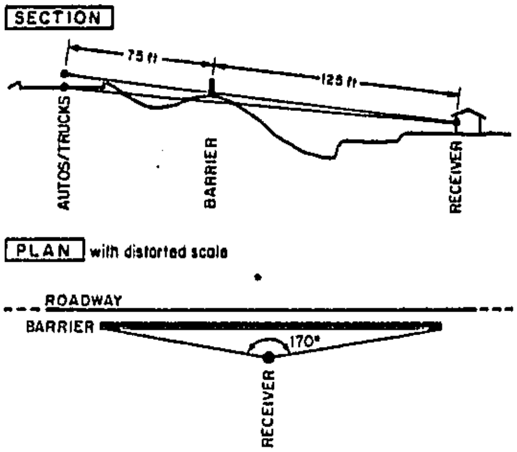
NOISE SOURCE	NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
Trucks	80.0	7.0	73.0
	—		—
Autos	75.0	10.0	65.0
	=81.0		=73.5
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
TOTAL	81.0	TOTAL	73.5

NET BARRIER ATTENUATION: 7.5 dBA for L_{10}

SKETCH 5.9

All the geometry is the same, except that trucks have been added. Again the truck no-barrier L_{10} was chosen arbitrarily. As can be seen from the worksheet, the barrier attenuation for trucks is less than for automobiles. After both L_{10} columns are added by dB-addition at the bottom, they are subtracted to obtain the net barrier attenuation of 7½ dBA. This is significantly less than the attenuation for automobiles alone.

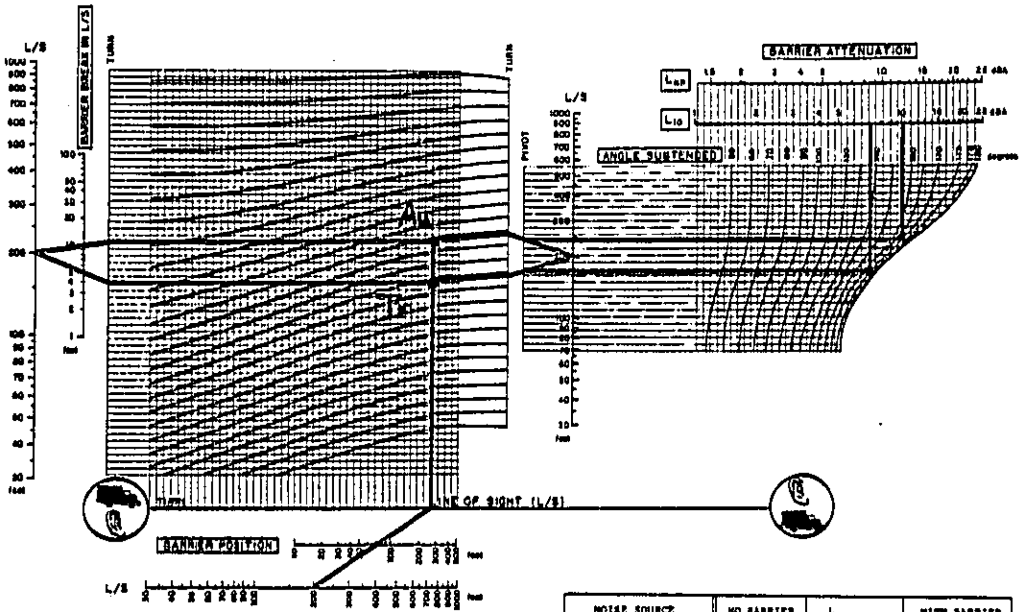
Let us backtrack now to find the truck attenuation. The revised section is shown in Sketch 5.10.



SKETCH 5.10

The barrier designed for the previous example is shown in place. The automobile L/S is unchanged from the previous example. The truck L/S is new. It terminates 8 feet above the pavement, as discussed in Chapter 2. As can be seen, the break in the truck L/S is significantly less than in the auto L/S (5 feet compared to 10 feet). How much less depends upon the slant and the relative distances involved, and cannot be generalized. The reader should solve the barrier attenuation from the dimensions in this sketch. The completed nomograph is included as Sketch 5.11.

Both the automobile and the truck solutions are shown. The break-in-L/S is the only significant difference between the two.



SKETCH 5.11

Example #4

For Example #4, an elevated highway closely adjacent to a residence is considered first in its full complexity and then in a simplified form. The section is shown in Sketch 5.12. Six lanes of traffic times two vehicle heights requires twelve solutions of the barrier nomograph. Most barrier parameters - L/S length, barrier break-in-L/S, and barrier position - are significantly different for each lane of traffic. A ten-foot barrier has been constructed at the edge of the structure as shown. The angle subtended is 180 degrees for all traffic. The reader should solve each of the barrier attenuations before proceeding. The completed worksheet is included as Sketch 5.13.

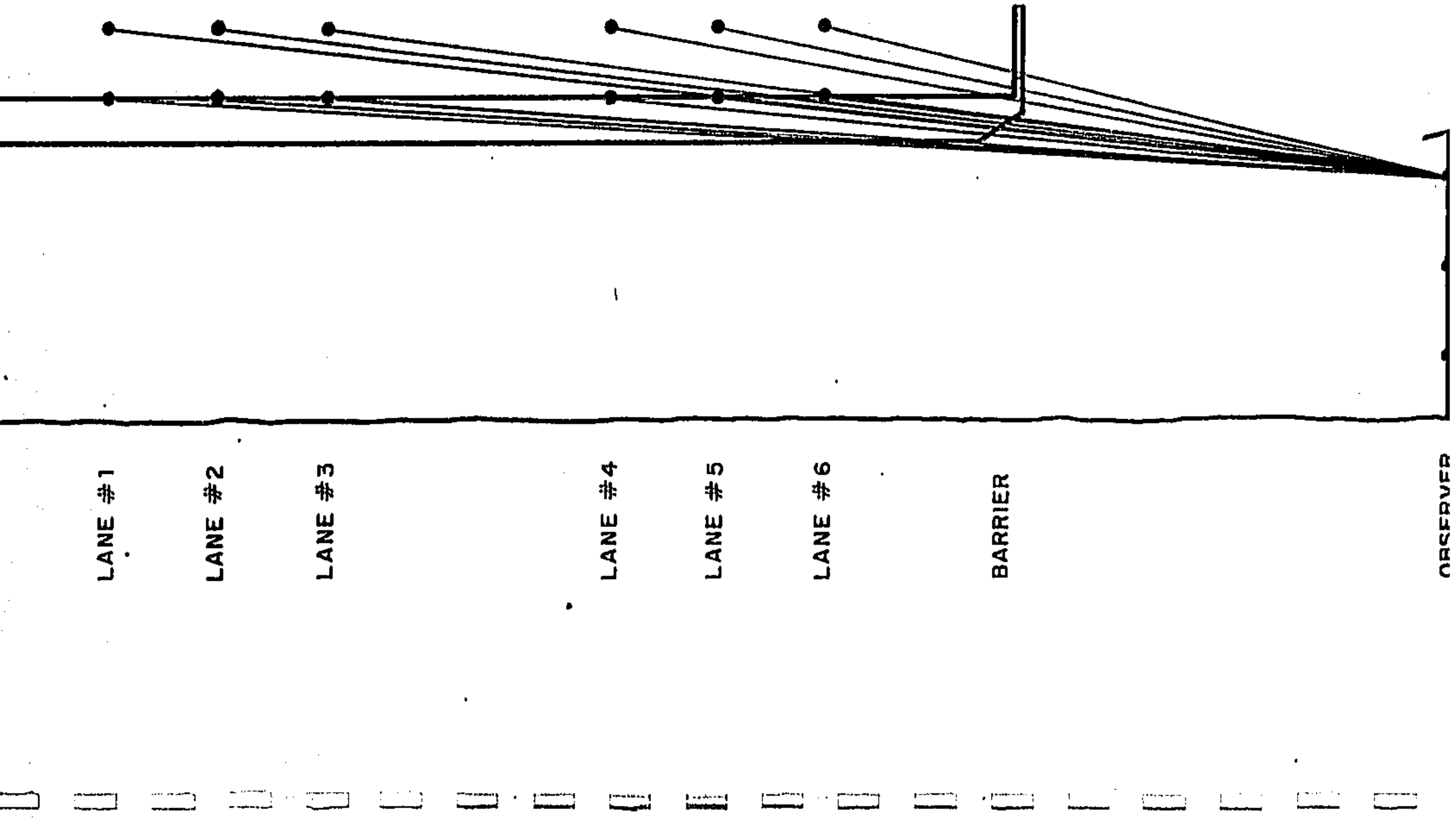
If an incorrect entry was obtained, the reader should try to find his mistake before proceeding. The nomograph is left to the reader.

NOISE SOURCE		NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
LANE 1	Trucks	70.0	15.0	55.0
	Autos	68.5 =72.5	16.0	52.5 =57.0
LANE 2	Trucks	64.0 =73.0	14.5	49.5 =57.5
	Autos	68.5 =74.5	16.0	52.5 =58.5
LANE 3	Trucks	64.5 =75.0	15.0	49.5 =59.0
	Autos	69.0 =76.0	16.5	52.5 =60.0
LANE 4	Trucks	65.5 =76.5	14.0	51.5 =60.5
	Autos	70.5 =77.5	16.5	54.0 =61.5
LANE 5	Trucks	66.5 =78.0	13.5	53.0 =62.0
	Autos	71.0 =79.0	17.0	54.0 =62.5
LANE 6	Trucks	73.5 =80.0	13.0	60.5 =64.5
	Autos	72.0 =80.5	18.0	54.0 =65.0
	TOTAL	80.5	TOTAL	65.0

NET BARRIER ATTENUATION: 15.5 dBA for L_{10}

SKETCH 5.13

SKETCH 5.12



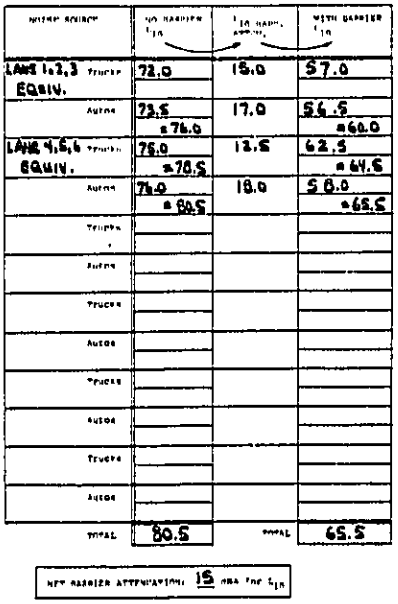
For this example, the no-barrier L_{10} was obtained from the L_{10} nomograph with the following traffic input:

Automobiles:	1000 autos/hour in each lane
Trucks:	
Lanes 1 & 6:	50 trucks/hour 60 miles/hour
Other Lanes:	10 trucks/hour 60 miles/hour

The trucks in the near lane are <u>least</u> attenuated by the barrier. Since they are also closest to the residence they tend to control the net noise with the barrier in place. The traffic at the far side would be attenuated by the lip of the structure, without any additional barrier.

For this reason, the no-barrier L_{10} is unrealistic. A true no-barrier L_{10} would include attenuation from the structure's lip. This case is included below as Example #5.

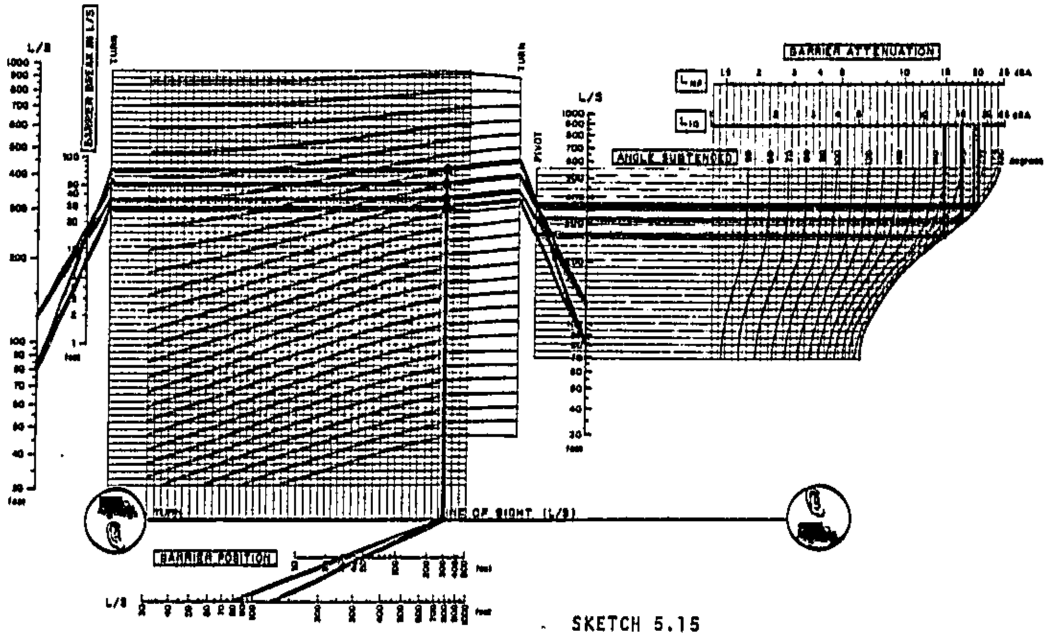
Before proceeding to Example #5, let us examine a simpler solution to this same elevated barrier. Let us concentrate all of the traffic into two lanes - one in each direction. The resulting worksheet and nomograph are included as Sketches 5.14 and 5.15.



NOISE SOURCE		NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
LANE 1,2,3 EQUIV.	Trucks	72.0	15.0	57.0
	Autos	73.5 = 76.0	17.0	56.5 = 60.0
LANE 4,5,6 EQUIV.	Trucks	76.0 = 78.5	13.5	62.5 = 64.5
	Autos	76.0 = 80.5	18.0	58.0 = 65.5
	Trucks			
	Autos			
	Trucks			
	Autos			
	Trucks			
	Autos			
	Trucks			
	Autos			
	TOTAL	80.5	TOTAL	65.5

NET BARRIER ATTENUATION: 15 dBA for L_{10}

SKETCH 5.14



SKETCH 5.15

As discussed above, when combining several lanes into one for barrier calculations, the equivalent lane is placed at the equivalent distance from the barrier, rather than from the receiver. For this example, the equivalent distances are computed as follows:

$$\text{For Lanes 1-3: } D_e = \sqrt{(45.5\text{ ft})(21.5\text{ ft})}$$
$$= 31\text{ ft}$$
$$\text{For Lanes 4-6: } D_e = \sqrt{(101.5\text{ ft})(77.5\text{ ft})}$$
$$= 88.5\text{ ft}$$

Example #5

The same elevated roadway with only a two-foot high lip barrier is discussed for Example #5.

Again the nomograph is left to the reader. The resulting worksheet is included as Sketch 5.16.

NOISE SOURCE		NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
LANE 1	Trucks	70.0	8.5	61.5
	Autos	68.5 =72.5	11.0	57.5 =63.0
LANE 2	Trucks	64.0 =73.0	8.0	56.0 =64.0
	Autos	68.5 =74.5	11.0	57.5 =65.0
LANE 3	Trucks	64.5 =75.0	7.5	57.0 =65.5
	Autos	69.0 =76.0	11.0	58.0 =66.0
LANE 4	Trucks	65.5 =76.5	6.5	59.0 =67.0
	Autos	70.5 =77.5	10.5	60.0 =68.0
LANE 5	Trucks	66.5 =78.0	5.5	61.0 =69.0
	Autos	71.0 =79.0	10.0	61.0 =69.5
LANE 6	Trucks	73.5 =80.0	0	73.5 =75.0
	Autos	72.0 =80.5	10.0	62.0 =75.0
	TOTAL	80.5	TOTAL	75.0

NET BARRIER ATTENUATION: 5.5 dBA for L_{10}

SKETCH 5.16

As is apparent, the near-lane trucks receive no benefit from the 2-foot barrier, and the resulting overall attenuation is minimal.

How much error would be introduced by concentrating the traffic into two lanes for this example? The trucks would be located further from the structure's lip than in reality, and the overall attenuation might be artificially high. The resulting worksheet is included as Sketch 5.17.

NOISE SOURCE		NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
LANE 1,2,3 EQUIV.	Trucks	72.0	8.0	64.0
	Autos	73.5 =76.0	11.0	62.5 =66.5
LANE 4,5,6 EQUIV.	Trucks	75.0 =78.5	0	75.0 =75.5
	Autos	76.0 =80.5	10.0	66.0 =76.0
	Trucks			
	Autos			
	Trucks			
	Autos			
	Trucks			
	Autos			
	Trucks			
	Autos			
	TOTAL	80.5	TOTAL	76.0

NET BARRIER ATTENUATION: 4.5 dBA for L_{10}

SKETCH 5.17

As can be seen, even in this rather severe case, combining lanes into one equivalent lane does not result in a significant error in the calculated barrier attenuation. In general, the barrier nomograph is of great value in testing the geometry of the situation, to determine whether or not lanes can be combined in this manner - to simplify the TSC computer input whenever possible.

What would be the error if an unrealistic truck proportion were assigned the various lanes - for example, if equal truck volumes were assumed for all six lanes? Would this be important for a roadway on grade?

<u>Example #6</u>

In Example #6, the concept of noise reflection is introduced. The roadway is depressed with reflecting retaining walls on both sides as shown in Sketch 5.18.

The traffic has been condensed into only two lanes to simplify the discussion, although it should not be condensed before testing with the nomograph. The reflection from the retaining wall is incorporated by adding the mirror images of the traffic in the wall, as shown in the figure. Again, the barrier is assumed to subtend an angle of 180 degrees at the receiver. The full line-of-sight (L/S) distance is used in the nomograph - the distance from traffic to reflecting wall to receiver. The corresponding worksheet is included as Sketch 5.19.

Notice that the reflected noise dominates the L_{10}. Without reflection, the noise level at the receiver would be 82.0 dBA, a significant underestimate of the impact.

In some cases, especially for very high receivers, the reflected path may miss the opposite retaining wall - over its top. In this case, the reflected path does not exist and should not be used.

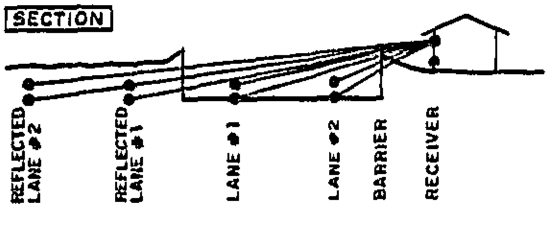
If the reflecting wall was made acoustically absorptive, then the reflected noise would be reduced in level. For example, if the absorption coefficient (of A-weighted traffic noise) were 0.6, then the reflected noise would be reduced by 4 dBA. This reduction is discussed in detail below.

It is also possible that noise due to <u>multiple</u> reflections is significant. For example, if the reflected noise in the example had been attenuated by the barrier (higher barrier), then perhaps some multiply reflected noise - reflected first from the right, then from the left, then over the barrier - would not be attenuated by the barrier and might control the noise at the receiver. This possibility is discussed below also.

NOISE SOURCE		NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
LANE 2 REFLECTED	Trucks	82.5 —	0	82.5 —
SAME	Autos	77.5 = 83.5	0	77.5 = 83.5
LANE 1 REFLECTED	Trucks	84.0 = 87.0	0	84.0 = 87.0
SAME	Autos	79.0 = 87.5	5.5	73.5 = 87.0
LANE 1	Trucks	86.0 = 90.0	6.0	80.0 = 88.0
SAME	Autos	81.0 = 90.5	8.5	72.5 = 88.0
LANE 2	Trucks	88.5 = 92.5	13.0	75.5 = 88.5
SAME	Autos	83.5 = 93.0	16.0	67.5 = 88.5
	Trucks			
	Autos			
	Trucks			
	Autos			
	TOTAL	93.0	TOTAL	88.5

NET BARRIER ATTENUATION: 4.5 dBA for L_{10}

SKETCH 5.19



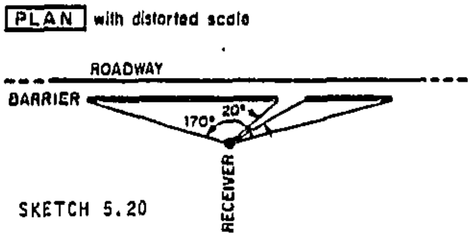
SKETCH 5.18

	L/S length	Barrier position	Break in L/S
Reflected Lane 2, trucks	120 ft	-----	----
autos	122 ft	-----	----
Reflected Lane 1, trucks	93 ft	-----	----
autos	95 ft	16 ft	1 ft
Lane 1, trucks	61 ft	16 ft	1 ft
autos	64 ft	15 ft	3 ft
Lane 2, trucks	34 ft	14 ft	5 ft
autos	38 ft	13 ft	8 ft

Some general comments can be made concerning the attenuation of depressed and elevated roadways. As Figure 5.13 indicates, the attenuation of depressed roadways increases for more remote receivers, since the line-of-sight is broken more and more as the receiver distance is increased. In an opposite manner, the break in the line-of-sight decreases for more remote receivers adjacent to elevated roadways. For this reason, elevated roadways are not effective in reducing the noise at larger distances. In addition, when the roadway is elevated above the terrain, the natural barriers afforded by scattered buildings, rolling terrain, etc., are usually lost.

