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Measurement of Highway-Related Noise

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FOREWORD

Noise is an important environmental consideration for highway planners and designers. It can annoy and cause psychological or physiological harm, depending on frequency characteristics and loudness. The U.S. Department of Transportation and State transportation agencies are charged with the responsibility of optimizing compatibility of highway operations with environmental concerns. Highway noise problems have been addressed by numerous investigations, including evaluations of the following:

(1) noise sources and highway noise reference energy mean emission levels;
(2) noise impacts at receptor locations;
(3) effects of site geometry, meteorology, ground surface conditions, and barriers on noise propagation; and
(4) alternative methods of mitigating noise impacts.

Precise, uniform, state-of-the-art, highway traffic noise measurement procedures for assessing impacts in the vicinity of roadways, and designing effective, cost-efficient noise barriers, are a recognized need in the highway noise community.

This report provides Federal, State, and local transportation agencies with a set of standardized procedures for measuring and assessing highway-related noise. It replaces "Sound Procedures for Measuring Highway Noise" published by the FHWA in 1981.

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The U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Highway Administration (FHWA), Office of Environment and Planning, has developed the “Measurement of Highway-Related Noise.” This document reflects significant improvements and changes in noise measurement technologies that have evolved since the 1981 FHWA publication, Sound Procedures for Measuring Highway Noise.

This report documents the recommended procedures for the measurement of (1) existing noise; (2) vehicle noise emissions; (3) barrier insertion loss; (4) construction equipment noise; (5) noise reduction due to buildings; and (6) occupational noise exposure.

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conversion chart

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1. INTRODUCTION

The U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Highway Administration (FHWA), Office of Environment and Planning, has developed the “Measurement of Highway-Related Noise.” This document reflects substantial improvements and changes in noise measurement technologies that have evolved since the 1981 FHWA publication, Sound Procedures for Measuring Highway Noise.

Section 1 presents a general overview, as well as an historical perspective. Section 2 presents definitions of terminology used throughout the document. Section 3 presents field measurement instrumentation generalized to subsequent sections of the document. Section 4 describes the recommended practice for performing existing-noise measurements in the vicinity of a highway. Section 5 describes the recommended practice for the measurement of vehicle noise emissions for use with highway noise prediction models. Section 6 describes the procedures for the measurement of highway barrier insertion loss. Section 7 describes the procedures for the measurement of construction equipment noise for highway-related projects. Section 8 describes the procedures for the measurement of the noise reduction performance of buildings in the vicinity of a highway. Section 9 describes the measurement of highway-related occupational noise exposure. Section 10 details the recommended information for properly documenting final reports prepared in support of a highway project.

1.1 BACKGROUND

Noise is an important environmental consideration for highway planners and designers. Transportation agencies measure different aspects of highway noise to determine or predict community impacts during urban planning. However, measurement instrumentation and procedures have varied from program to program and agency to agency.[1] Precise, uniform, field measurement practice allows for valid comparison of results from similar studies performed by a variety of transportation practitioners and researchers.

Sound Procedures for Measuring Highway Noise was written over a decade ago. Since then, substantial advancements have been made in the methodology and technology of noise measurement, barrier analysis and design, and noise measurement instrumentation. In addition, highway noise modeling software has recently improved. The Federal Highway Administration has replaced the STAndard Method In Noise Analysis (STAMINA, Version 2.0)[2] with the FHWA Traffic Noise Model (FHWA TNM®), Version 1.0.[3] The FHWA TNM uses a Microsoft Windows-based interface and includes a 1994/1995 Reference Energy Mean Emission Level (REMEL) data base,[4] as well as state-of-the-art acoustic algorithms. Consequently, the FHWA identified the need to develop and document a new highway-traffic noise measurement document which reflects these recent advancements.

1.2 OBJECTIVE

The objective of this document is to provide a uniform, state-of-the-art reference for highway noise practitioners and researchers, which addresses measurement and analysis instrumentation, site selection, measurement procedures, and data reduction and analysis techniques. Each of these topics is addressed separately for each of the following areas of concern:

(1) Existing-noise in the vicinity of a highway (Section 4);
(2) Vehicle noise emissions for use with highway noise prediction models (Section 5);
(3) Highway barrier insertion loss (Section 6);

(4) Construction equipment noise for highway-related projects Section 7);

(5) Noise reduction due to buildings in the vicinity of a highway (Section 8); and

(6) Highway-related occupational noise exposure (Section 9).