Example #7

The final example will reconsider Example #1, this time with a gap in the barrier - perhaps necessitated by an underpass. The plan is shown in Sketch 5.20.



SKETCH 5.20

In such a situation, the problem is approached in two steps. First, the net noise coming over the barrier is computed, ignoring the gap in the barrier. Second, the noise from the small piece of exposed highway is computed, and added to the noise coming over the barrier.

This second noise contribution can be calculated using either NCHRP Report 117 or using the L_{10} nomograph. In either case, the angle of the exposed roadway is only 20 degrees as shown in the sketch. 10 log 20°/180° is used to adjust the infinite road level, as discussed in Chapter 4, to account for the finite length of the roadway segment. 10 log 20°/180° = -9 dBA.

For our example here, the no-barrier L_{10} is 70 dBA. The 20° exposure reduces this to 61 dBA. Separately, the with-barrier L_{10} is 59 dBA. Adding 61 dBA and 59 dBA by dB-addition, we obtain 63 dBA, a compromise of 4 dBA on the barrier's performance.

5.1.5 Points to Remember in Using the Barrier Nomograph and Worksheet

- The simplest line-of-sight (L/S) is always used - from the receiver perpendicular to the roadway.

- At the roadway, this L/S terminates either at the pavement for automobiles, or 8 feet above the pavement for trucks.

- The barrier position is measured to either the roadway or the receiver, whichever is closer.

- The L/S generally slants from roadway to receiver. The L/S length is this slant distance, not the horizontal distance.

- The amount the barrier breaks the L/S is always measured perpendicular to the L/S, not vertically.

- The barrier position is also a slant distance, along the L/S.

- The vertical and horizontal scales on all sectional drawings must be identical.

- The sketch on the nomograph is pictorial only. No attempt should be made to place the barrier onto the sketch by inspection only.

- When concentrating traffic into a reduced number of lanes, place these lanes at the equivalent distance from the barrier.

- For depressed roadways, use the full L/S distance for the reflected noise.

- For depressed roadways, or roadways flanked by barriers on both sides, in some cases multiple reflections within the confined roadway space are important.

5.1.6 Three Additional Complications

a) Receiver Beyond the End of the Barrier

When the receiver is just at the end of the barrier (receiver #1, Figure 5.11), the largest angle the barrier can subtend is 90 degrees. A full one-half of the roadway is unshielded by the barrier. In such a situation, the maximum attenuation achievable is 3 dBA, as can be verified on the nomograph. For receivers beyond the end of a barrier (same figure, receiver #4), the attenuation is even less. The nomograph is inaccurate for these receivers; it is recommended that no attenuation be attributed to the barrier for receivers beyond the ends of barriers.

b) Barriers in Series

Sometimes two or more barriers break the line-of-sight between the receiver and the roadway. This was the case in Example #2 above. When this occurs, both barriers attenuate the noise and should properly be considered "in series". This additional complication is not worth the slight improvement in accuracy. Even in the TSC computer program, only the individual attenuation from the most effective barrier is considered. The others are ignored. The error is generally very slight.

c) Barrier Attenuation for Receivers Just Outside the Shadow Zone

In reality, receivers just outside the barrier shadow zone (Figure 5.14) do receive some benefit from the barrier. It is the noise that was headed their way that passed very close above the barrier and that was diffracted downward into the shadow. Just on the grazing line-of-sight for example, the attenuation is 5 dBA. It drops off quickly then above the grazing line-of-sight. For these cases where the barrier almost - but not quite - breaks the L/S, no attenuation is given by the nomograph. The computer program, however, does incorporate this attenuation.

These three complexities are summarized in Figure 5.15.

In highly urbanized areas, the barrier nomograph may overestimate the barrier attenuation, say from a building shielding a courtyard area. In such situations, illustrated in Figure 5.16, other large surfaces tend to reflect noise energy into the shadow zone behind the building. Such reflected noise fills in the shadow zone with noise, and thereby reduces the amount of shielding provided. It is good practice to assume a maximum of 10 dBA shielding in such urban areas.

5.1.7 Pitfalls in Barrier Input - TSC Computer Program

The mechanics of using the Transportation Systems Center computer program, including the barrier input routines, were discussed in Chapter 4. In this section, several common pitfalls concerning this barrier input will be discussed.

a) Insufficient exposed roadway

For receivers with no barrier blocking their lines-of-sight, the traffic far down the roadway is insignificant compared to the very nearby traffic. For this reason, it is generally sufficient to consider only a distance of 3-times-D or 4-times-D down the roadway, where D equals the distance from roadway to receiver. This 145- to 150-degree segment directly in front of the receiver controls the noise; the remainder contributes less than 1 dBA to the total.

However, if a barrier shields the receiver from this central segment, then the highway far down the road becomes important; it is no longer 10 dBA down from the nearby segment, because the nearby segment's noise has been reduced by the barrier. It is important to realize this, and to include enough of the exposed roadway in the computer input.

b) Imprecise barrier elevation, relative to roadway

Figure 5.17 illustrates a common mistake made in preparing the computer input. The actual situation consists of a roadside barrier that follows the roadway grades, always remaining a constant height above the roadway. The proper input is shown at the top of the figure, where the barrier follows the road precisely. At the bottom, the barrier input has been simplified, and although the simplification does not look extreme, the inaccuracies introduced can be great. The height of the barrier, relative to the roadway, is a very sensitive parameter in barrier performance. The simplification shown at the bottom should not be used.

c) Imprecise barrier position, relative to roadway

Small-scale maps are often used to determine the coordinates for the computer input. Relative positions - say between the roadway and the receivers - are sufficiently accurate on such maps to allow an accurate computation of the noise level. However, barrier-roadway distances are sometimes very small, and in such cases, larger-scale maps must be used. The distance between barriers and roadways is a very sensitive parameter. It should not be obtained by subtracting two very large distances obtained from a small-scale map.

d) Noise cannot pass under elevated barriers

Figure 5.18 indicates an inflexibility in the TSC computer program that should be understood. In the figure, a barrier has been explicitly input along the lip of the elevated ramp, to shield the receiver from the ramp noise. Unfortunately, this barrier will also shield the receiver from the main line noise. All barriers extend downwards to the ground; no noise can pass under any barrier in the TSC program. Such situations usually require two computer runs - one with and one without the barrier on the ramp.

Parenthetically, the computer does not automatically assign such a barrier to elevated roadways. First, there is no input that tells the computer when a roadway is elevated. Second, the flexibility has been retained to input such barriers explicitly - at the proper position and proper elevation.

e) Too much barrier input

It is very easy to input too much information on barriers. It is recommended that the barrier nomograph be used to determine if a barrier effects the noise at the receivers in question - as an aid in eliminating superfluous input. It is also a good idea to run the program in stages, with small blocks of receivers and their associated barriers. In this way, the computer does not waste time testing superfluous barriers for large numbers of receivers.

f) Very low barriers

The computer assigns too much attenuation to very low barriers. As mentioned above, 5 dBA reduction is calculated for receivers just on the grazing line-of-sight. The missing energy has diffracted into the shadow zone. However, as indicated on Figure 5.19, very low barriers have no shadow zone. Even in the limit of zero height - as shown at the bottom of the figure - the program assigns 5 dBA attenuation if the barrier is entered as input.

PITFALLS IN BARRIER INPUT - TSC COMPUTER

- INSUFFICIENT EXPOSED ROADWAY
- IMPRECISE BARRIER ELEVATION RELATIVE TO ROADWAY
- IMPRECISE BARRIER POSITION RELATIVE TO ROADWAY
- NOISE CANNOT PASS UNDER ELEVATED BARRIERS
- TOO MUCH BARRIER INPUT
- VERY LOW BARRIERS

5.2 COMPLICATION IN BARRIER DESIGN CAUSED BY NOISE FLUCTUATION

As mentioned in Chapter 1, roadside barriers may cause an increase in the fluctuation of traffic noise, and thereby a possible increase in annoyance to the road's neighbors. This is most likely to occur when the barrier is effective in reducing the automobile noise, but does nothing to the more intermittent truck noise.

The increase in annoyance caused by noise fluctuation is a common experience. People living near airports are annoyed during flyovers that cause them to miss parts of their TV programs. It is annoying to have to turn the volume up just for the flyover, and then to turn it back down again when the aircraft is past. Often automobile radios must be turned up and down as the vehicle cruises and then stops for traffic signals. While cruising, the interior noise of the automobile masks the radio, and it must be turned up. It is then uncomfortably loud when the vehicle is stopped at a signal, and must be turned down. In noisy environments people stand closer together during conversation to be understood. When the noise fluctuates, no equilibrium distance can be established, increasing annoyance.

Most important, falling asleep is more difficult in fluctuating noise than in steady noise. Just as a person is dozing, a truck passes and wakes him. It is common practice for people living close to freeways to install some steady noise source in their bedroom to cover up the fluctuations - sources such as the commercial sleep machines or window air conditioners. These devices increase the total noise, including the L_{10}, but decrease the fluctuations.

How important are these fluctuations? If the L_{10} drops by 5 dBA, how much can the fluctuations be allowed to increase without negating the benefit?

5.2.1 Noise Pollution Level

No completely acceptable method has been agreed upon for dealing with noise fluctuations. To date, the most promising format in the literature that takes fluctuations into account in a fully developed form is the Noise Pollution Level, L_{NP}. The L_{NP} was derived to account for general ovservations common to a number of studies of distinctly different character.

It is precisely the fact that the L_{NP} explains convincingly the results of several unrelated studies for which no other explanation can be offered, coupled with the amply-demonstrated reliability of the A-weighted sound level, that constitutes the stoutest argument favoring the L_{NP} over competitive ratings.

Most encouragingly, the Noise Pollution Level can relate steady freeway annoyance to very intermittent aircraft annoyance, under the same formulation. The same definition of L_{NP} and the same criterion of acceptability apply to these disparate noise sources - one quite steady, the other very intermittent.

The same comparison is necessary in a full consideration of traffic noise annoyance. It is common for traffic noise to be much more intermittent during the early morning and late evening than during peak hours, especially along intercity freeways. In fact, late at night, the noise intermittency is quite similar to some typical aircraft flyover histories. A proper measure that incorporates fluctuations is needed to compare peak-hour noise with late evening noise.

One example is included to indicate the full concern. Recent measurements were made along a freeway in New York State. Figure 5.20 shows 5-minute time histories 250 feet from the freeway. The top history, measured at midnight, shows large fluctuations. The fluctuations during rush hour are much less severe, since the traffic is continuous rather than intermittent. Note that the L_{10} is nearly identical for both of these histories, however.

How do these two histories compare by the L_{10} measure and by the L_{NP} measure? From rush hour to midnight, the L_{10} went <u>down</u> 4 dBA and the L_{NP} went <u>up</u> 18 dBA. In other words, taking fluctuation into account, midnight noise is much more disrupting than rush hour noise; and L_{10} doesn't indicate this at all.

Of course, automobiles cannot be enticed to travel at midnight to reduce the annoyance. But on the other hand, we can avoid constructing barriers that turn our highways into midnight conditions throughout the day - that attenuate the automobiles without attacking the real source of the problem, the trucks. The procedure described below is intended to prevent such barrier designs.

How is L_{NP} incorporated? Do we have to work from the basic definition:

$$L_{NP} = L_{eq} + 2.56\sigma$$

$$L_{NP} = 10\log\left[\frac{1}{T}\int_0^T 10^{\frac{L(t)}{10}}dt\right] + 2.56\left[\frac{1}{T}\int_0^T\left(L(t) - \frac{1}{T}\int_0^T L(t)\,dt\right)^2 dt\right]^{\frac{1}{2}}$$

No, fortunately. The Transportation System Center program has incorporated this equation into its mathematics. The computer program predicts the L_{NP} for any system of roadways and barriers, no matter how complex. For this reason, it offers the ultimate test for whether fluctuations are increased or decreased. The results from the computer program have been condensed into the procedure below, which can be used as a design tool to check the barrier design. If the barrier system increases the Noise Pollution Level L_{NP}, then it is highly recommended that the barrier not be built.

5.2.2 Graphical Procedure to Compare L_{NP}, with and without Barrier

The procedure described below predicts the Noise Pollution Level both with and without the barrier as designed. A comparison then of these two L_{NP}'s indicates whether or not the barrier will increase or decrease the traffic annoyance.

The procedure is outlined in Figure 5.21. More than half the work has been already completed during the L_{10} barrier design. The new steps are included in heavy outlines.

<u>No-barrier calculations</u>:

First, the L_{10} for both automobiles and trucks is transcribed from earlier calculations. L_{10}'s are converted to L_{NP}'s using an additional nomograph, discussed below, and then added together for the total L_{NP}.

<u>With-barrier calculations</u>:

First, the L_{NP} for both automobiles and trucks is transferred from above. Then these are reduced by the barrier L_{NP} attenuation, obtained from the basic barrier nomograph. Finally, the two L_{NP}'s are added together for the total L_{NP}.

A comparison - with and without the barrier - indicates whether the barrier design is sufficient. The new steps can be summarized as follows:

1. Conversion of L_{10} to L_{NP}: very simple nomograph.

2. L_{NP} barrier attenuation: essentially complete already.

3. Addition of L_{NP}'s: <u>complex</u>.

a) <u>Conversion of L_{10} to L_{NP}</u>

Conversion from L_{10} to L_{NP} is accomplished with the nomograph of Figure 5.22. This conversion is similar to the conversion in NCHRP Report 117 from L_{50} to L_{10} - it depends only upon the dimensionless parameter VD/S. A single example will suffice to illustrate the nomograph.

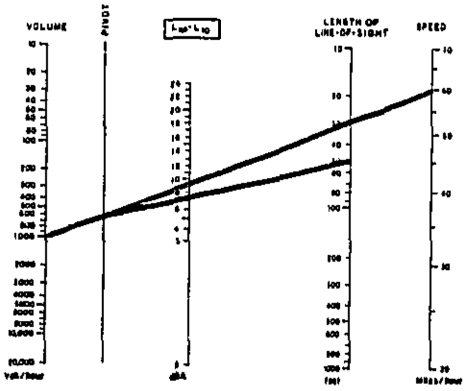
Parameters: Volume = 1000 vehicles/hour
(either autos or trucks)
Speed = 60 miles/hour
L/S length = 50 feet

The completed nomograph is included as Sketch 5.21.

Starting at Volume = 1000, a line is drawn to 60 on the speed scale. Where this line crosses the pivot line, a line is drawn to L/S = 50 feet. The result is then

$L_{NP} - L_{10} = 7\frac{1}{2}$ dBA.

Then, $L_{NP} = L_{10} + 7\frac{1}{2}$ dBA.



SKETCH 5.21

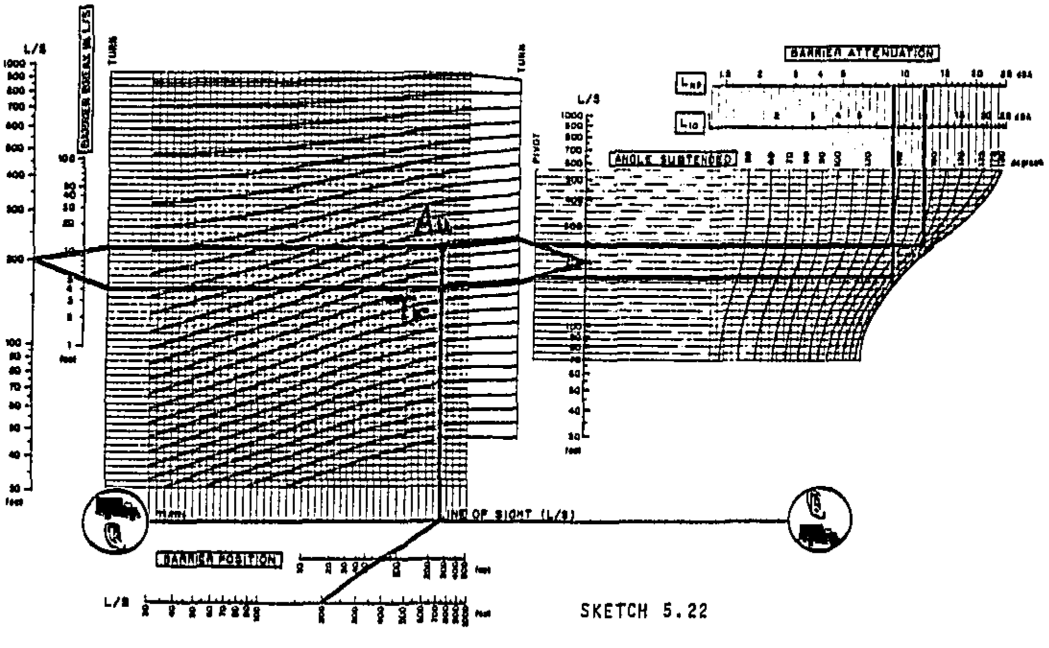
b) Barrier Attenuation of L_{NP}

The barrier nomograph for Example #3 above is repeated as Sketch 5.22.

Please recall that this example concerned a single lane of traffic containing both automobiles and trucks. As the nomograph shows, the barrier reduced the L_{NP} slightly more than it did the L_{10}: 12.5 dBA compared to 10 dBA for automobiles and 8.5 dBA compared to 7 dBA for trucks.

For this example, the receiver was centered along the barrier. When this is not the case, a different angle must be used for L_{NP} attenuation. This is illustrated in Figure 5.23. For receivers that are not centered, only a part of the full angle is used in the barrier nomograph - just the centered piece, as shown in parts (b) and (c) of the figure. As is apparent, when the receiver is opposite the end of the barrier, the barrier angle becomes zero, and no L_{NP} attenuation is obtained. Also, for receivers beyond the end of the barrier, as in part (d) of the figure, the barrier does not attenuate the L_{NP}.

Therefore, when the receiver is off-center, the nomograph line will have to be reflected upward from a different angle to the L_{NP} scale. In general, for off-center receivers, the barrier has less effect upon the L_{NP} than upon the L_{10}.



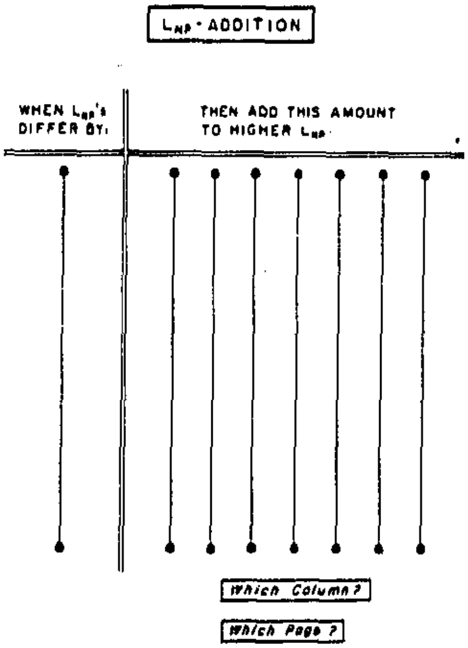
SKETCH 5.22

c) L_{NP} Addition

Addition of individual L_{NP}'s to obtain the overall L_{NP} is complex. Indeed, adding 70 dBA for automobiles with 75 dBA for trucks may yield 65 dBA for the total. This is hardly normal dB-addition. Yet the addition of automobiles to the truck noise can reduce the fluctuations enough to reduce the L_{NP}.

A review of normal dB-addition is in order. Table 5.3 is reproduced from Chapter 1. It has been expanded to explicitly include all half-integer values in the left column. To add two L_{10}'s by dB-addition, first find their difference in the left column. Then add the tabulated value in the right column to the larger L_{10}. The reader should be very familiar with this process.

A similar procedure is followed for adding two L_{NP}'s, using Table 5.4 instead. First their difference is found in the left column, and then the tabulated value is added to the larger L_{NP}. Sketch 5.23 shows the similarity with the L_{10} table. The complexity comes in (1) choosing the proper page of the table and (2) choosing the proper column of tabulated values.



SKETCH 5.23

Example #8

A single lane of traffic carries both automobiles and trucks.

	L_{10}	$L_{NP}-L_{10}$	L_{NP}
Trucks	70.0	12.0	82.0
Autos	68.0	4.0	72.0

First the proper table page must be chosen. Trucks have the higher L_{NP}, which satisfies $L_{NP} - L_{10} = 12$. This determines the page. Second, autos have the lower L_{NP}, which satisfies $L_{NP} - L_{10} = 4$. This determines the column. Once these are determined, then the addition proceeds as with normal dB-addition. The L_{NP} difference (10 dBA) is found at the left, and the corresponding table entry (-6 dBA) is added to the higher L_{NP}.

Therefore, the net L_{NP} is 82-6 = 76 dBA.

Example #9

A single lane of traffic carries both automobiles and trucks.

	L_{10}	$L_{NP}-L_{10}$	L_{NP}
Trucks	70.5	10.5	81.0
Autos	61.0	2.5	63.5

First, the proper table page is chosen. Trucks have the higher L_{NP}, which satisfies $L_{NP}-L_{10} = 10$, rounding off to the nearest even integer. This determines the page. Second, autos have the lower L_{NP}, which satisfies $L_{NP}-L_{10} = 2$, again rounding off to the nearest even integer. This determines the column. For this page and this column, the L_{NP} difference (18 dBA) is found at the left, and the corresponding table entry is -4 dBA. Then the sum equals 81-4 = 77 dBA.

When will L_{NP}-addition increase the total? Examination of Table 5.4 reveals that the table entries are positive in the upper left-hand corners of each page. The highest entry is +2 dBA, on the first page. This entry is used when adding two identical noises with low fluctuations: the L_{NP} difference is zero, and both noises satisfy $L_{NP}-L_{10}=2$ dBA. If we had entries for $L_{NP}-L_{10} = 0$ dBA, then the table entry would be +3 dBA, as with normal dB-addition. In general, these positive table entries occur for low-fluctuation noises with nearly identical L_{NP}'s.

Example #10

Next, another lane of traffic is added to Example #9. The first lane is identical.

		L_{10}	$L_{NP}-L_{10}$	L_{NP}
Lane 1:	Trucks	70.5	10.5	81.0
	Autos	61.0	2.5	63.5
		71.0	6.0	77.0
Lane 2:	Trucks	72.0	7.5	79.5
	Autos	60.5	3.0	63.5

The results of the first addition have been circled. The L_{NP} result came from the above example; the L_{10} sum was accomplished by normal dB-addition; the $L_{NP}-L_{10}$ result is the difference between these two.

This intermediate sum is needed as a starting point for the next addition, when the second lane of trucks is added. For this next L_{NP} addition, first the proper table page is chosen. The second lane of trucks has the higher L_{NP}, which satisfies $L_{NP}-L_{10} = 8$, after rounding off. This determines the proper page. The intermediate sum has the lower L_{NP}, which satisfies $L_{NP}-L_{10}=6$. This determines the column. For this page and this column, the L_{NP} difference (2 dBA) is found at the left and the table entry is read as -1 dBA. The sum is therefore 79.5 - 1.0 = 78.5 dBA. The intermediate sum, in total, is

L_{10}	$L_{NP}-L_{10}$	L_{NP}
74.5	4.0	78.5

As before, the L_{10} sum was obtained by normal dB-addition, and then the $L_{NP}-L_{10}$ was obtained by subtraction of the outer two columns.

Now we proceed to add in the second lane of autos. First, the proper table page is chosen. The intermediate sum has the higher L_{NP}, which satisfies $L_{NP}-L_{10} = 4$. This determines the page. The autos have the lower L_{NP}, which satisfies $L_{NP}-L_{10} = 4$, rounding up to the nearest even integer. This determines the proper column. For this page and this column, the L_{NP} difference (16 dBA, rounded up) is found at the left, and the table entry is read as 0 dBA. The sum is therefore 78.5 - 0 = 78.5 dBA. The final tally is

L_{10}	$L_{NP}-L_{10}$	L_{NP}
74.5	4.0	78.5

The last lane of autos neither increased the L_{10} nor decreased the L_{NP}.

Problem: The reader is asked to work the following problem for himself.

	L_{10}	$L_{NP}-L_{10}$	L_{NP}
Trucks	70.5	14.5	85.0
Trucks	70.5	14.5	85.0
Trucks	75.0	10.5	85.5
Autos	73.0	2.0	75.0
Sum	79.0	3.5	82.5

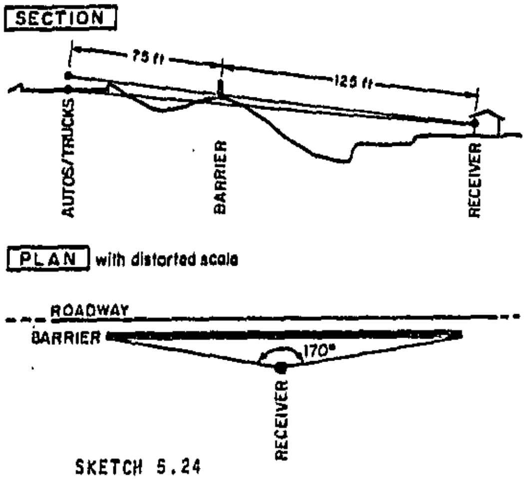
d) Worksheet for L_{NP} Addition and Barrier Attenuation

Exactly the same procedure is used to add L_{NP}'s, whether there is a barrier along the roadside or not. The examples above did not include roadside barriers. If a barrier had existed, then the with-barrier L_{10} and the with-barrier L_{NP} would be carried along in the addition process in an identical manner.

Two additions, one with and one without the barrier, must be carried out to evaluate the effectiveness of the barrier - to determine if the barrier decreases the L_{NP}. A worksheet for carrying out both of these additions together is included as Worksheet 5.2. The no-barrier addition is carried out down the left side, the with-barrier addition down the right side. Note that the L_{NP} barrier attenuation separates the two summations. Also note that the three rightmost columns are duplications of the L_{10} - addition worksheet. Whenever this new worksheet is used therefore, the L_{10} barrier worksheet can be eliminated.

Example #11

To illustrate the use of this worksheet, the barrier of Example #3 above will be tested to see if it reduces the L_{NP}. The sketch and worksheet for this example are repeated as Sketches 5.24 and 5.25.



SKETCH 5.24

In this worksheet, the traffic volumes have been changed from those used in Example #3. The barrier attenuation, separately for trucks and automobiles, remains unchanged of course.

The barrier shields the receiver from a single lane of traffic that carries both automobiles and trucks. We shall proceed from the beginning of the problem. The traffic parameters are as follows: 1000 autos/hour; 100 trucks/hour; 60 miles/hour.

- First, the L_{10} nomograph is used to obtain the no-barrier L_{10}'s, as shown in Sketch 5.26.

- Second, the barrier nomograph is used to obtain the barrier attenuation for L_{10}, as shown in Sketch 5.27. The barrier attenuation for L_{NP} is also obtained in the process.

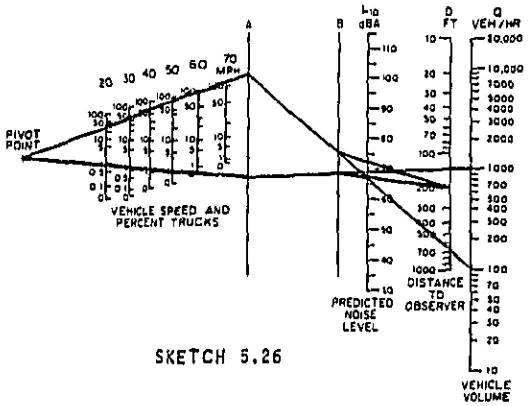
- Third, the L_{NP} nomograph is used to obtain the L_{NP}-L_{10}, as shown in Sketch 5.28.

- Next the worksheet is filled in, as shown in Sketch 5.29.

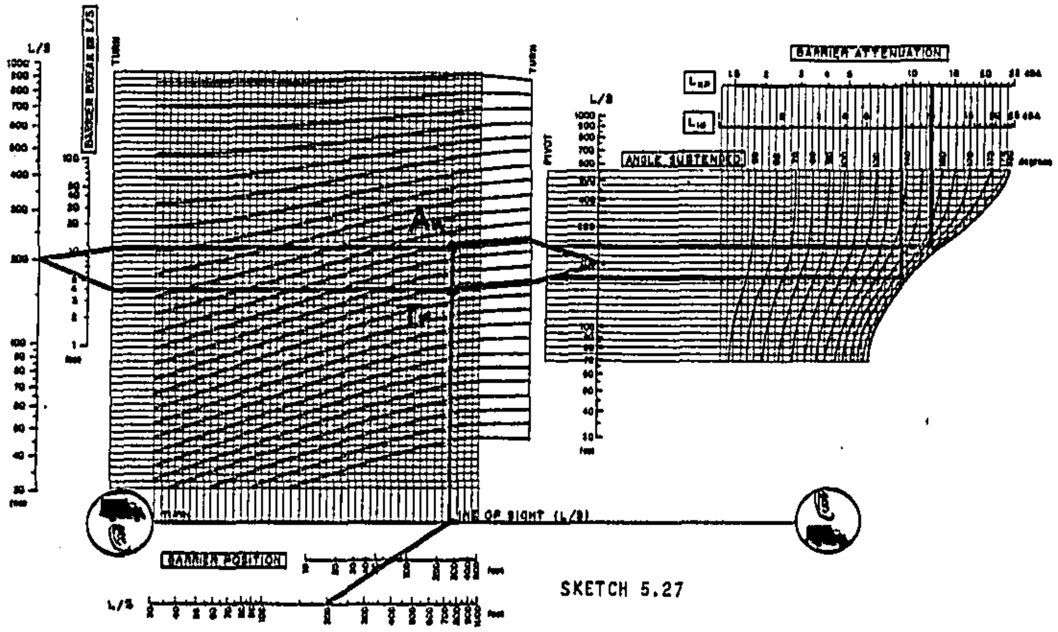
NOISE SOURCE	NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
Trucks	72.5	7.0	65.5
Autos	67.0 = 73.5	10.0	57.0 = 66.0
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
TOTAL	73.5	TOTAL	66.0

NET BARRIER ATTENUATION: 7.5 dBA for L_{10}

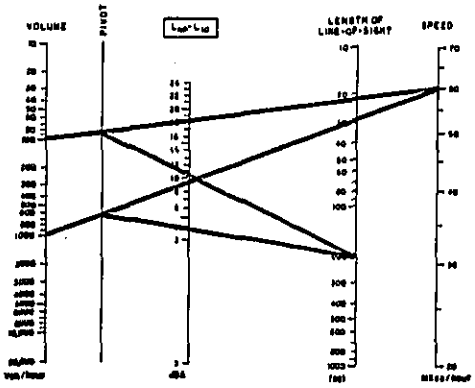
SKETCH 5.25



SKETCH 5.26



SKETCH 5.27



SKETCH 5.28

NOISE SOURCE	NO BARRIER			L_{NP} BARR. ATTEN.	WITH BARRIER			L_{10} BARR. ATTEN.	NO BARRIER
	L_{10}	$L_{NP}-L_{10}$	L_{NP}		L_{NP}	$L_{NP}-L_{10}$	L_{10}		L_{10}
Trucks	72.5	10.5	81.0	6.5	74.5	9.0	65.5	7.0	72.5
Autos	67.0	4.0	71.0	12.5	58.5	1.5	57.0	10.0	67.0
⊕	73.5		81.0		74.5		66.0		
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
TOTAL	73.5		81.0	TOTAL	74.5		66.0		

NET BARRIER ATTENUATION: 7.5 dBA for L_{10}
6.5 dBA for L_{NP}

SKETCH 5.29

Note that the $L_{NP}-L_{10}$ (with barrier) is always obtained by subtracting the values in the two adjacent columns. It is not obtained from the L_{NP} nomogram, which only works for the no-barrier case.

- Finally, we add down the columns for both the no-barrier and the with-barrier cases. The L_{10}'s are added by regular dB-addition using Table 5.3. The L_{NP}'s are added by L_{NP}-addition using Table 5.4. The resulting L_{10}'s and L_{NP}'s are shown at the bottom. As can be seen, the barrier reduced the L_{NP} approximately the same as the L_{10}.

Example #12

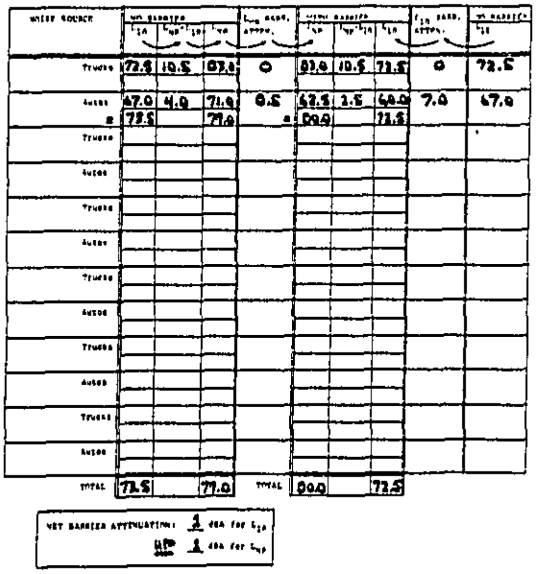
Let us now reduce the height of this barrier so that it breaks the line-of-sight to the autos by only 5 feet, and does not break the line-of-sight to the trucks. For this situation, the barrier will reduce the automobile noise without reducing the truck noise. The resulting increase in fluctuation may very well increase the L_{NP}.

- The basic L_{10} nomograph is unchanged.

- The new barrier nomograph shows a reduction in the automobile noise by 7 for L_{10} and by 8.5 for L_{NP}. The nomograph is left to the reader.

- The L_{NP} nomograph is also unchanged.

- The filled out worksheet is included as Sketch 5.30.



[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Trucks	72.5	10.5	83.0	0	83.0	10.5	72.5	0	72.5
Autos	67.0	4.0	71.0	8.5	62.5	2.5	60.0	7.0	67.0
Σ	73.5		77.0	Σ	[illegible]		72.5		
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
TOTAL	73.5		77.0	TOTAL	[illegible]		72.5		

NET BARRIER ATTENUATION: 1 dBA for L_{10}

UP 1 dBA for L_{NP}

SKETCH 5.30

- Finally, we add down the columns for the no-barrier and the with-barrier cases. The results are shown at the bottom. As can be seen, the barrier did reduce the L_{10}. However, the barrier <u>increased</u> the L_{NP}, resulting in no noise improvement.

The following problems are left to the reader:

- It is desired to shield a ground-floor receiver from a highway 100 feet from his window (L/S distance). The traffic includes: 16 trucks/hour and 1200 automobiles/hour, both at 40 miles/hour. Computed total L_{10} is 71.0 dBA. As a first design, a barrier is constructed 25 feet from the traffic, and 7 feet high, subtending 180 degrees at the receiver. The terrain is flat. How much will this barrier reduce the L_{10}? Answer: 1.5 dBA, to 69.5 dBA, below the FHWA standard. What will this barrier do to the L_{NP}? Answer: Increase it 5 dBA. A higher barrier must be built to avoid deterioration of the noise environment.

- The barrier height above the ground is increased to 10 feet. Now how much is the L_{10} reduced? Answer: 8 dBA, to 63 dBA. What will this barrier do to the L_{NP}? Answer: Reduce it 5.5 dBA.

- Another receiver's window is the same distance behind the 10-foot barrier of problem 2, except that he is at the end of the barrier, rather than centered. Therefore, the barrier subtends an angle of 90 degrees. All other distances are the same. How much does the barrier reduce this second receiver's L_{10}? Answer: 3 dBA, to 68 dBA. What does the barrier do to his L_{NP}? Answer: it does not change it. Although the barrier reduces the L_{10} below the FHWA standard, it does not reduce the L_{NP}, and would therefore be difficult to justify for this receiver alone.

5.3 BARRIER CONSTRUCTION - ACOUSTICAL CONSTRAINTS

The primary requirements of acoustical barriers have already been discussed - the position, length, and required break in the line-of-sight, L/S. The remaining constraint - the required resistance to sound transmission - will be discussed in this section. As Figure 5.1 indicated above, the noise transmitted through the barrier can short-circuit the barrier attenuation, resulting in less attenuation than calculated from the barrier nomograph. To prevent this, restrictions are needed to the minimum allowable surface weight of the barrier and the maximum allowable open area through the barrier (slots, louvers, undercut openings, etc.).

BARRIERS - ACOUSTICAL CONSTRAINTS

- BREAK IN L/S
- POSITION
- ANGLE SUBTENDED
- SURFACE WEIGHT
- HOLES

5.3.1 Surface Weight

The technical term for the "resistance to transmission" is the Transmission Loss, TL. This is the ratio of incident noise energy to transmitted noise energy.

TRANSMISSION LOSS

$$TL = 10 \log \left[\frac{\text{INCIDENT NOISE}}{\text{TRANSMITTED NOISE}}\right]$$

The larger the TL, the less energy gets through. The TL of any wall depends in a complicated way upon the wall's weight, stiffness, loss factor, the angle of incidence of the approaching noise, and lastly the frequency of the noise. It is beyond the scope of this text to describe the complex interplay between these parameters. Instead, we shall present some conservative guidelines here to avoid underdesigning barriers.

The surface weight density of the barrier is the most important parameter affecting the Transmission Loss. Heavier barriers allow less noise to pass through. How heavy must a roadside barrier be? This depends upon the attenuation expected from the barrier - in other words, upon the expected reduction in the noise diffracted over the top of the barrier. For example, if a barrier is designed to attenuate the diffracted noise only 5 to 10 dBA, then quite a large amount of noise can be allowed to pass through the barrier without compromising the attenuation. If however, the barrier is expected to provide 20 dBA attenuation over the top, then it must be much heavier, to reduce the transmitted energy a comparable amount. Our simplified rule guarantees that the transmitted noise be some 3-6 dBA lower than the noise over the top. Therefore, the transmitted noise will increase the total by 1 dBA, at most.

The weight requirement is shown in Table 5.5. For example, if the barrier is designed to reduce the diffracted noise 10 dBA then it must have a minimum surface weight of 3.5 lb/ft^2. It can be heavier than this, of course.

Two important points to remember in using the table:

- The surface weight does <u>not</u> include the weight of bracing, framing, etc. It includes only the weight of the skin material. In some cases such framing can be included in the weight calculation (for orthotropic, stiff panels, for example), but it is beyond the scope of this simplified table to include such cases. Do not use the weight of framing members.

- The transmitted noise must be compared to the noise diffracting over the top of the barrier. The left column in the table is the attenuation of this diffracted noise. This is obtained from the barrier nomograph, assuming the barrier subtends <u>180 degrees</u>. This is the attenuation over the top. (For smaller angles, the nomograph gives the net attenuation - over the top plus around the ends.)

It is a common design error to design very high barriers that subtend only a small angle. A small piece of the noise, from directly in front of the receiver, is thereby reduced greatly, while the great bulk of the noise is not blocked by the barrier at all. As can be seen from the nomograph, for example, a 50-degree barrier lets so much noise around its ends that it cannot provide more than 1.5 dBA reduction in the L_{10}, no matter how much it breaks the line-of-sight. If this is not noticed, the barrier will be built much higher than is of any use. For such cases, Table 5.5 will also cause an overdesign in the barrier weight. Both design errors go hand in hand and should be avoided.

In some cases, this surface weight table is very conservative. Technically, it assumes a critical frequency in the worst range (500 to 1000 Hz), and assumes no extra benefit from a high sub-panel first resonance or from a double wall construction. For this reason, it may be desired to <u>measure</u> the Transmission Loss of a proposed test panel. The facilities of an approved reverberant-room test laboratory must be used. The technicians will measure the TL in third-octave bands, and will be able to compute the net TL for A-weighted automotive noise, using the spectra in Chapter 2. What must be determined? The A-weighted TL, for traffic spectra, must be at least 4-6 dBA greater than the barrier attenuation of the diffracted noise over the top of the barrier. Assistance is recommended here.

5.3.2 Holes in Barriers

How much do holes compromise the Transmission Loss of barriers? More than would be expected, by far. For example, let us assume we have 80 dBA at the source side of a barrier and that the TL of the barrier is 30 dBA. Without holes, the noise on the opposite side would be 50 dBA. Now let us open up one-tenth of the area of the barrier. The barrier surface is now 10% open. What is the net TL of the barrier-plus-hole?

First, ninety percent of the noise energy hits the barrier itself and is reduced by 30 dBA. Ninety percent is converted to decibels using Table 5.6. From the table, ninety percent of 80 dBA is 80-0.5 = 79.5 dBA. In decibels, nearly all the energy hits the barrier itself. This 79.5 is reduced by 30, yielding 49.5 dBA.

Second, ten percent of the noise energy hits the hole, and is increased by 6 dBA. From the table, 10 percent of 80 dBA is 70 dBA. This is increased by 6, yielding 76 dBA. Finally, the total energy is the dB-sum of 49.5 dBA and 76 dBA, which is 76 dBA. The barrier has provided only 4 dBA reduction.

One reason that the hole compromised the barrier attenuation so drastically is due to the logarithmic nature of noise. The barrier itself essentially eliminates 90 percent of the noise energy, but this is only a reduction of 10 dBA. Even more extreme, if the barrier got rid of 99 percent of the noise energy, the reduction would be only 20 dBA.

The second reason for the poor performance of the barrier-with-hole is the 6 dBA increase in noise through the hole.

HOLE AMPLIFICATION

$$TL_{HOLE} = -6 \text{ dBA}$$

This increase is due to so-called "pressure-doubling" at the barrier's surface. More energy passed through the hole than was straight-incident on it. The phenomenon is complex, but real. A very good absorptive treatment of the source side of the barrier can eliminate this 6 dBA amplification through the hole. In the example, then, the net attenuation would be 10 dBA. The absorption must be broad-band, rather than confined to discreet frequencies, such as provided by resonant absorbers.

Table 5.7 combines these phenomena to indicate the maximum Transmission Loss of a barrier with a hole. As can be seen, very small holes indeed can put low limits on the TL of barriers.

Holes in barriers provide two further complications.

- The 6 dBA amplification discussed above is due to an averaging over the entire frequency range. Throughout most of the range, the noise is attenuated. But at the resonance frequencies of the holes, it is amplified, sometimes by 15-20 dBA. The resulting noise through the hole is not only amplified an average of 6 dBA, but its character can be changed from a broad-band noise to one with discreet pure tones. These pure tones would be more objectionable than their A-level indicates.