2. TERMINOLOGY

This section presents pertinent terminology used throughout the document. These terms are highlighted with boldface type when they first appear in subsequent sections. Note: Definitions are generally consistent with those of the American National Standards Institute (ANSI) and References 5 through 8.

A-WEIGHTING: A frequency weighting network used to account for changes in sensitivity as a function of frequency (See Section 3.1.3.4.2).

ABSORPTION COEFFICIENT: See Sound absorption coefficient.

ACOUSTIC ENERGY: Commonly referred to as sound energy, or just plain energy, acoustic energy is arithmetically equivalent to $10^{[\text{Sound Pressure level (SPL)}/10]}$, where SPL is expressed in decibels re 20 :Pa.

AMBIENT NOISE: All-encompassing sound that is associated with a given environment, excluding the analysis system's electrical noise and the sound source of interest.

ARTIFICIAL NOISE SOURCE: An acoustical source that is controlled in position and calibrated as to output power, spectral content, and directivity.

AUDIOMETRY: The measurement of human hearing acuity.

ANTI-ALIAS FILTER: A low-pass filter applied to the input signal of a digital system prior to the digitization process. This filter, unique to digital systems, ensures that spurious signals (alias signals) resulting from the digitization process are not contributing components of the sampled signal. An anti-alias filter must be included in all digital systems, prior to the analog-to-digital conversion.

BACKGROUND NOISE: All-encompassing sound of a given environment that includes ambient, as well as analysis system noise, excluding the sound source of interest.

COMMUNITY-NOISE EXPOSURE LEVEL (CNEL, denoted by the symbol L_{den}): A 24-hour time-averaged L_{AE} (see definition below), adjusted for average-day sound source operations. In the case of highway noise, a single operation is equivalent to a single vehicle pass-by. The adjustment includes a 5-dB penalty for vehicle pass-bys occurring between 1900 and 2200 hours, local time, and a 10-dB penalty for those occurring between 2200 and 0700 hours, local time. The L_{den} noise descriptor is used primarily in the state of California. L_{den} is computed as follows:

$$L_{den} = L_{AE} + 10*\log_{10}(N_{day} + 3*N_{eve} + 10*N_{night}) - 49.4 \qquad \text{(dB)}$$

where:

L_{AE} = Sound exposure level in dB (See definition below);

N_{day} = Number of vehicle pass-bys between 0700 and 1900 hours, local time;

N_{eve} = Number of vehicle pass-bys between 1900 and 2200 hours, local time;

N_{night} = Number of vehicle pass-bys between 2200 and 0700 hours, local time; and

49.4 = A normalization constant which spreads the acoustic energy associated with highway vehicle pass-bys over a 24-hour period, i.e., $10*\log_{10}$(86,400 seconds per day) = 49.4 dB.

CONTAMINATION: (See Noise Contamination).

DAY-NIGHT AVERAGE SOUND LEVEL (DNL, denoted by the symbol L_{dn}): A 24-hour time-averaged L_{AE} (See definition on Page 14), adjusted for average-day sound source operations. In the case of highway noise, a single operation is equivalent to a single vehicle pass-by. The adjustment includes a 10-dB penalty for vehicle pass-bys occurring between 2200 and 0700 hours, local time. L_{dn} is computed as follows:

$$L_{dn} = L_{AE} + 10*\log_{10}(N_{day} + N_{eve} + 10*N_{night}) - 49.4 \quad \text{(dB)}$$

where:

L_{AE} = Sound exposure level in dB (See definition on Page 14);

N_{day} = Number of vehicle pass-bys between 0700 and 1900 hours, local time;

N_{eve} = Number of vehicle pass-bys between 1900 and 2200 hours, local time;

N_{night} = Number of vehicle pass-bys between 2200 and 0700 hours, local time; and

49.4 = A normalization constant which spreads the acoustic energy associated with highway vehicle pass-bys over a 24-hour period, i.e., $10*\log_{10}$(86,400 seconds per day) = 49.4 dB.