- Figure 5.24 demonstrates another complication due to holes. When a barrier is slotted vertically at regular intervals, the slots could behave as a diffraction grating. The noise emanating from a single source passes through all the slots and can produce sharp constructive interference bands on the receiver side of the barrier. The more slots the more localized would be these bands of constructive interference. As the truck moves along the highway, these bands would move with it, sweeping past the receiver. The effect might be similar to an explosion or cannon shot as the truck passes by.

5.3.3 Absorptive Barriers

In Figure 5.1 above, the reflected energy is shown to be important for receivers on the opposite side of the roadway from a reflective barrier. In Example #6 above, the effect of this reflected noise was calculated explicitly. If the barrier walls could be made acoustically absorptive, then this reflected component would be reduced. In some cases, this would provide significant benefit to the opposite receivers.

How much is the reflected noise reduced? This depends upon the absorption coefficient of the barrier wall. For a full answer, the absorption coefficient must be known as a function of frequency. Then the traffic spectrum (most importantly the truck spectrum) is reduced by the absorption at each frequency, to obtain the reflected spectrum. After the A-level of this new spectrum is calculated, it is compared to the original A-level to obtain a reduction in dBA. This procedure is cumbersome, and can generally be simplified as described below.

A single-number absorption coefficient is catalogued by the Acoustical and Insulating Materials Association. This single-number coefficient is called the Noise Reduction Coefficient, NRC. It is an average of the absorption coefficients in the frequency region from approximately 200 to 3000 Hz.

NOISE REDUCTION COEFFICIENT

$$NRC = \frac{ABS_{250\,Hz} + ABS_{500\,Hz} + ABS_{1000\,Hz} + ABS_{2000\,Hz}}{4}$$

Since these frequencies are most important in speech communication, and since the A-level of traffic noise is controlled by the energy in this frequency region, we can use this single number NRC. For any NRC, the reflected noise level is reduced by the amount shown in Table 5.8. The mathematical relation is

$$\text{Reduction in level} = 10 \log\left[\frac{1}{1 - NRC}\right]$$

If a barrier wall is absorptive, then the reflected level should be reduced by the amount in the table. Nothing else is changed in the calculation.

It is necessary that barrier absorption be "broad band". In other words, the barrier should absorb energy over a broad range of frequencies. Most absorptive surfaces do have broad-band absorption, with correspondingly large NRC's. Some structures however, only absorb energy in narrow frequency bands. Such structures include Helmholtz resonators and similar resonant-cavity structures. Such structures leave most of the energy unabsorbed, and have resultingly low NRC's. The bulk of the broad-band traffic noise will not be absorbed, and the A-level will be reduced very little.

a) Receivers Opposite the Barrier

How important is this reflected noise for receivers opposite the barrier? When the direct noise is blocked by a barrier, then the unblocked, reflected noise can control. In such cases, barrier absorption can significantly benefit the receiver. When the direct noise is not blocked however, then the reflected noise can add 3 dBA at most, since at most it can double the energy at the observer. Usually it does not fully double the energy, since the reflected noise has further to travel to the receiver. With no absorption, the resulting increase is usually not significant; little benefit would be derived from making the barrier absorptive.

For depressed roadways, with vertical retaining walls on each side, multiple reflections may be important. Insufficient information is known about this phenomenon to estimate the reverberant build-up and resultant spillage of noise out of the depression. It is suspected that when both the direct noise and the first-reflected noise are shielded from the receiver, then this additional contribution is important; otherwise, not. A planned DoT study should answer this important question.

b) Drivers Within Vertical Depressions

How important is this reverberant build-up to the driver in such a depressed section (with vertical retaining walls)? Again, the answer awaits further study. An upper and lower bound on the noise level can be estimated however.

Upper bound: The noise inside most existing tunnels is certainly an upper bound on the noise in vertical depressions. In such tunnels, the lack of shoulders, the narrow lanes and the low ceilings all increase the reverberant build-up beyond anything that would be encountered in vertical depressions. The lack of a roof over depressed sections will allow most of the energy to quickly escape and not contribute to the reverberant field. Noise in such tunnels is certainly an upper bound.

Lower bound: When driving alongside a single wall, the driver hears the reflection of his own noise (mostly tire noise) from the wall. If he is a shoulder-width from the wall, then it sounds the same as another car travelling with him some three lanes over (the shoulder, the reflected shoulder, and his reflected lane). This is a lower bound on the driver noise in a vertical depression.

DRIVERS WITHIN VERTICAL DEPRESSION

NOISE LESS THAN IN TUNNEL

NOISE GREATER THAN DRIVING ALONG
SINGLE WALL

c) Increased Barrier Attenuation due to Absorption

When noise is diffracted over the top of a barrier, absorption along the top edge and on the faces of the barrier can reduce the diffracted noise level by several dBA, above the amount predicted by the nomograph. The actual amount depends in a complicated way upon the angle of approach relative to the barrier (and even the angle of retreat from the back side of the barrier, if this side is also absorptive). In practice, no more than 3 dBA can be obtained by such absorption, even if the absorption coefficient is unity. An additional 3 dBA can generally be obtained with a higher barrier at much less cost.

5.3.4 Non-acoustical Considerations in Barrier Design

It is beyond the scope of this text to discuss non-acoustical consideration in detail. The highway engineer is generally better acquainted with the non-acoustical constraints than are the authors of this text.

Obviously cost and esthetics are important. Costs vary considerably from barrier to barrier, depending in general upon the height required and the construction materials. The cheapest barrier is generally the earth berm, which at times can be built from surplus fill at very low cost. The esthetics of earth berms are also generally superior to other types of barriers. Landscaping can virtually hide berms from sight, or disguise them as natural hills. Even depressed sections, with retaining walls, can be improved esthetically by breaking the interior wall with a ledge and slight set-back. If the retaining wall is continued upward above the terrain, by perhaps ten feet, the terrain can be sloped upwards toward this wall to leave only a five-foot wall exposed to the neighbors. Many esthetic improvements have been suggested by both architects and engineers who have examined the feasibility of noise barriers.

Barriers on both sides of a freeway tend to decrease the air quality for the drivers. Even single barriers can cause significant snow drift. At times, barriers may interfere with necessary sight-lines for the driver, if care is not taken. And of course, free-standing walls must be able to withstand large wind loads.

The problems are solvable barrier-by-barrier, with imagination and good engineering knowledge.

5.4 NOISE CONTROL DESIGN OTHER THAN ROADSIDE BARRIERS

Beside the construction of roadside barriers, other methods are available to reduce the noise impact adjacent to highways. Some of these, such as the use of quieter pavement materials, have been discussed above. Others involve common-sense application of the propagation laws for highway traffic noise. Others, such as atmospherics, provide no permanent relief. For completeness, all will be listed here. Rather than repeat information given above however, this section will be devoted to pitfalls that may be encountered when putting these methods into practice.

a) Atmospherics

At any given time, atmospherics can significantly reduce the noise level, and thereby confuse the results of single noise measurements. Averaged out, however, they provide no permanent noise reduction, except in the most unusual circumstances.

b) Grade Separation

Traffic signals are eliminated by grade separations, and therefore the more annoying stop-and-go-traffic is eliminated. Whether or not this produces a net benefit is ambiguous, nowever.

Where most traffic is passing through without turning, the benefit is generally significant; where a large percentage of the traffic is turning, there is generally little difference. Even though the stop-and-go traffic at the signal is eliminated, the turning traffic will still accelerate onto the freeway. This full-throttle acceleration produces much noise.

In addition, the on-ramps may be located closer to residential areas, because of the greater land area required for such interchanges. Also, some ramps, or even the main line, may be elevated above the terrain, thereby decreasing the shielding from the terrain. It is definitely a good design policy to depress the main line at such grade separations. In this way, the loudest traffic is shielded by the depression, and uphill grades are not required for the on-ramps.

c) Decks Over Depressed Roadways

Decks over depressed roadways obviously reduce the noise adjacent to the highway. The amount of actual reduction depends upon the Transmission Loss of the deck itself. In urban situations, it nearly always reduces the noise below the general ambient - in other words, it essentially eliminates the noise for completely decked roadways.

At times, vent openings are left in the deck. Such openings seriously compromise the noise reduction of the deck. The amount of compromise is always serious; but is very difficult to compute. It depends upon the size of the vent opening, its relation to the various lanes of traffic underneath, and the amount of acoustic absorption inside the decked area. Also, the noise will emanate from the opening with different intensities in different directions. Without absorption in the tunnel, nearly all the noise energy will escape through the vent opening, no matter how narrow it is (for practical size openings). Since the effective source is now narrowed to a thin vent opening, shielding of the receiver may be easier than from the entire undecked roadway. Apart from this however, little benefit is gained without absorption. If the tunnel has absorption, then the deck can provide significant benefit, even with vent openings.

The seriousness of noise emanating from the portals of tunnels is generally overrated. Figure 5.25 shows noise contours around a typical tunnel portal. Half of all the energy generated within the tunnel is assumed to be emanating from the portal. Even so, the resulting bulge in the noise contours is small. The noise generated by the traffic in direct view outside the tunnel predominates over the portal noise. Furthermore, spherical spreading was assumed from the portal, when in fact the noise is more likely to be aimed somewhat down the roadway, where it is even more effectively masked by the outside traffic noise.

Although most deck structures are very substantial, noise and vibration passing through them must be considered if sensitive air-rights uses are contemplated. The problems are very complex, but amenable to an engineering solution. Difficult trade-offs must be made between cost and weight of the deck and the chance of success.

d) Right-of-way Acquisition

Purchase of additional right-of-way can be effective in preventing future sensitive land use from developing directly adjacent to a highway. The additional land needed is usually great. For example, if the equivalent distance from the highway to the right-of-way fence is initially planned as 150 feet, then this must be increased to 300 feet to gain 3 to 4 dBA reduction in noise at the fence. Generally the increased distance alone will not provide enough reduction to justify the cost. However, if the additional right-of-way is heavily wooded, then the additional distance, plus the tree attenuation, can be very effective. For example, if the additional 150 feet is wooded, then some 5 to 10 dBA additional attenuation will be derived from the trees. This, added to the distance attenuation, results in a total reduction of some 8 to 14 dBA, very significant. Such a combination of effects is far better than allowing development up to the 150-foot fence, with the resulting loss of the trees.

e) Change in Alignment

Changing the alignment can produce very significant changes in the noise impact. The benefit depends completely upon the relative positions of the highway and the adjacent land uses for the two alignments. However, a slight shift in highway position away from a sensitive land-use generally results in a negligible reduction, since the distances would have to be doubled to yield 3 - 4 dBA reduction. Sometimes the alignment can be judiciously chosen to preserve shielding by heavy woods or by the natural terrain. Sometimes a shift of only 100 feet can preserve a small knoll that was effectively shielding a row of residences, for example.

f) Use of Quieter Surfaces

Although the calculation procedure allows a 5 dBA reduction for quiet roadway surfaces, this is generally not attainable. First, quiet means slippery; such surfaces are very rarely used for new highways. Second, the benefit applies only to automobiles, and the L_{10} is often controlled by trucks.

New surfaces will require detailed measurements before they can be certified as "quieter". It is not necessarily true that a quieter ride, judged from inside the automobile, means less noise outside.

g) Heavy Woods and Shrubbery

The tabulated values for attenuation due to heavy woods is given in Chapter 4. It is necessary to warn against a quick measurement of tree attenuation, sometimes attempted to justify larger attenuations than tabulated. Such measurements are subject to all sorts of error, some actually tainting data in the professional literature. The attenuation is not linear with distance; some edge effects are significant; wind and thermal gradients often produce additional attenuation, transient in nature; in a similar way, ground reflection can introduce serious errors. The attenuation ascribed to heavy woods in the Transportation Systems Center computer program is very optimistic. It should not be used. For the same reason, the TSC attenuation ascribed to tall grass and shrubbery should not be used.

h) Intervening Rows of Buildings

Tabulated attenuation values were given in Chapter 4. These should only be used when the buildings actually block the lines-of-sight from the roadway to the receiver. For tall apartment buildings looking over single-family structures, no attenuation is obtained. Similarly, for elevated highways, less than the tabulated values are often observed.

i) Ground Effect

One additional phenomenon must be discussed at this time. When noise travels from source to receiver above the ground, it travels along two separate paths - one directly to the receiver, and one reflected from the ground. The situation is illustrated in Figure 5.26.

Noise arriving by these two paths is coherent; the two contributions may therefore interfere with one another, as in the analogous optical situation. Whether they interfere constructively or destructively depends upon (1) the path length difference of the two rays and (2) upon what happens at the reflection. For source and receiver close to the ground, and for large source-receiver distances, the path length difference is nearly zero for all audible frequencies. For a mirror-type reflection, this would cause the two rays to constructively interfere (add) at the receiver for up to a 6 dBA increase in level. However, over soft ground, there is a phase reversal upon reflection, for small grazing angles. As a result, the two rays destructively interfere. The resulting reduction in the A-level at the receiver is often severe. It is not uncommon to experience a 10 - 15 dBA reduction in noise level for distant receivers. The phenomenon requires relatively flat terrain between the receiver and the great bulk of the roadway. Moreover, the effect is less for trucks than for automobiles, and far less for receivers on the second and third floors than for ground-floor receivers. Although no attempt will be made here to further explain the phenomenon, its consequences will be pointed out:

- Some 10-15 dBA additional noise reduction can be obtained for ground-floor receivers when the terrain is nearly flat and the noise is dominated by automobiles, for receiver distances greater than several hundred feet.
- Very little reduction is afforded receivers at second and third-floor elevations. In fact, this phenomenon accounts in part for the observed increase in noise between the first, and second/third floors (Figure 5.27).
- Since the mathematics in the TSC computer program ignores this phenomenon, it is more likely to correctly predict upper-floor noise than ground-floor noise. The data upon which NCHRP Report 117 is based were obtained at ground elevation, and presumably have this effect incorporated, especially since most of the data were taken in simplified (flat) geometry conditions.

GROUND EFFECT

IGNORED IN TSC → VALID FOR UPPER FLOORS
INCLUDED IN 117 → VALID AT GROUND ELEVATION

5.5 NOISE CONTROL NOT INTEGRAL WITH HIGHWAY DESIGN

The thrust of this chapter has been to give the reader the skills to build noise control into highway design. Although not within the highway engineer's direct influence, noise control is possible on two other fronts: at the source of the noise, and at the receiver's end.

NON-HIGHWAY NOISE CONTROL

- QUIETER VEHICLES
- LAND ZONING
- IMPROVED OUTDOOR-TO-INDOOR NOISE REDUCTION

5.5.1 Noise Control at the Source

The Department of Transportation is currently funding three projects to design quieter (slow-speed) trucks. The goal is to reduce the emission level from the present average of 87 dBA down to 75 dBA (at 50 feet, full throttle). It is likely that such efforts will succeed in the near future. This reduction will bring a very substantial reduction in urban truck noise, where the noise is dominated by engine and exhaust. At freeway speeds, however, tire noise remains an unsolved problem and puts limits upon the achievable noise reduction.

We have looked several years into the future and estimated an intermediate, half-quiet freeway truck. We have not assumed the ultimate goal of 75 dBA trucks, nor have we just considered the first step in enforcement - the 90 dBA limit of California. We have estimated a half-quiet truck population governed by an 86 dBA truck limit. The quietest trucks have not changed, but the noisier ones have been successfully controlled to 86 dBA, at freeway speeds. We assumed that 10 percent of the trucks would violate the limit, in the same pattern as now exists in California.

The noise emission levels for present-day California trucks are shown in Figure 5.28. The percentage of trucks above any given noise emission level can be read directly from the graph. For example, 10% of the trucks (read on the vertical axis) are above 90 dBA (read on the horizontal axis). On this type of graph paper, the vertical axis is distorted so that a Gaussian distribution will plot as a straight line. As can be seen from the figure, the California truck noise emission levels approximate a Gaussian distribution.

Two characteristics of these California data have been used to approximate the half-quiet truck distribution: (1) 8% of the trucks in California are below 83 dBA; and (2) 10% of the trucks are above 90 dBA, the current California noise emission limit. The half-quiet truck distribution shown in this same figure was constructed to duplicate the 8% below 83 dBA, and to duplicate 10% violators above an 86 dBA emission limit. Figure 5.29 shows the same information drawn in histogram form. This makes the Gaussian characteristic of the distributions more apparent.

How much benefit then can we expect from these half-quiet trucks? How much will they reduce the L_{10} and L_{NP} adjacent to freeways? Such an analysis has recently been made along an east-coast interstate, for typical traffic conditions dominated by trucks. Close to the freeway, the L_{10} would drop by only 2.5 dBA, the L_{NP} by 8 dBA. The benefit is significant, but not sufficient to eliminate the impact.

In summary, freeway noise will be significantly reduced by quieter trucks, but not sufficiently reduced in the foreseeable future to satisfy the needs of the adjacent communities.

5.5.2 Noise Control at the Receiver

a) Noise Zoning

Proper zoning along newly constructed freeways can greatly reduce future noise impact. Highway officials have been asked by the FHWA to encourage such zoning. The distances involved are generally large, unless heavy woods and/or industrial buildings provide additional shielding.

b) Improvement of Outdoor-to-Indoor Noise Reduction

For public buildings, PPM 90-2 authorizes money to be spent to improve the outdoor-to-indoor noise reduction of the structure. It is beyond the scope of this text to discuss the engineering principles and procedures of use here. It is generally difficult and expensive. The tabulated values for average outdoor-to-indoor noise reductions are repeated from PPM 90-2 in Chapter 1, Table 1.6. This table provides some estimate of the increase in noise reduction possible from one situation to another.

Measurement of this indoor-to-outdoor noise reduction can be difficult. Simultaneous tape recordings are generally required to allow correction for the source spectrum used. Estimates can be made of the noise reduction from knowledge of the wall and window areas and Transmission Losses, the source spectrum, and the so-called indoor Room Constant.

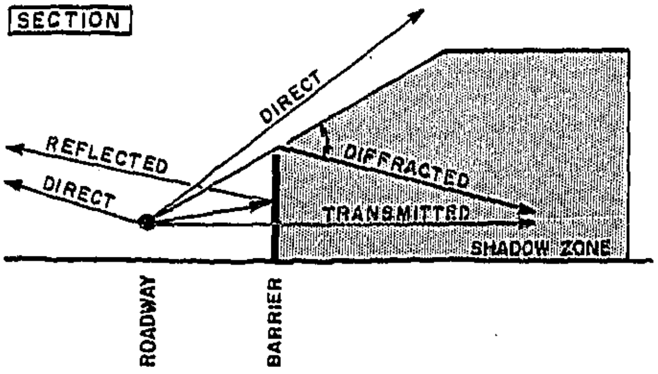


FIGURE 5.1 NOISE PATHS FROM ROADWAY TO RECEIVER

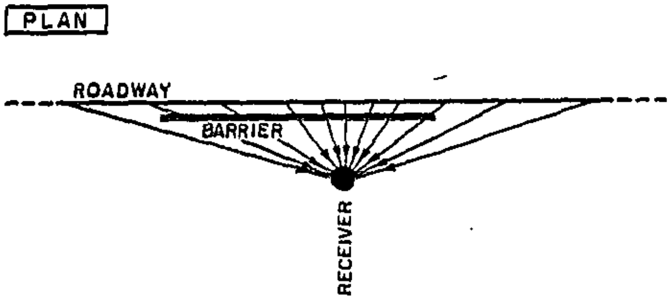


FIGURE 5.2 SHORT-CIRCUIT OF BARRIER AROUND ENDS

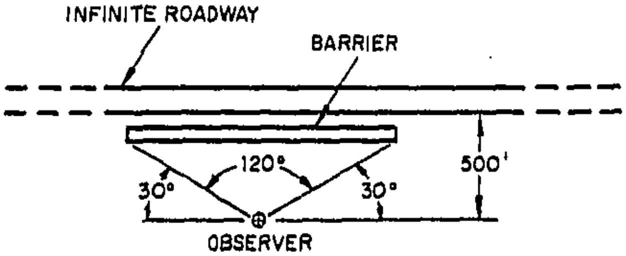


FIGURE 5.3 ROADWAY SEGMENTS WITH UNIFORM BARRIER CHARACTERISTICS

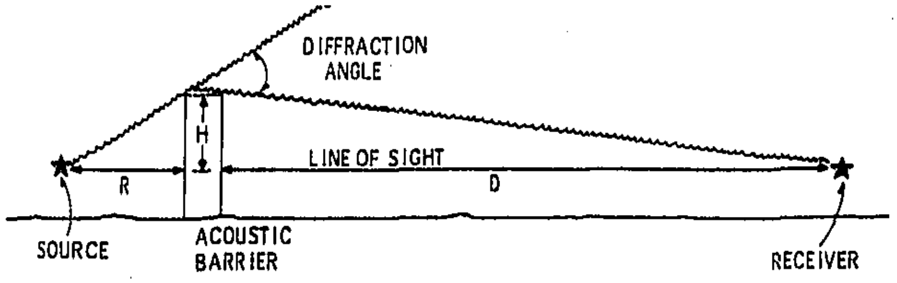


FIGURE 5.4 BARRIER PARAMETERS

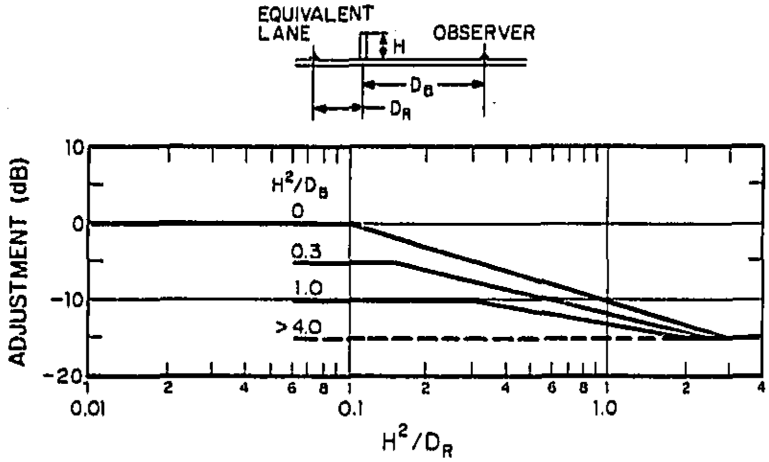
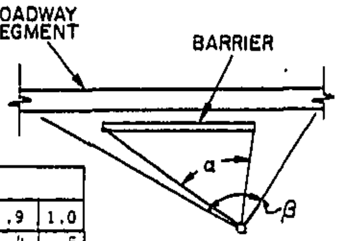


FIGURE 5.5 BARRIER ATTENUATION, PER NCHRP REPORT 117



Infinite Barrier Performance	Ratio α/β										
	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
-5 dB	0	0	-1	-1	-1	-2	-2	-3	-4	-4	-5
-10 dB	0	0	-1	-1	-2	-3	-3	-4	-6	-7	-10
-15 dB	0	0	-1	-2	-2	-3	-4	-5	-7	-10	-15

FIGURE 5.6 ADJUSTMENT TO BARRIER ATTENUATION FOR FINITE BARRIERS, PER NCHRP REPORT 117

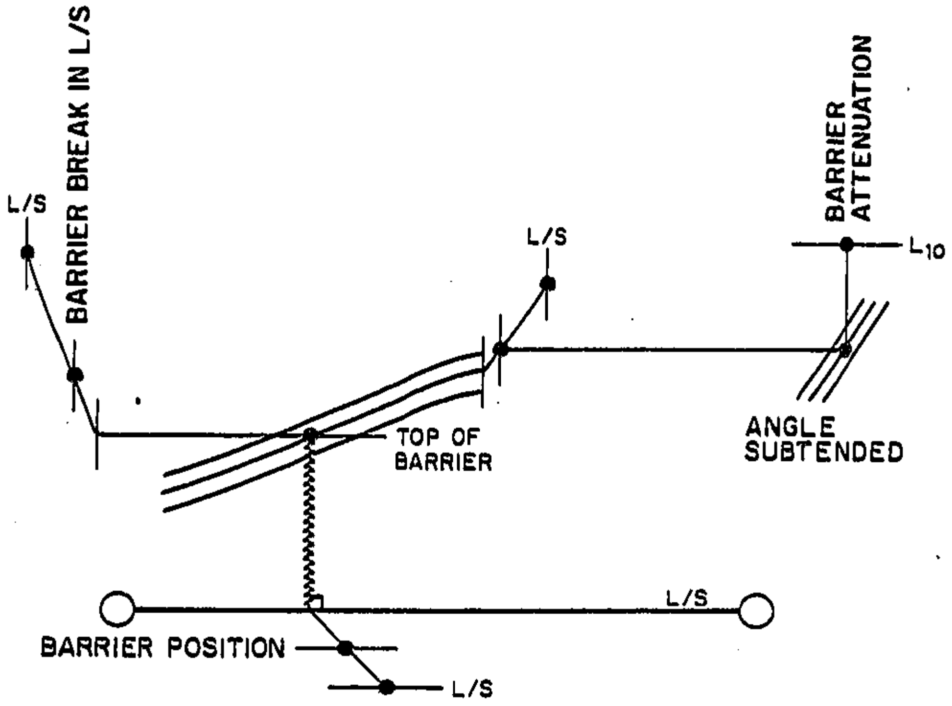


FIGURE 5.7 OVERVIEW OF BARRIER NOMOGRAPH

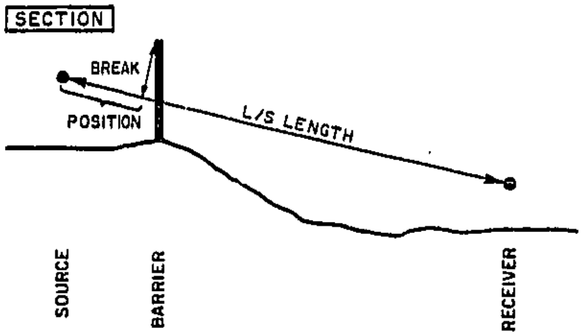


FIGURE 5.8 BARRIER PARAMETERS FOR SIMPLE BARRIER, SECTION VIEW

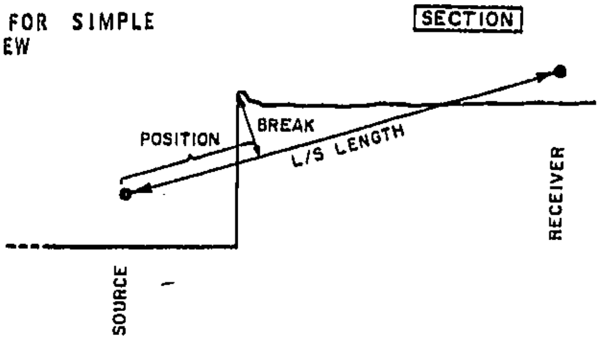


FIGURE 5.9 BARRIER PARAMETERS FOR DEPRESSED ROADWAY, SECTION VIEW

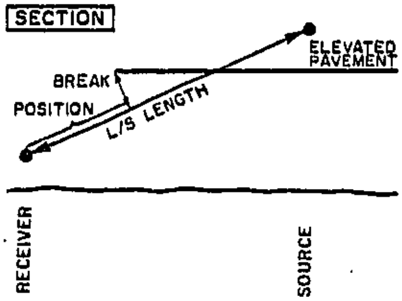


FIGURE 5.10 BARRIER PARAMETERS FOR ELEVATED ROADWAY, SECTION VIEW

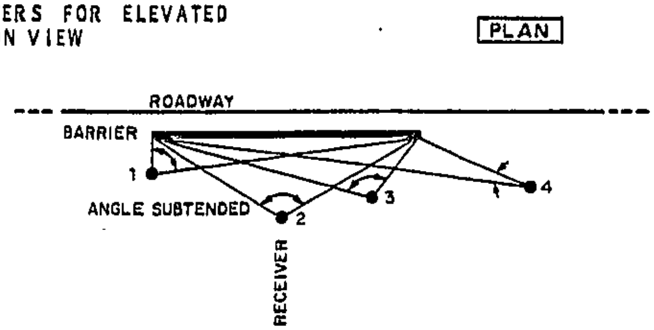
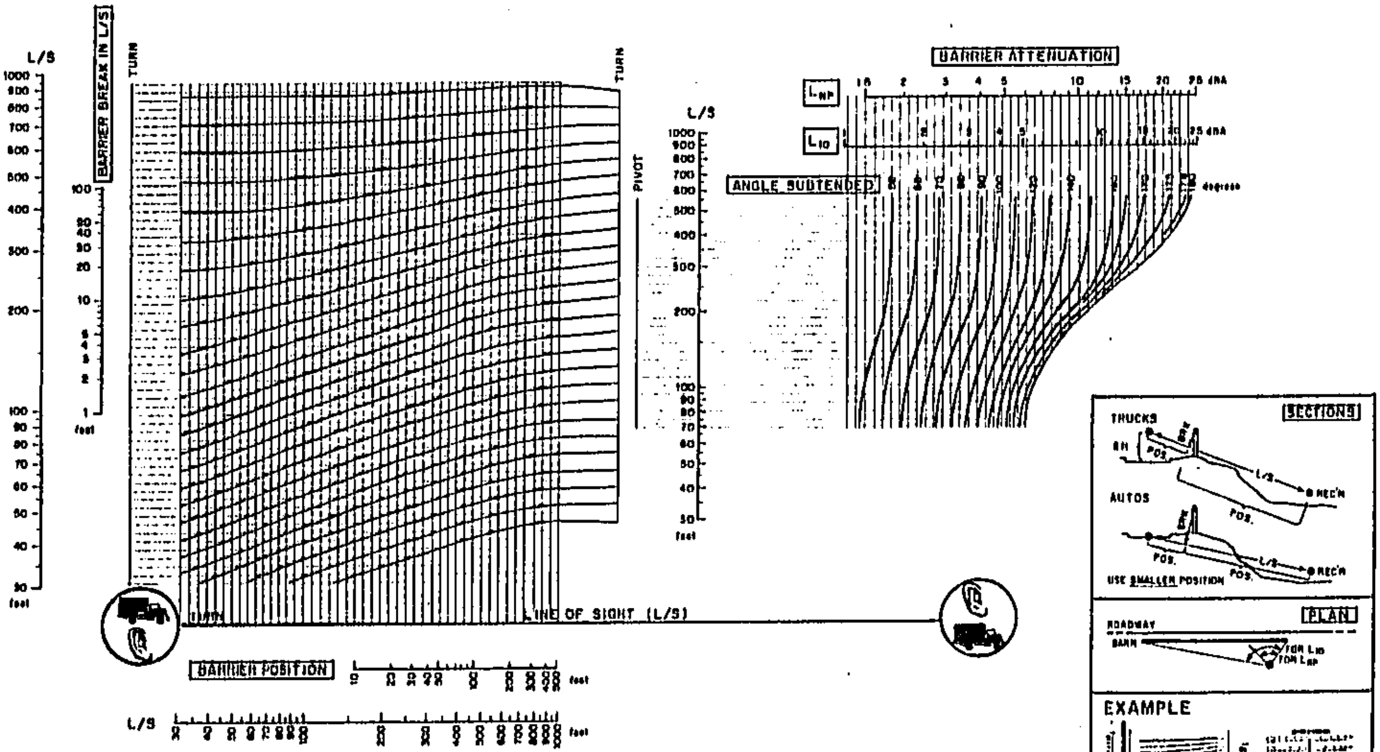


FIGURE 5.11 BARRIER PARAMETERS, PLAN VIEW

BARRIER NOMOGRAPH



Project:

Barrier Description:

Engineer:

Date:

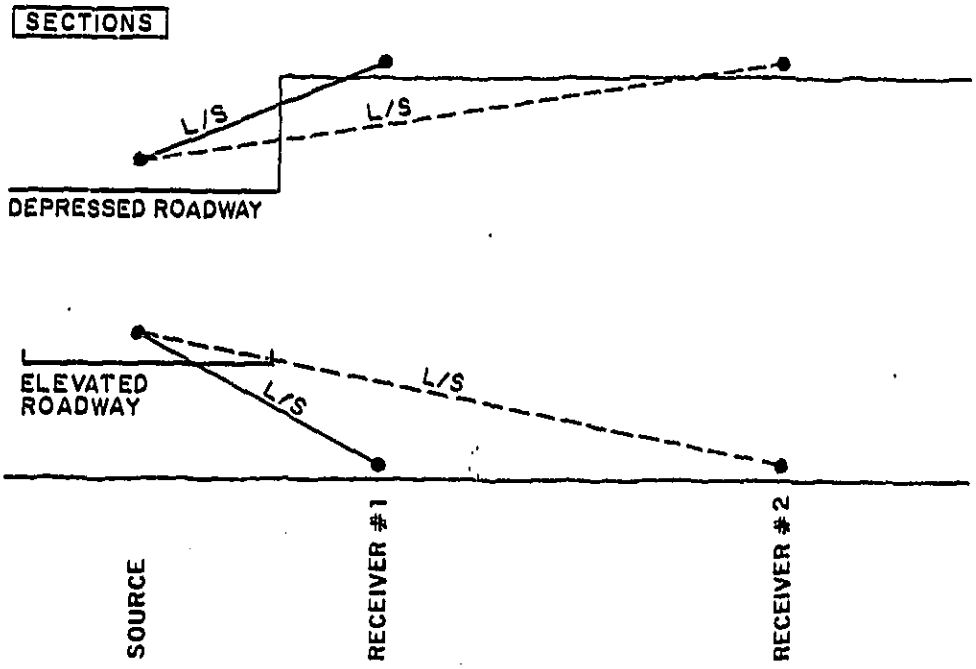


FIGURE 5.13 DEPENDENCE OF BARRIER ATTENUATION UPON DISTANCE TO ROADWAY

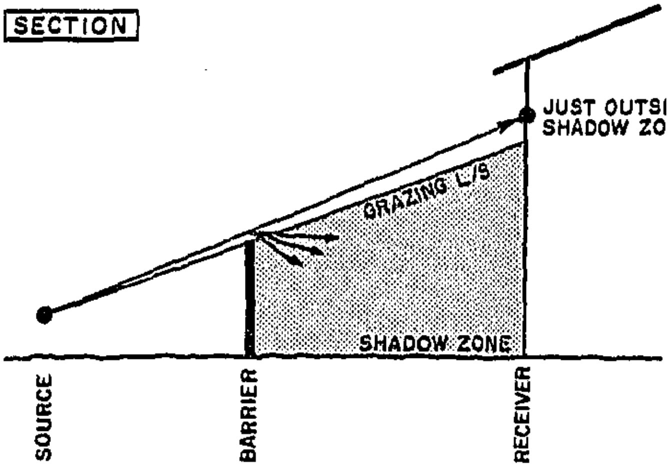


FIGURE 5.14 RECEIVER JUST OUTSIDE SHADOW ZONE

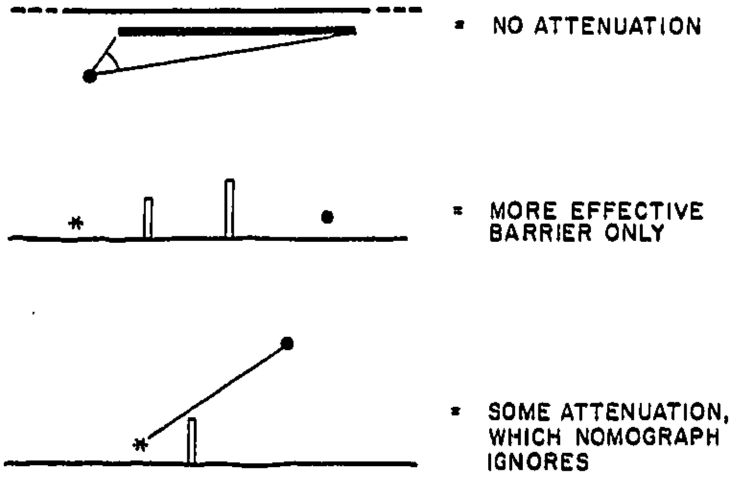


FIGURE 5.15 COMPLEXITIES

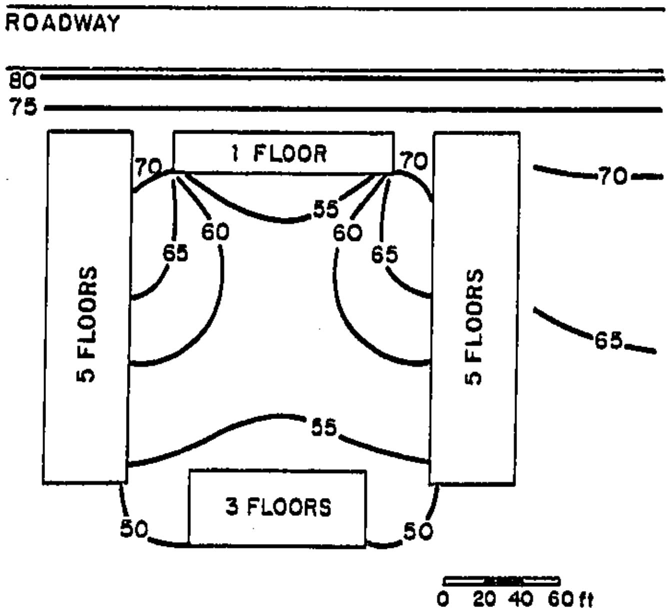


FIGURE 5.16 EXAMPLE OF URBAN SHIELDING

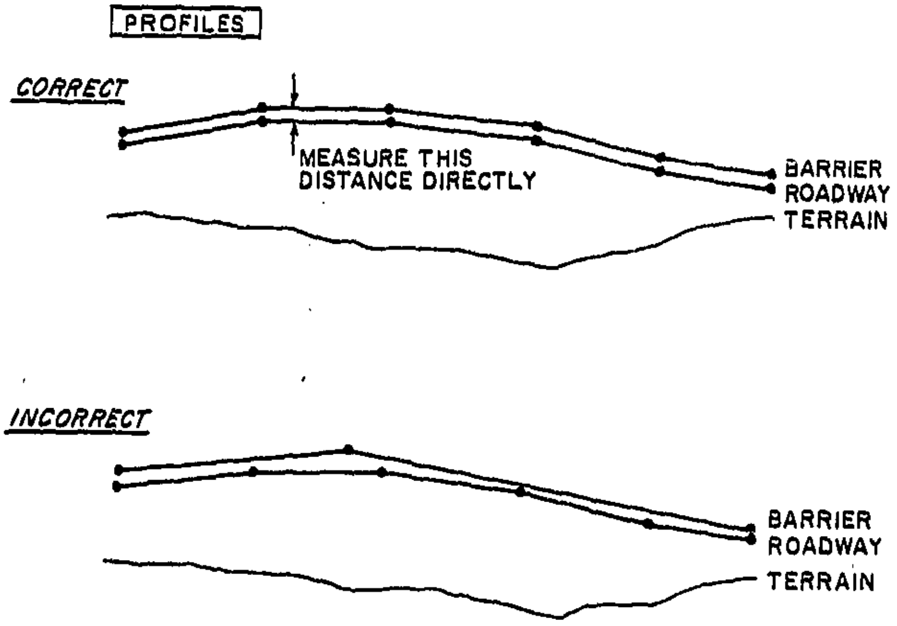


FIGURE 5.17 PRECISE BARRIER ELEVATION - RELATIVE TO ROADWAY

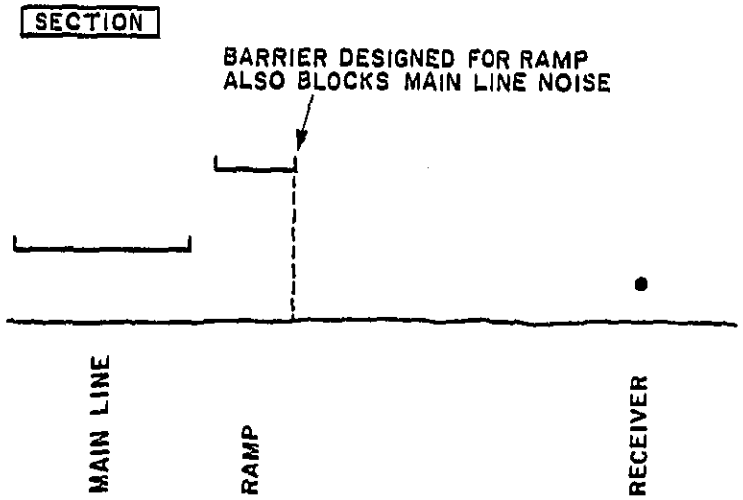
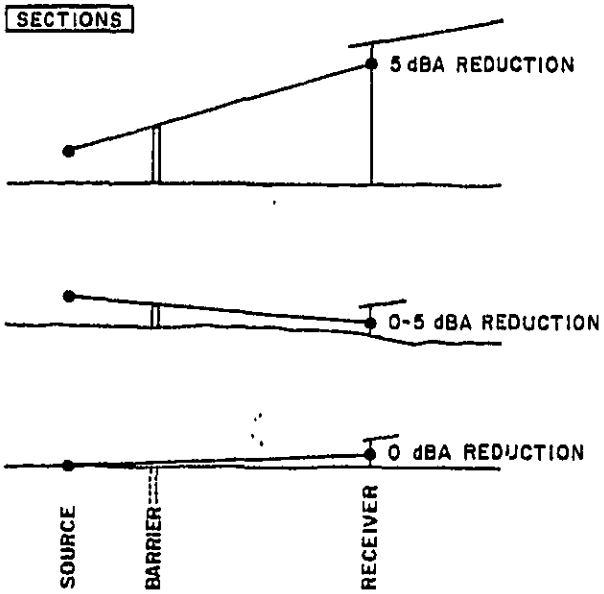


FIGURE 5.18 NOISE CANNOT PASS UNDER ELEVATED BARRIERS



TSC Computer Attributes 5 dBA to All 3 Cases

FIGURE 5.19 ERRONEOUS BARRIER ATTENUATION FOR VERY LOW BARRIERS

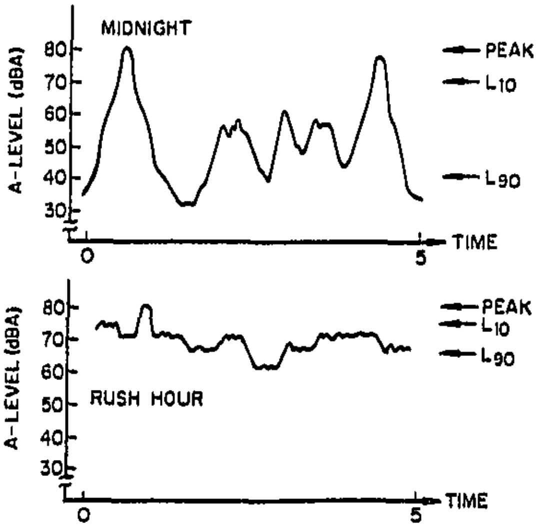


FIGURE 5.20 5-MINUTE HISTORIES

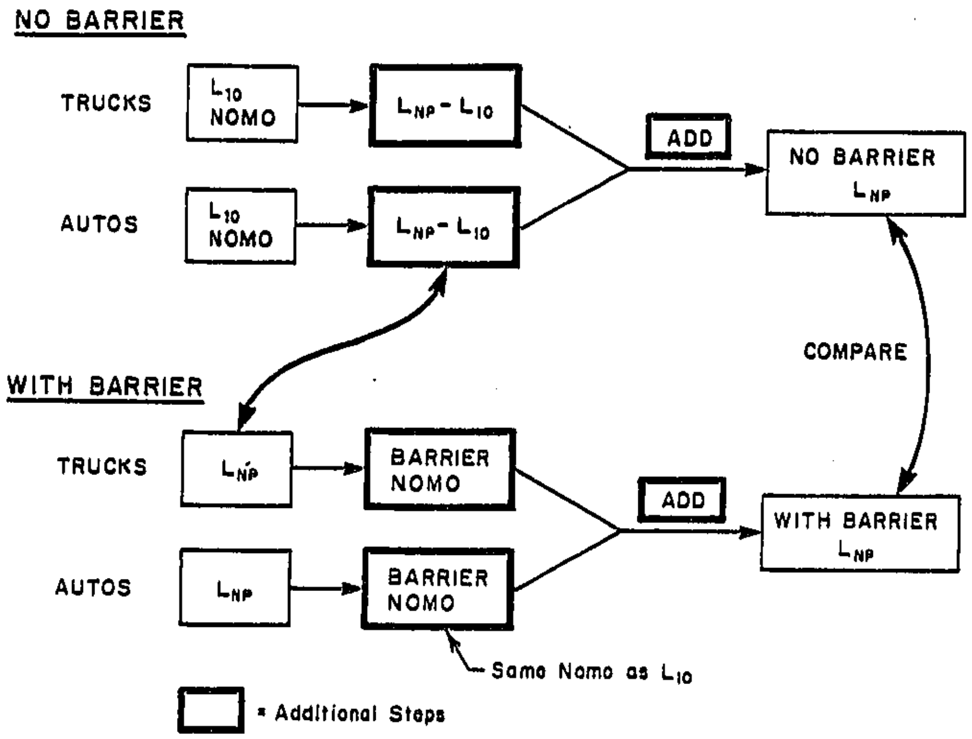


FIGURE 5.21 OVERVIEW OF L_{NP} CHECK ON BARRIER DESIGN

$L_{NP} - L_{10}$ NOMOGRAPH

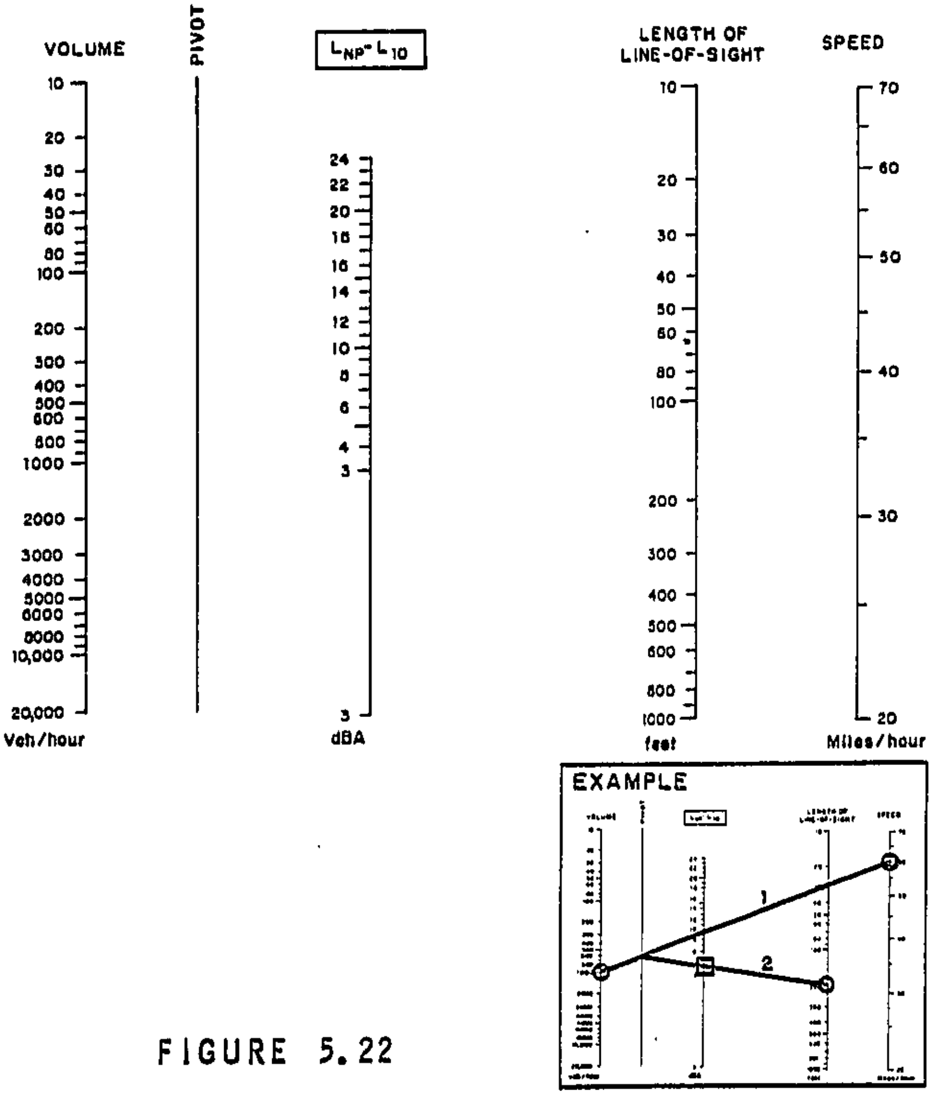


FIGURE 5.22

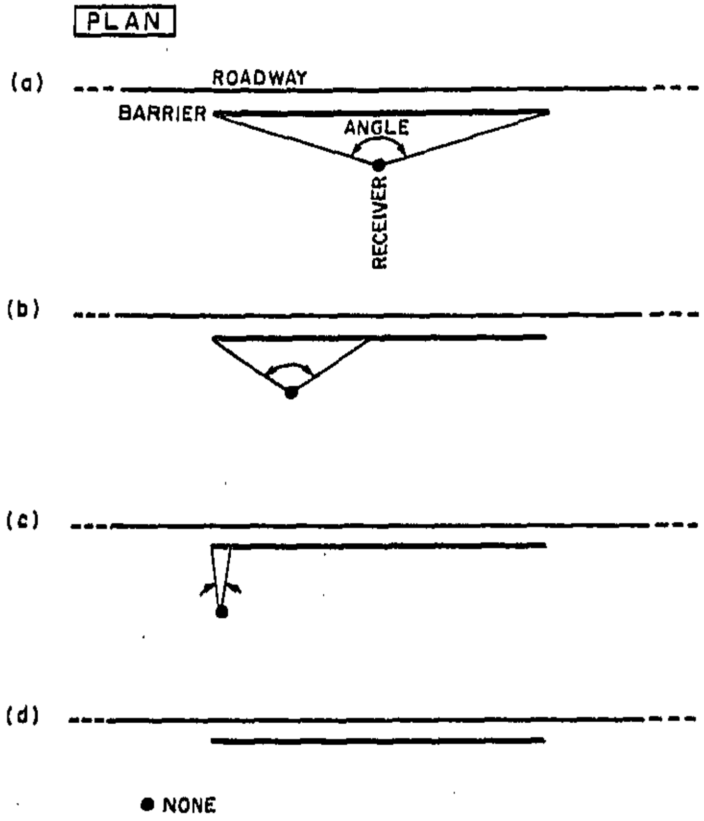


FIGURE 5.23 ANGLE SUBTENDED FOR L_{NP} BARRIER CALCULATION

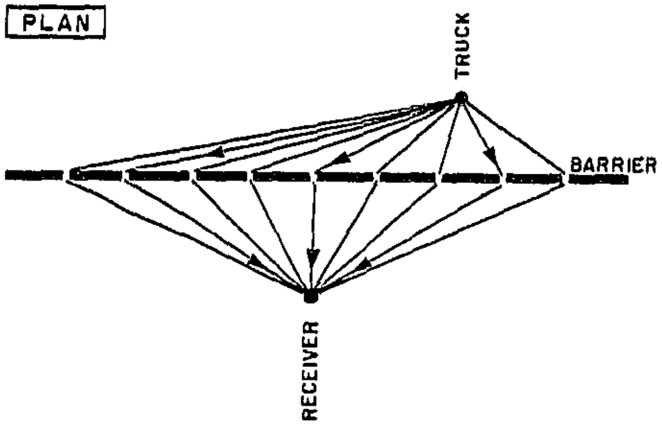
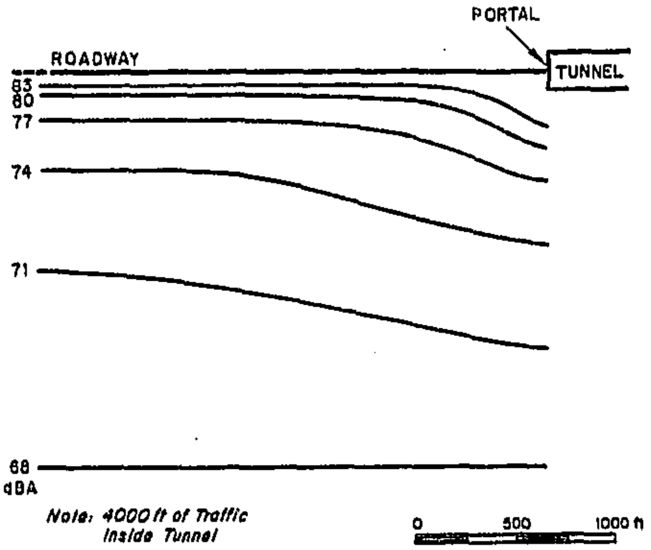


FIGURE 5.24 DIFFRACTION GRATING EFFECT OF SLOTTED BARRIERS



Note: 4000 ft of Traffic Inside Tunnel

FIGURE 5.25 NOISE CONTOURS AROUND A TYPICAL TUNNEL PORTAL

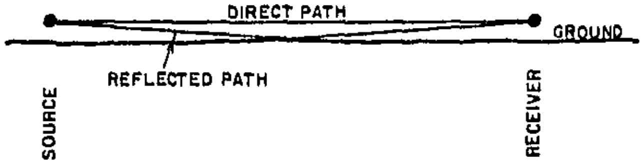
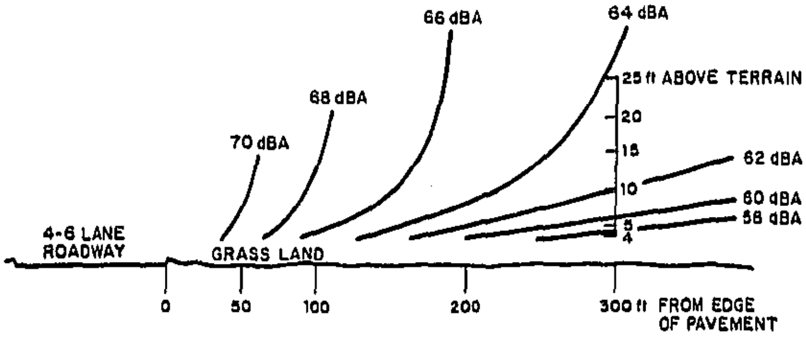


FIGURE 5.26 ILLUSTRATION OF GROUND EFFECT PATHS



Adapted from Fig. 3 National Physical Laboratory Report Ac 57, July 1972

FIGURE 5.27 INCREASE IN NOISE LEVEL WITH INCREASING RECEIVER HEIGHT

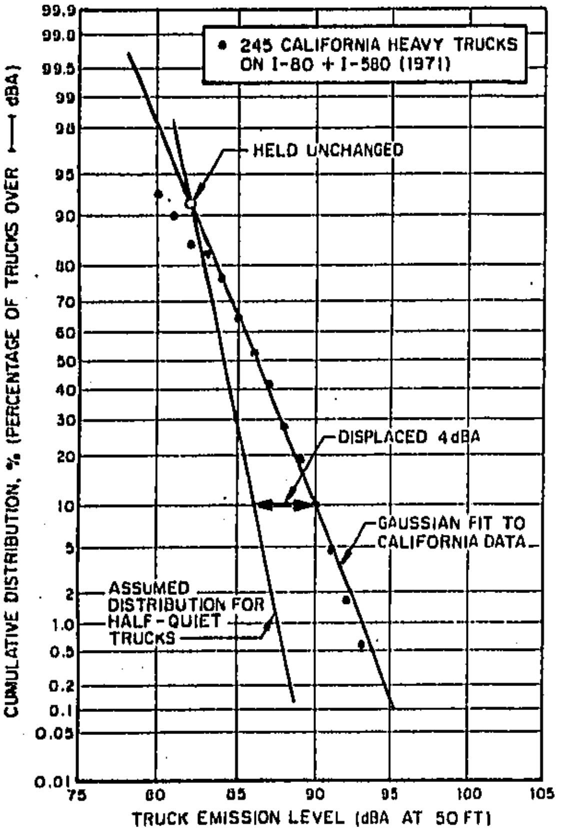


FIGURE 5.28 DEVELOPMENT OF HALF-QUIET TRUCK DISTRIBUTION

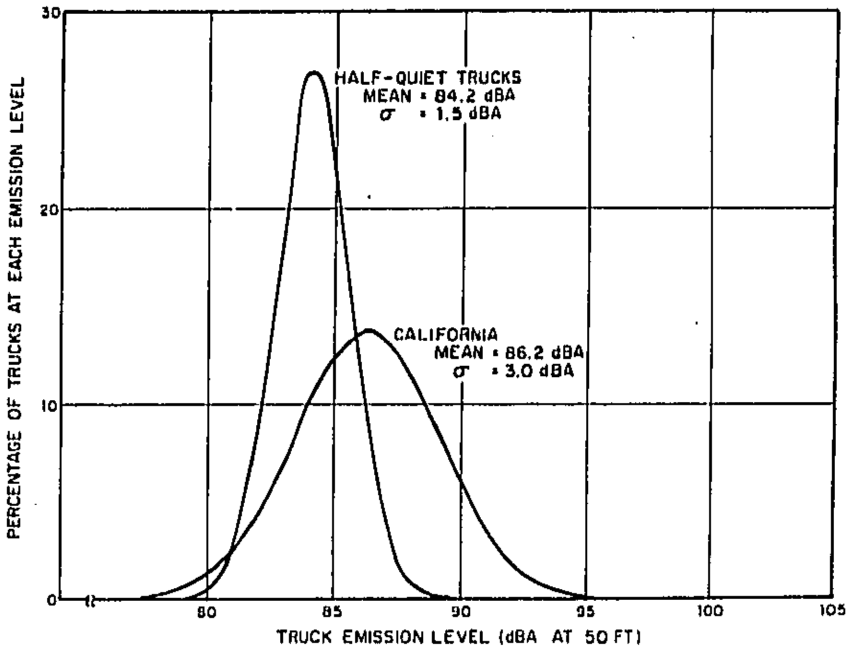


FIGURE 5.29 TRUCK EMISSION DISTRIBUTIONS

TABLE 5.1. RELATION BETWEEN DECIBELS, ENERGY, AND LOUDNESS

A-Level Down	Remove ___% of Energy	Divide Loudness By
3 dBA	50%	1.2
6 dBA	75%	1.5
10 dBA	90%	2
20 dBA	99%	4
30 dBA	99.9%	8
40 dBA	99.99%	16

TABLE 5.2. DEFINITION OF BARRIER PARAMETERS

Parameter	Definition
Line-of-sight, L/S	Straight line from the receiver to the source of noise. For roadway sources, this L/S is drawn perpendicular to the roadway. At the source end, the L/S must terminate at the proper source height: 0 ft for automobiles, 8 ft for trucks. At the receiver end, the L/S must terminate at ear height: 5, 15, 25, ... ft above the ground depending upon the number of floors. See Figs. 5.4 through 5.6. The L/S length is the slant-length of this L/S, not the horizontal distance only.
Break in the L/S	The perpendicular distance from the top of the barrier to the L/S. If the L/S slants, then this break distance will slant also. This is not the height of the barrier above the terrain. See Figs. 5.4 through 5.6.
Barrier position	Distance from the perpendicular break point in the L/S to the closer end of the L/S. This is also a slant distance. See Figs. 5.4 through 5.6.
Angle subtended	Measured at the receiver in the horizontal plane, the angle subtended by the ends of the barrier. See Fig. 5.7. For a barrier always parallel to the roadway, an infinite barrier would subtend 180°. For finite barriers, the angle may also be 180° in the following cases: (1) If the barrier ends bend away from the roadway, so that the actual angle subtended is 180° or more; (2) If the observer cannot see the roadway past the ends of the barrier, due perhaps to terrain; and (3) If the barrier blocks the noise from the full length of a finite or semi-infinite roadway segment.

TABLE 5.3. L_{10} ADDITION

When L_{10}'s Differ by:	Then Add This Amount to the Higher L_{10}:
0	3.0
0.5	3.0
1	2.5
1.5	2.5
2	2.0
2.5	2.0
3	2.0
3.5	1.5
4	1.5
4.5	1.5
5	1.0
5.5	1.0
6	1.0
6.5	1.0
7	1.0
7.5	0.5
8	0.5
8.5	0.5
9	0.5
9.5	0.5
10	0.5
10.5	0.5
11	0.5
11.5	0.5
12	0.5
12.5 or more	0

TABLE 5.4. L_{NP} ADDITION

PARTIAL TABLE	USE WHEN NOISE WITH HIGHER L_{NP} SATISFIES: $\boxed{L_{NP} - L_{10} = 2}$

When L_{NP}'s Differ by:	Then Add This Amount to the Higher L_{NP}:								
0	2	1	1	1	1	0	0	0	0
2	1	1	1	1	0	0	0	0	0
4	1	1	0	0	0	0	0	0	0
6	1	1	0	0	0	0	0	0	0
8	1	0	0	0	0	0	0	0	0
10	1	0	0	0	0	0	0	0	0
12-42	0	0	0	0	0	0	0	0	0
	2	4	6	8	10	12	14	16	18 = $L_{NP} - L_{10}$ OF NOISE WITH THE LOWER L_{NP}

TABLE 5.4 *(Continued)*

PARTIAL TABLE	USE WHEN NOISE WITH HIGHER L_{NP} SATISFIES: $\boxed{L_{NP} - L_{10} = 4}$

When L_{NP}'s Differ by:	Then Add This Amount to the Higher L_{NP}:								
0	1	1	1	1	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
8	-1	0	0	0	0	0	0	0	0
10	-1	0	0	0	0	0	0	0	0
12-42	0	0	0	0	0	0	0	0	0
	2	4	6	8	10	12	14	16	18 = $L_{NP} - L_{10}$ OF NOISE WITH THE LOWER L_{NP}

TABLE 5.4 *(Continued)*

PARTIAL TABLE	USE WHEN NOISE WITH HIGHER L_{NP} SATISFIES: $\boxed{L_{NP} - L_{10} = 6}$

When L_{NP}'s Differ by:	Then Add This Amount to the Higher L_{NP}:								
0	1	1	1	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
4	-1	-1	-1	-1	0	0	0	0	0
6	-2	-1	-1	-1	-1	0	0	0	0
8	-2	-1	-1	-1	-1	0	0	0	0
10	-2	-1	-1	-1	0	0	0	0	0
12	-1	-1	-1	-1	0	0	0	0	0
14	-1	-1	-1	0	0	0	0	0	0
16	-1	-1	0	0	0	0	0	0	0
18	-1	-1	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0
22-42	0	0	0	0	0	0	0	0	0
	2	4	6	8	10	12	14	16	18 = $L_{NP} - L_{10}$ OF NOISE WITH THE LOWER L_{NP}

TABLE 5.4 *(Continued)*

PARTIAL TABLE	USE WHEN NOISE WITH HIGHER L_{NP} SATISFIES: $\boxed{L_{NP} - L_{10} = 8}$

When L_{NP}'s Differ by:	Then Add This Amount to the Higher L_{NP}:								
0	1	1	0	0	0	0	0	0	0
2	-1	-1	-1	-1	-1	-1	-1	0	0
4	-2	-2	-1	-1	-1	-1	-1	0	0
6	-3	-2	-2	-1	-1	-1	-1	0	0
8	-3	-2	-2	-1	-1	-1	-1	0	0
10	-3	-2	-2	-1	-1	-1	-1	0	0
12	-3	-2	-2	-1	-1	-1	0	0	0
14	-3	-2	-1	-1	-1	0	0	0	0
16	-2	-2	-1	-1	0	0	0	0	0
18	-2	-1	-1	-1	0	0	0	0	0
20	-1	-1	-1	0	0	0	0	0	0
22	-1	-1	0	0	0	0	0	0	0
26	-1	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0
32-42	0	0	0	0	0	0	0	0	0
	2	4	6	8	10	12	14	16	18 = $L_{NP} - L_{10}$ OF NOISE WITH THE LOWER L_{NP}

TABLE 5.4 *(Continued)*

PARTIAL TABLE	USE WHEN NOISE WITH HIGHER L_{NP} SATISFIES: $\boxed{L_{NP} - L_{10} = 10}$

When L_{NP}'s Differ by:	Then Add This Amount to the Higher L_{NP}:								
0	1	0	0	0	0	0	0	0	0
2	-1	-1	-1	-1	-1	-1	-1	-1	-1
4	-3	-2	-2	-2	-2	-2	-1	-1	-1
6	-4	-3	-3	-2	-2	-2	-1	-1	-1
8	-4	-4	-3	-2	-2	-2	-1	-1	-1
10	-5	-4	-3	-2	-2	-1	-1	-1	0
12	-5	-4	-3	-2	-2	-1	-1	0	0
14	-5	-4	-3	-2	-1	-1	-1	0	0
16	-4	-3	-2	-1	-1	-1	0	0	0
18	-4	-3	-2	-1	-1	0	0	0	0
20	-3	-2	-1	-1	-1	0	0	0	0
22	-2	-2	-1	-1	0	0	0	0	0
24	-2	-1	-1	0	0	0	0	0	0
26	-1	-1	0	0	0	0	0	0	0
28	-1	-1	0	0	0	0	0	0	0
30	-1	0	0	0	0	0	0	0	0
32-42	0	0	0	0	0	0	0	0	0
	2	4	6	8	10	12	14	16	18 = $L_{NP} - L_{10}$ OF NOISE WITH THE LOWER L_{NP}

TABLE 5.4 *(Continued)*

PARTIAL TABLE	USE WHEN NOISE WITH HIGHER L_{NP} SATISFIES: $\boxed{L_{NP} - L_{10} = 12}$

When L_{NP}'s Differ by:	Then Add This Amount to the Higher L_{NP}:								
0	0	0	0	0	0	-1	-1	-1	-1
2	-1	-1	-1	-2	-2	-2	-2	-1	-1
4	-3	-3	-3	-3	-3	-2	-2	-2	-1
6	-5	-4	-4	-3	-3	-2	-2	-2	-1
8	-6	-5	-4	-4	-3	-2	-2	-1	-1
10	-7	-6	-4	-4	-3	-2	-2	-1	-1
12	-7	-6	-4	-3	-3	-2	-1	-1	0
14	-7	-5	-4	-3	-2	-1	-1	0	0
16	-6	-5	-3	-2	-2	-1	-1	0	0
18	-5	-4	-3	-2	-1	-1	-1	0	0
20	-5	-3	-2	-1	-1	-1	0	0	0
22	-4	-3	-2	-1	-1	0	0	0	0
24	-3	-2	-1	-1	0	0	0	0	0
26	-2	-1	-1	0	0	0	0	0	0
28	-1	-1	-1	0	0	0	0	0	0
30	-1	-1	0	0	0	0	0	0	0
32	-1	0	0	0	0	0	0	0	0
34-42	0	0	0	0	0	0	0	0	0
	2	4	6	8	10	12	14	16	18 = $L_{NP} - L_{10}$ OF NOISE WITH THE LOWER L_{NP}

TABLE 5.4 *(Continued)*

PARTIAL TABLE	USE WHEN NOISE WITH HIGHER L_{NP} SATISFIES: $\boxed{L_{NP} - L_{10} = 14}$

When L_{NP}'s Differ by:	Then Add This Amount to the Higher L_{NP}:								
0	0	0	0	0	0	-1	0	0	0
2	-2	-2	-2	-2	-2	-2	-1	-1	0
4	-3	-3	-3	-3	-3	-3	-2	-2	-1
6	-5	-5	-4	-4	-4	-3	-3	-2	-1
8	-6	-6	-5	-5	-4	-3	-3	-2	-1
10	-7	-7	-6	-5	-4	-3	-2	-2	-1
12	-8	-7	-6	-5	-4	-3	-2	-1	-1
14	-8	-7	-6	-5	-3	-2	-2	-1	-1
16	-8	-7	-5	-4	-3	-2	-1	-1	-1
18	-8	-6	-5	-4	-3	-2	-1	-1	-1
20	-7	-6	-4	-3	-2	-1	-1	-1	0
22	-6	-5	-4	-2	-2	-1	-1	0	0
24	-5	-4	-3	-2	-1	0	0	0	0
26	-4	-3	-2	-1	-1	0	0	0	0
28	-4	-3	-2	-1	-1	0	0	0	0
30	-3	-2	-1	-1	0	0	0	0	0
32	-2	-1	-1	0	0	0	0	0	0
34	-2	-1	-1	0	0	0	0	0	0
36	-1	-1	0	0	0	0	0	0	0
38	-1	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0
	2	4	6	8	10	12	14	26	18 = $L_{NP} - L_{10}$ OF NOISE WITH THE LOWER L_{NP}

TABLE 5.4 *(Continued)*

PARTIAL TABLE

USE WHEN NOISE WITH HIGHER L_{NP} SATISFIES: $\boxed{L_{NP} - L_{10} = 16}$

When L_{NP}'s Differ by:	Then Add This Amount to the Higher L_{NP}:									
0	0	0	0	0	-1	-1	0	1	1	
2	-2	-2	-2	-2	-2	-2	-1	0	1	
4	-4	-4	-3	-3	-3	-3	-2	-2	-1	
6	-5	-5	-5	-5	-4	-4	-3	-2	-1	
8	-7	-7	-6	-6	-5	-5	-4	-3	-2	
10	-8	-8	-7	-6	-5	-4	-3	-2	-2	
12	-9	-9	-8	-6	-5	-3	-3	-2	-1	
14	-10	-9	-8	-6	-5	-3	-2	-2	-1	
16	-10	-9	-7	-6	-4	-3	-2	-2	-1	
18	-10	-9	-7	-5	-4	-2	-2	-2	-1	
20	-10	-8	-6	-5	-3	-2	-2	-1	-1	
22	-9	-7	-5	-4	-2	-1	-1	-1	-1	
24	-8	-6	-4	-3	-2	-1	-1	0	0	
26	-7	-5	-4	-2	-1	0	0	0	0	
28	-6	-4	-3	-2	-1	-1	0	0	0	
30	-5	-3	-2	-1	-1	0	0	0	0	
32	-4	-3	-1	-1	-1	0	0	0	0	
34	-3	-2	-1	0	0	0	0	0	0	
36	-2	-1	-1	0	0	0	0	0	0	
38	-1	-1	0	0	0	0	0	0	0	
40	-1	0	0	0	0	0	0	0	0	
42	0	0	0	0	0	0	0	0	0	
	2	4	6	8	10	12	14	16	18	= $L_{NP} - L_{10}$ OF NOISE WITH THE LOWER L_{NP}

TABLE 5.4 *(Continued)*

PARTIAL TABLE

USE WHEN NOISE WITH HIGHER L_{NP} SATISFIES: $\boxed{L_{NP} - L_{10} = 18}$

When L_{NP}'s Differ by:	Then Add This Amount to the Higher L_{NP}:									
0	0	0	0	0	-1	-1	0	1	2	
2	-2	-2	-2	-2	-2	-2	-1	0	2	
4	-4	-4	-4	-4	-4	-4	-3	-2	-1	
6	-6	-6	-5	-5	-5	-5	-4	-3	-1	
8	-8	-7	-7	-7	-6	-6	-4	-3	-2	
10	-9	-9	-8	-7	-6	-5	-4	-3	-2	
12	-10	-10	-9	-8	-6	-4	-4	-3	-2	
14	-11	-11	-10	-8	-6	-4	-3	-3	-2	
16	-12	-11	-9	-8	-6	-4	-3	-2	-2	
18	-13	-11	-9	-7	-5	-3	-3	-2	-2	
20	-12	-10	-8	-6	-4	-2	-2	-2	-1	
22	-11	-9	-7	-5	-3	-1	-1	-1	-1	
24	-10	-8	-6	-4	-2	-1	-1	-1	-1	
26	-9	-7	-5	-3	-2	-1	-1	0	0	
28	-8	-6	-4	-3	-2	-1	-1	0	0	
30	-6	-5	-3	-2	-1	-1	0	0	0	
32	-5	-4	-2	-1	-1	0	0	0	0	
34	-4	-3	-1	-1	0	0	0	0	0	
36	-3	-2	-1	-1	0	0	0	0	0	
38	-2	-1	0	0	0	0	0	0	0	
40	-1	-1	0	0	0	0	0	0	0	
42	-1	0	0	0	0	0	0	0	0	
	2	4	6	8	10	12	14	16	18	= $L_{NP} - L_{10}$ OF NOISE WITH THE LOWER L_{NP}

TABLE 5.5 MINIMUM SURFACE WEIGHT FOR ROADSIDE BARRIERS

If Barrier is Designed To Reduce the Diffracted Noise By This Amount: (dBA)	Then it Must Have This Minimum Surface Weight: (lb/ft²)
5	3
10	3.5
12	3.5
14	3.5
16	4.0
18	4.5
20	5.0
22	6.5
24	8.0

Notes:
1. Surface weight does *not* include the weight of bracing, framing, etc.
2. The reduction in diffracted noise (column 1) is found from the barrier nomograph, *using 180 degrees as the angle subtended.*
3. This surface weight will guarantee that the transmitted noise is some 3-6 dBA lower than the diffracted noise. For equal contributions – transmitted and diffracted – the surface weight may be halved.
4. For many materials, this minimum surface weight may be very conservative.
5. Surface weight equals the weight density (in lb/ft³) times the thickness (in ft).

TABLE 5.6 CONVERSION OF PERCENTAGE AREA TO DECIBELS

If Percent of Total Surface Area Is: (%)	Then Subtract This Amount From the Incident Level: (dBA)
100	0
90	0.5
80	1
63	2
50	3
40	4
25	6
16	8
10	10
6	12
4	14
2.5	16
1.6	18
1	20
0.6	22
0.4	24
0.25	26
0.16	28
0.1	30

The result is the fraction of energy (in decibels) incident upon *that* portion of the total surface area.

TABLE 5.7 MAXIMUM TRANSMISSION LOSS OF BARRIERS WITH HOLES

Percent of Barrier Area That is Open	Maximum Transmission Loss Possible On Source Side	
	No Absorption (dBA)	With Absorption (dBA)
50	0	3
10	4	10
5	7	13
1	14	20
0.5	17	23
0.1	24	30

TABLE 5.8 REDUCTION IN REFLECTED NOISE LEVEL

NOISE REDUCTION COEFFICIENT, NRC	REFLECTED ENERGY REDUCED BY THIS AMOUNT
0.95	13 dBA
0.90	10 dBA
0.85	8 dBA
0.80	7 dBA
0.75	6 dBA
0.70	5 dBA
0.65	4.5 dBA
0.60	4 dBA
0.55	3.5 dBA
0.50	3 dBA

WORKSHEET 5.1	BARRIERS AND dB-ADDITION FOR L_{10}

Use with Tally Sheet #___ of ___

Engineer:

Project:

Date:

Barrier Description:

NOISE SOURCE	NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
TOTAL		TOTAL	

NET BARRIER ATTENUATION: ___ dBA for L_{10}

WORKSHEET 5.2	BARRIERS AND dB-ADDITION FOR L_{10} AND L_{NP}

Use with Tally Sheet #___ of ___ Engineer:

Project: Date:

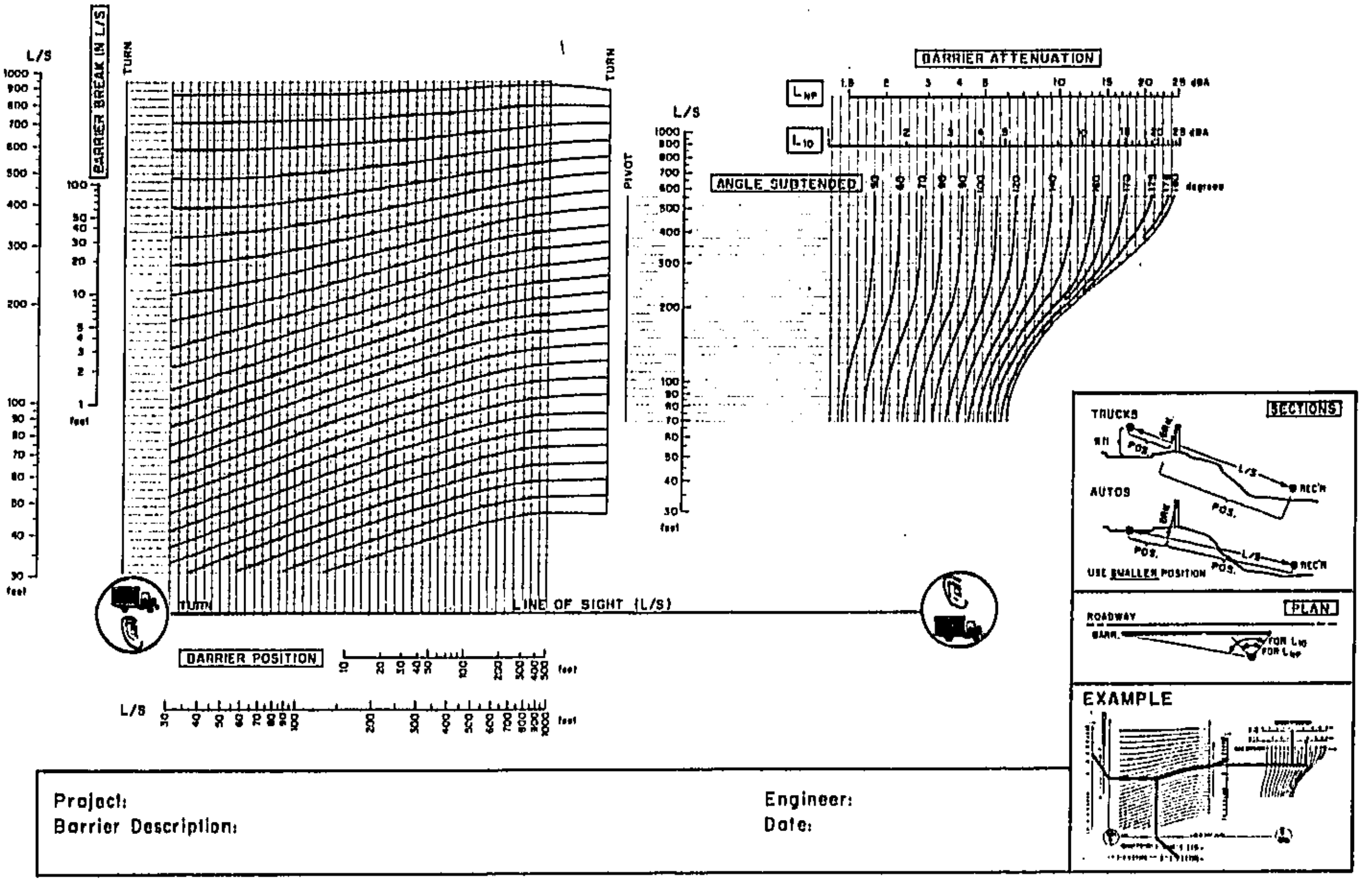
Barrier Description:

NOISE SOURCE	NO BARRIER			L_{NP} BARR. ATTEN.	WITH BARRIER			L_{10} BARR. ATTEN.	NO BARRIER
	L_{10}	$L_{NP}-L_{10}$	L_{NP}		L_{NP}	$L_{NP}-L_{10}$	L_{10}		L_{10}
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
Trucks									
Autos									
TOTAL				TOTAL					

NET BARRIER ATTENUATION: ___ dBA for L_{10}

___ dBA for L_{NP}

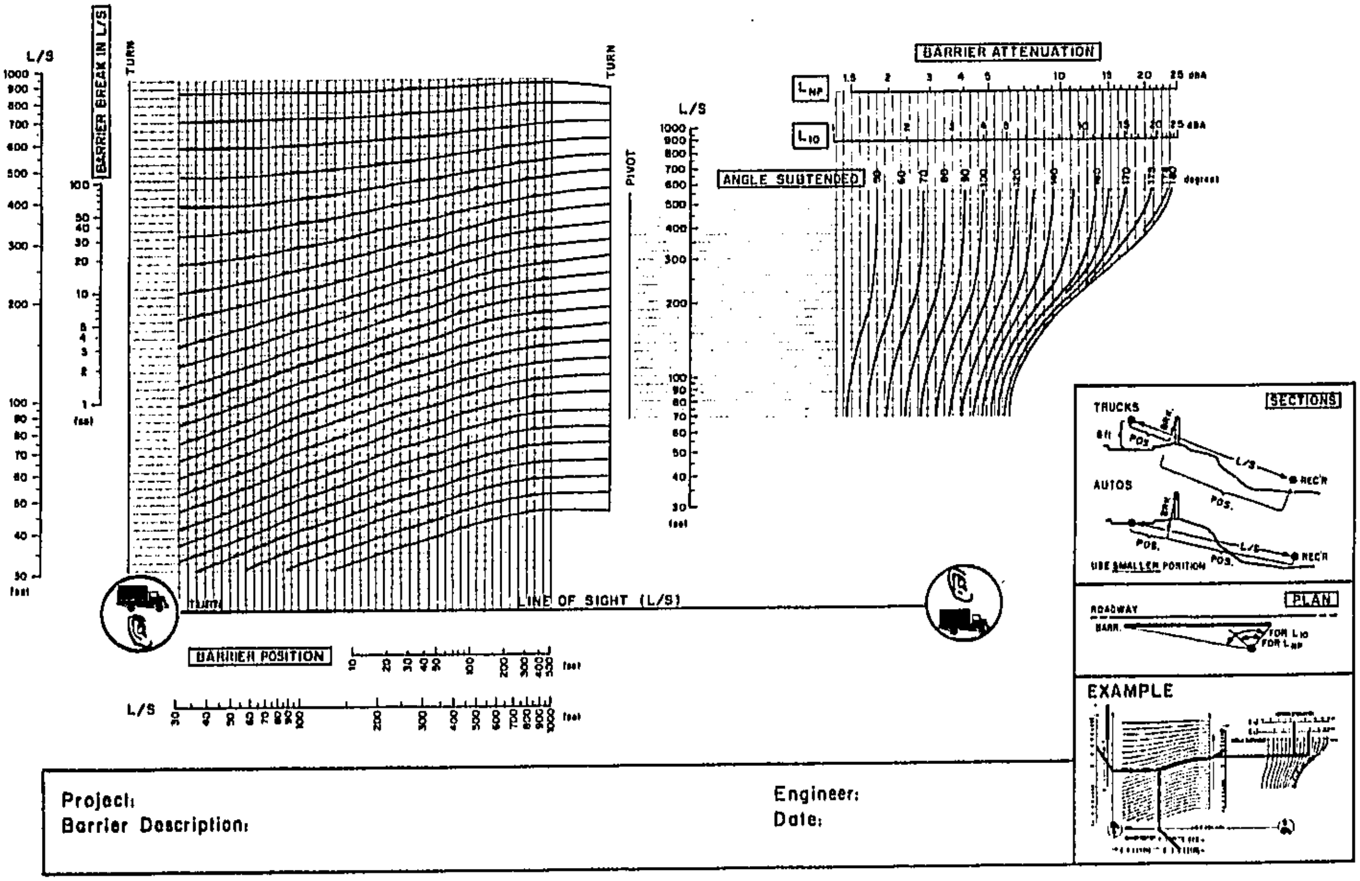
BARRIER NOMOGRAPH



Project:
Barrier Description:

Engineer:
Date:

BARRIER NOMOGRAPH



Project:
Barrier Description:

Engineer:
Date:

WORKSHEET 5.1	BARRIERS AND dB-ADDITION FOR L_{10}

Use with Tally Sheet #___ of ___ Engineer:

Project: Date:

Barrier Description:

NOISE SOURCE	NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
TOTAL		TOTAL	

NET BARRIER ATTENUATION: ___ dBA for L_{10}

WORKSHEET 5.1	BARRIERS AND dB-ADDITION FOR L_{10}

Use with Tally Sheet #___ of ___

Engineer:

Project:

Date:

Barrier Description:

NOISE SOURCE	NO BARRIER L_{10}	L_{10} BARR. ATTEN.	WITH BARRIER L_{10}
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
Trucks			
Autos			
TOTAL		TOTAL	

NET BARRIER ATTENUATION: ___ dBA for L_{10}

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
WASHINGTON, D.C. 20590

POLICY AND PROCEDURE MEMORANDUM

Transmittal 279
February 8, 1973

HEV-10

1. MATERIAL TRANSMITTED

PPM 90-2, Subject: Noise Standards and Procedures

2. EXISTING ISSUANCES AFFECTED

Supersedes Advance Copy of PPM 90-2 dated April 26, 1972.

3. COMMENTS

PPM 90-2 has been revised to incorporate suggestions and respond to comments resulting from circulation of a draft environmental statement. Significant changes are:

a. Table A, Low Noise Level Highways, has been deleted
b. The level of detail required during location phase has been clarified
c. The use of quiet vehicle noise prediction methods has been deleted

The design noise levels in the standards represent a balancing of that which may be desirable and that which may be achievable. Consequently, noise impacts can occur even though the design noise levels are achieved. The values in Table 1 should be viewed as maximum values, recognizing that in many cases, the achievement of lower noise levels would result in even greater benefits to the community. Highway agencies are urged, therefore, to strive for noise levels below the values in Table 1 where the lower levels can be achieved at reasonable cost, without undue difficulty, and where the benefits appear to clearly outweigh the costs and efforts required.

Projects which received location approval prior to July 1, 1972, are not required to adhere to the standards provided design approval is

NOTE: This PPM is being reissued due to incorrect assembly of the original printing obtained before July 1, 1974. However, the Federal Highway Administration encourages application of the noise standards to such projects whenever possible.

For a 12-month period beginning with the date of this issue, copies of each exception approval letter together with the State's request shall be forwarded to both the Regional Administrator and direct to the Washington office (HEV-10), unless advised to the contrary by the Regional Administrator.

4. **Effective Date**

The effective date of this PPM is the date of issuance.

R. R. Bartelsmeyer

R. R. Bartelsmeyer
Acting Federal Highway Administrator

DISTRIBUTION:
Basic

	Remove			Insert
	Page(s)			Page(s)
	1 thru 6	April 26, 1972		1 thru 4
Attachment 1	1	April 26, 1972	Appendix A	
Attachment 2	1 thru 2	April 26, 1972	Appendix B,	B-1 thru B-4
Attachment 3	1 thru 4	April 26, 1972		

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
POLICY AND PROCEDURE MEMORANDUM

Transmittal 279
90-2
February 8, 1973

NOISE STANDARDS AND PROCEDURES

Par. 1. Purpose
2. Authority
3. Noise Standards
4. Applicability
5. Procedures

Appendix A - Definitions
Appendix B - Noise Standards

1. PURPOSE

To provide noise standards and procedures for use by State highway agencies and the Federal Highway Administration (FHWA) in the planning and design of highways approved pursuant to Title 23, United States Code, and to assure that measures are taken in the overall public interest to achieve highway noise levels that are compatible with different land uses, with due consideration also given to other social, economic and environmental effects.

2. AUTHORITY

Sections 109(h) and (i), Title 23, United States Code, state that guidelines shall be promulgated "to assure that possible adverse economic, social, and environmental effects relating to any proposed project on any Federal-aid system have been fully considered in developing such project, and that the final decisions on the project are made in the best overall public interest, taking into consideration the need for fast, safe and efficient transportation, public services, and the costs of eliminating or minimizing such adverse effects and the following: (1) air, noise, and water pollution; . . ." and that "The Secretary, after consultation with appropriate Federal, State, and local officials, shall develop and promulgate standards for highway noise levels compatible with different land uses and after July 1, 1972, shall not approve plans and specifications for any proposed project on any Federal-aid system for which location approval has not yet been secured unless he determines that such plans and specifications include adequate measures to implement the appropriate noise level standards."

3. NOISE STANDARDS

a. Noise standards are appended as Appendix B. Federal Highway Administration encourages application of the noise standards at the earliest appropriate stage in the project development process.

b. There may be sections of highways where it would be impossible or impracticable to apply noise abatement measures. This could occur where abatement measures would not be feasible or effective due to physical conditions, where the costs of abatement measures are high in relation to the benefits achieved, or where the measures required to abate the noise condition conflict with other important values, such as desirable esthetic quality, important ecological conditions, highway safety, or air quality. In these situations, highway agencies should weigh the anticipated noise impacts together with other effects against the need for and the scope of the project in accordance with other FHWA directives (PPM's 20-8, 90-1, and 90-4).

4. APPLICABILITY

In order to be eligible for Federal-aid participation, all projects to which the noise standards apply shall include noise abatement measures to obtain the design noise levels in these standards unless exceptions have been approved as provided herein.

a. Projects to which noise standards apply. The noise standards apply to all highway projects planned or constructed pursuant to Title 23, United States Code, except projects unrelated to increased traffic noise levels, such as lighting, signing, landscaping, safety and bridge replacement. Pavement overlays or pavement reconstruction can be considered as falling within this category unless the new pavement is of a type which produces more noise than the type replaced.

b. Approvals to Which Compliance with Noise Standards Is Prerequisite

(1) Projects for which location was approved prior to July 1, 1972: Compliance

with noise standards shall not be a prerequisite to any subsequent approval provided design approval is secured prior to July 1, 1974. If design approval is not secured for such a project prior to July 1, 1974, compliance with the noise standards shall be a prerequisite to securing both design approval and approval of plans and specifications. However, such compliance shall not be a basis for requiring reconsideration of the highway location or any other approval action which has previously been taken for such projects.

(2) Projects for which location is approved on or after July 1, 1972:

(a) If location approval was requested on or before December 31, 1972, compliance with the noise standards shall be a prerequisite to obtaining design approval and approval of plans and specifications. Compliance with the noise standards shall not be a prerequisite to obtaining location approval, nor shall such compliance be a basis for requiring reconsideration of the highway location or any other approval action which has previously been taken for such projects. Combined location and design approval shall be handled in the same manner as separate design approval.

(b) If location approval is requested after December 31, 1972, compliance with the noise standards shall be a prerequisite to obtaining location and design approvals as well as approval of plans and specifications.

5. PROCEDURES

The noise standards should be implemented at the earliest appropriate stage in the project development process. These procedures have been developed accordingly:

a. Project Development. A report on traffic noise will be required during the location planning stage and the project design stage. The reports may be sections in the location and design study reports, or they may be separate. The procedures for noise analysis, identification of solutions, coordination with local officials, and incorporation of noise abatement measures are as follows:

(1) Nonapplicable Projects. If a State highway department determines (in accordance with paragraph 4a) that noise standards do not apply to a particular project, the requests for location approval and design approval shall contain statements to that effect, including the basis on which the State made its determination.

(2) Noise Analysis. For applicable projects, analyses of noise and evaluation of effects are to be made during project development studies using the following general steps:

(a) Predict the highway-generated noise level as described in the standards for each alternative under detailed study.

(b) Identify existing land uses or activities which may be affected by noise from the highway section.

(c) By measurement, determine the existing noise levels for developed land uses or activities.

(d) Compare the predicted noise levels with the design level values listed in the standards. Also compare the predicted noise levels with existing noise levels determined in paragraph 5a(2)(c). These comparisons will be the basis for determining the anticipated impact upon land uses and activities.

(e) Based upon the noise impacts determined in paragraph 5a(2)(d), evaluate alternative noise abatement measures for reducing or eliminating the noise impact for developed lands.

(f) Identify those situations where it appears that an exception to the design noise levels will be needed. Prepare recommendations to be included in the traffic noise report. (This report may be a portion of the location and design study reports or it may be a separate report.)

(3) Location Phase and Environmental Impact Statement Requirements. To the extent this PPM is applicable to the location phase of projects under paragraph 4, the noise report shall describe the noise problems which may be created and the plans for dealing with such problems for each alternative under detailed study. The level of detail of the noise analysis in the location phase should be consistent with the level of detail in which the location study itself is made. This information including a preliminary discussion of exceptions anticipated, shall be set forth in the location study report and summarized in the environmental impact statement (if one is prepared) and, as appropriate, at the location hearing (for location hearings after December 31, 1972). Studies and reports for highway locations approved before December 31, 1972, need not include an analysis and report on noise. In such instances, the noise analysis and report will be required only for the design approval.

(4) Design Phase Requirements. The noise analysis prepared for the location phase is to be updated and expanded using the refined alignment and design information developed during the design studies. The report on traffic noise will include a detailed analysis of the anticipated noise impact, alternative or proposed abatement measures, discussion of coordination with local officials, and recommended exceptions.

(5) Coordination with Local Officials on Undeveloped Lands. Highway agencies have the responsibility for taking measures that are prudent and feasible to assure that the location and design of highways are compatible with existing land use. Local governments, on the other hand, have responsibility for land development control and zoning. Highway agencies can be of considerable assistance to local officials in these efforts with a view toward promoting compatibility between land development and highways. Therefore, for undeveloped lands (or properties) highway agencies shall cooperate with local officials by furnishing approximate generalized future noise levels for various distances from the highway improvement, and shall make available information that may be useful to local communities to protect future land development from becoming incompatible with anticipated highway noise levels.

(6) Noise Abatement Measures for Lands Which are Undeveloped at Time of Location Approval

(a) Noise abatement measures are not required for lands which are undeveloped at the time of location approval; however, the highway agency may incorporate noise abatement measures for such undeveloped lands in the project design (if approved by FHWA) when a case can be made for doing so based on consideration of anticipated future land use, future need, expected long term benefits, and the difficulty and increased cost of later incorporating abatement measures.

(b) For land uses or activities which develop after location approval, noise abatement measures should be considered for incorporation in the project in the following situations:

1 It can be demonstrated that all practicable and prudent planning and design were exercised by the local government and the developer of the property to make the activity compatible with the predicted noise levels which were furnished to the local government and especially that a considerable amount of time has elapsed between location approval and highway construction thus limiting local government's ability to maintain control over adjoining land uses.

2 The benefits to be derived from the use of highway funds to provide noise abatement measures is determined to outweigh the overall costs.

3 The noise abatement measures can be provided within the highway's proposed right-of-way or wider rights-of-way or easements acquired for that purpose.

(c) There are some situations where the design noise levels should be applied to lands which are undeveloped at the time of location approval. Some of these instances occur where the development of new land uses or activities is planned at the same time as the highway location studies. Other instances occur where planning for the new development has preceded the highway location studies but the development has been delayed. These types of situations should be treated as though the land use or activity were in existence at the time of location approval provided:

1 The State highway agency is apprised of such prior planning.

2 The construction of the new land use or activity is started prior to highway construction or there is good reason to believe that it will start before highway construction.

(7) Incorporation of Noise Abatement Measures in Plans and Specifications. For those projects to which the standards apply, the plans and specifications for the highway section shall incorporate noise abatement measures to attain the design noise levels in the standards, except where an exception has been granted.

(8) Requests for Exceptions. Requirements and supporting materials for requests for exceptions to the design noise levels are described in paragraph 2 of Appendix B to this PPM. To the extent possible, consistent with the level of detail of the location study, identifiable exceptions should be reported in the location study report. The request for location approval shall contain or be accompanied by a request for approval of exceptions that have been identified in the location stage. Supporting material may be contained in the location study report. Subsequent requests for review and approval of additional exceptions, if any, will be similarly processed in conjunction with design approval.

b. Federal Participation

(1) Shifts in alignment and grade are design measures which can be used to reduce noise impacts. The following noise abatement measures may also be incorporated in a project to reduce highway-generated noise impacts. The costs of such measures may be included in project costs.

(a) The acquisition of property rights (either in fee or a lesser interest) for providing buffer zones or for installation or construction of noise abatement barriers or devices.

(b) The installation or construction of noise barriers or devices, whether within the highway right-of-way or on an easement obtained for that purpose.

(2) In some specific cases there may be compelling reasons to consider measures to "sound-proof" structures. Situations of this kind may be considered on a case by case basis when they involve such public or non-profit institutional structures as schools, churches, libraries, hospitals, and auditoriums. Proposals of this type, together with the State's recommendation for approval, shall be submitted to FHWA for consideration.

c. Approval Authority

(1) Exceptions to the Design Noise Levels. The FHWA Division Engineer is authorized to approve exceptions to the design noise levels and alternate traffic characteristics for noise prediction as provided in paragraph 3b, Appendix B.

(2) Noise Prediction Method. Noise levels to be used in applying the noise standards shall be obtained from a prediction method approved by FHWA. The noise prediction method contained in National Cooperative Highway Research Program Report 117 and the method contained in Department of Transportation, Transportation Systems Center Report DOT-TSC-FHWA-72-1 are approved as of the date of this issue for use in applying the noise standards. Other noise prediction methods or variations of the above should be furnished to the FHWA Office of Environmental Policy together with supporting and validation information for approval.

R. R. Bartelsmeyer

R. R. Bartelsmeyer
Acting Federal Highway Administrator

DEFINITIONS (As used in this PPM)

Design Approval - the approval (described in PPM 20-8) given by the Federal Highway Administration (FHWA) (at the request of a State highway department) based upon a design study report and a design public hearing or opportunity therefor. This action establishes FHWA acceptance of a particular design and is prerequisite to authorization of right-of-way acquisition and construction.

Design Noise Level - the noise levels established by the noise standards set forth herein for various land uses or activities to be used for determining traffic noise impacts and the assessment of the need for and type of noise abatement treatment for a particular highway section.

Design Year - the future year used to estimate the probable traffic volume to be used as one of the primary bases for the roadway design. A time 20 years from construction is common for multilane and other major projects. Periods of 5 or 10 years are not uncommon for low volume roads.

Developed Land Uses or Activities - those tracts of land or portions thereof which contain improvements or activities devoted to frequent human use or habitation. The date of issue of a building permit (for improvements under construction or subsequently added) establishes the date of existence. Park lands in categories A and B of Table 1, Appendix B, include all such lands (public and private) which are actually used as parks on the date the highway location is approved and those public lands formally set aside or designated for such use by a governmental agency. Activities such as farming, mining, and logging are not considered developed activities. However, the associated residences could be considered as a developed portion of the tract.

Highway Section - a substantial length of highway between logical termini (major crossroads, population centers, major traffic generators, or similar major highway control elements) as normally included in a single location study.

L_{10} - the sound level that is exceeded 10 percent of the time (the 10th percentile) for the period under consideration. This value is an indicator of both the magnitude and frequency of occurrence of the loudest noise events.

Level of Service C - traffic conditions (used and described in the Highway Capacity Manual-Highway Research Board, Special Report 87) where speed and maneuverability are closely controlled by high volumes, and where vehicles are restricted in freedom to select speed, change lanes, or pass.

Location Approval - the approval (described in PPM 20-8) given by the FHWA (at the request of a State Highway Department) based upon a location study report and a corridor public hearing or opportunity therefor. This action establishes a particular location for a highway section and is prerequisite to authorization to proceed with the design. (Concurrent location and design approval is sometimes given for projects involving upgrading existing roads. In these instances, location approval is not a prerequisite to authorization of design.)

Noise Level - the weighted sound pressure level obtained by the use of a metering characteristic and weighting A as specified in American National Standard Specification S1.4-1971. The abbreviation herein used is dBA.

Operating Speed - the highest overall speed at which a driver can travel on a given highway under favorable weather conditions and under prevailing traffic conditions without at any time exceeding the safe speed as determined by the design speed on a section-by-section basis.

Project Development - studies, surveys, coordination, reviews, approvals, and other activities normally conducted during the location and design of a highway project.

Truck - a motor vehicle having a gross vehicle weight greater than 10,000 pounds and buses having a capacity exceeding 15 passengers.

NOISE STANDARDS

1. Design Noise Level/Land Use Relationship

a. The design noise levels in Table 1 (page B-4) are to be used during project development of a highway section to determine highway traffic noise impacts associated with different land uses or activities in existence at the time of location approval. In addition, the table is to be used to determine the need for abatement measures for traffic generated noise for developed land uses and activities in existence at the time of location approval. Exceptions to the design noise levels may be granted on certain types of highway improvements or portions thereof when the conditions outlined in paragraph 2 are met.

b. The exterior noise levels apply to outdoor areas which have regular human use and in which a lowered noise level would be of benefit. These design noise level values are to be applied at those points within the sphere of human activity (at approximate ear level height) where outdoor activities actually occur. The values do not apply to an entire tract upon which the activity is based, but only to that portion in which the activity occurs. The noise level values need not be applied to areas having limited human use or where lowered noise levels would produce little benefit. Such areas would include but not be limited to junkyards, industrial areas, railroad yards, parking lots, and storage yards.

c. The interior design noise level in Category E applies to indoor activities for those situations where no exterior noise sensitive land use or activity is identified. The interior design noise level in Category E may also be considered as a basis for noise abatement measures in special situations when, in the judgment of FHWA, such consideration is in the best public interest. In the absence of noise insulating values for specific structures, interior noise level predictions may be estimated from the predicted outdoor noise level by using the following noise reduction factors:

Building Type	Window Condition	Noise Reduction Due to Exterior of the Structure	Corresponding Highest Exterior Noise Level Which Would Achieve an Interior Design Noise Level of 55 dBA
All	Open	10 dB	65 dBA
Light Frame	Ordinary Sash		
	Closed	20	75
	With Storm Windows	25	80
Masonry	Single Glazed	25	80
Masonry	Double Glazed	35	90

Noise reduction factors higher than those shown above may be used when field measurements of the structure in question indicate that a higher value is justified. In determining whether to use open or closed windows, the choice should be governed by the normal condition of the windows. That is, any building having year round air treatment should be treated as the closed window case. Buildings not having air conditioning in warm and hot climates and which have open windows a substantial amount of time should be treated as the open window case.

2. Exceptions

a. The design noise levels set out in these standards represent the highest desirable noise level conditions. State highway departments shall endeavor to meet the design noise levels in planning, locating, and designing highway improvements. However, there may be sections of highways where it would be impracticable to apply noise abatement measures. This could occur where abatement measures would not be feasible or effective due to physical conditions, where the costs of abatement measures are high in relation to the benefits achieved or where the measures required to abate the noise condition conflict with other important values, such as desirable esthetic quality, important ecological conditions, highway safety, or air quality.

b. A request for an exception to the design noise levels can be approved by the FHWA provided the highway agency has supported its request by a written summary report demonstrating that the following steps have been taken and outlining the results.

(1) Identified noise sensitive land uses along the section of highway in question which are expected to experience future highway traffic noise levels in excess of the design levels.

(2) Thoroughly considered all feasible measures that might be taken to correct or improve the noise condition.

(3) Weighed the costs or effects of the noise abatement measures considered against the benefits which can be achieved as well as against other conflicting values such as economic reasonableness, esthetic impact, air quality, highway safety, or other similar values, and thereby established that reduction of noise levels to desirable design levels is not in the best overall public interest for that particular highway section.

These decisions must ultimately be based upon case-by-case judgment. However, every effort should be made to obtain detailed information on the costs, benefits and effects involved to assure that final decisions are based on a systematic, consistent and rigorous assessment of the overall public interest.

(4) Considered lesser measures that could result in a significant reduction of noise levels though not to the design levels, and included such partial measures in the plans and specifications to the extent that they meet the test of economic reasonableness, practicability, and impact on other values, in the same manner as outlined in paragraph 2b(3).

c. In reviewing request for exception, the FHWA will give consideration to the type of highway and the width of the right-of-way. New freeway projects and most projects for the major reconstruction or upgrading of freeways allow for the use of noise control measures. Noise control measures are progressively more difficult to apply on other highways, particularly on local roads and streets because of numerous points of access, at-grade intersections, limited ability to acquire additional right-of-way as buffer zones, and the impossibility of altering roadway grades, constructing noise barriers and taking advantage of the terrain and other natural features.

d. Except in the most unusual situations, exceptions will be approved when the predicted traffic noise level from the highway improvement does not exceed the existing ambient noise level (originating from other sources) for the activity or land use in question.

3. Noise Level Predictions

a. Noise levels to be used in applying these standards shall be obtained from a predictive method approved by the FHWA. The predictive method and the noise level predictions should account for variations in traffic characteristics (volume, speed, and truck traffic), topography (vegetation, barriers, height, and distance), and roadway characteristics (configuration, pavement type, and grades). In predicting the noise levels, the following traffic characteristics shall be used:

(1) Automotive volume - the future volume (adjusted for truck traffic) obtained from the lesser of the design hourly volume or the maximum volume which can be handled under traffic level of service C conditions. For automobiles, level of service C is considered to be the combination of speed and volume which creates the worst noise conditions. For those highway sections where the design hourly volume or the level of service C condition is not anticipated to occur on a regular basis during the design year, the average hourly volume for the highest 3 hours on an average day for the design year may be used.

(2) Speed - the operating speed (as defined in the Highway Capacity Manual) which corresponds with the design year traffic volume selected in paragraph 3a(1) and the truck traffic predicted from paragraph 3a(3). The operating speed must be consistent with the volume used.

(3) Truck volume - the design hourly truck volume shall be used for those cases where either the design hourly volume or level of service C was used for the automobile volume.

Where the average hourly volume for the highest 3 hours on an average day was used for automobile traffic, comparable truck volumes should be used.

b. There are instances where activities associated with a particular land use (such as churches, schools, and resort hotels or residences) do not coincide with design hourly volumes. This may be particularly true when the design hourly volumes are seasonally oriented or where the activity associated with the land use is somewhat infrequent. There are other instances where changes in land use can be reasonably expected to occur before design year volumes are realized. In such instances, State highway agencies may request approval to compute noise predictions using traffic characteristics different from those specified in paragraph 3a. Such requests should be made on a project-by-project basis and should be accompanied by a justification.

US. DOT
Should be used
as maximum values

TABLE 1

DESIGN NOISE LEVEL/LAND USE RELATIONSHIPS

Land Use Category	Design Noise Level - L_{10}	Description of Land Use Category
A	60dBA (Exterior)	Tracts of lands in which serenity and quiet are of extraordinary significance and serve an important public need, and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose. Such areas could include amphitheaters, particular parks or portions of parks, or open spaces which are dedicated or recognized by appropriate local officials for activities requiring special qualities of serenity and quiet.
B	70 dBA (Exterior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, picnic areas, recreation areas, playgrounds, active sports areas, and parks.
C	75 dBA (Exterior)	Developed lands, properties or activities not included in categories A and B above.
D	--	For requirements on undeveloped lands see paragraphs 5a(5) and (6), this PPM.
E*	55 dBA (Interior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals and auditoriums.

* See paragraph 1c of this Appendix for method of application.