DECIBEL (dB): A unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the base 10 logarithm of this ratio. For the purpose of this document, the reference level is 20 :Pa, or the threshold of human hearing.

DIFFRACTED WAVE: A sound wave whose front has been changed in direction by an obstacle in the propagation medium, typically air for the purposes of this document.

DIVERGENCE: The spreading of sound waves from a source in a free field environment. In the case of highway noise, two types of divergence are common, spherical and cylindrical. Spherical divergence is that which would occur for sound emanating from a point source, e.g., a single vehicle pass-by. It is independent of frequency, and is computed using a $20*\log_{10}(d1/d2)$ relationship. For example, if the sound level from a point source at 15 m was 90 dB, at 30 m it would be 84 dB due to divergence, i.e., $90 + 20*\log_{10}(15/30)$. Cylindrical divergence is that which would occur for sound emanating from a line source, e.g., a single vehicle pass-by. It is independent of frequency, and is computed using a $10*\log_{10}(d1/d2)$ relationship. For example, if the sound level from a point source at 15 m was 90 dB, at 30 m it would be 87 dB due to divergence, i.e., $90 + 10*\log_{10}(15/30)$.

DOPPLER EFFECT: The change in the observed frequency of a wave in a transmission system caused by a time rate of change in the effective length of the path of travel between the source and the point of observation.

DYNAMIC RANGE: The difference between the highest input sound pressure level achievable without exceeding a specified non-linearity or distortion of the output signal, for a specified frequency range, and the lowest input sound pressure level for which the level linearity is within specified tolerances.

EQUIVALENT SOUND LEVEL (TEQ, denoted by the symbol L_{AeqT}): Ten times the base-10 logarithm of the ratio of time-mean-squared instantaneous A-weighted sound pressure, during a stated time interval, T (where $T=t_2-t_1$), to the square of the standard reference sound pressure. For the purpose of this document, the reference sound pressure is 20

:Pa, or the threshold of human hearing. L_{AeqT} is related to L_{AE} by the following equation:

$$L_{AeqT} = L_{AE} - 10*\log_{10}(t_2-t_1) \qquad \text{(dB)}$$

where:

L_{AE} = Sound exposure level in dB (See definition on Page 14).

EXCHANGE RATE: The amount a sound level is increased or decreased to preserve a certain noise exposure when the exposure duration is doubled or halved. Typically, for transportation-related noise, an exchange rate of 3 dB is used; for occupational noise exposure, 5 dB is used.

FAR-FIELD: That portion of a point source's sound field in which the sound pressure level (due to this sound source) decreases by 6 dB per doubling of distance from the source, i.e., spherical divergence; or if the sound source is linear, then the far-field is the portion of the sound field in which the sound pressure level decreases by 3 dB per doubling of distance.

FREE FIELD: A sound field whose boundaries exert a negligible influence on the sound waves. In a free-field environment, sound spreads spherically from a source and decreases in level at a rate of 6 dB per doubling of distance from a point source, and at a rate of 3 dB per doubling of distance from a line source.

GROUND ATTENUATION: The change in sound level, either positive or negative, due to intervening ground between source and receiver. Ground attenuation is a relatively complex acoustic phenomenon, which is a function of ground characteristics, source-to-receiver geometry, and the spectral characteristics of the source. A commonly used rule-of-thumb for propagation over soft ground (i.e., grass, terrain) is that ground effects will account for about 1.5 dB per doubling of distance. However, this relationship is quite empirical and tends to break down for distances greater than about 30 to 61 m (100 to 200 ft).

GROUND IMPEDANCE: A complex function of frequency relating the sound transmission characteristics of a ground surface type. Measurements to determine ground impedance must be made in accordance with the ANSI Standard for measuring ground impedance scheduled for publication in the second half of 1996.[50]

HARD GROUND: Any highly reflective surface in which the phase of the sound energy is essentially preserved upon reflection; examples includes water, asphalt and concrete.

INSERTION LOSS (IL): The difference in levels before and after installation of a barrier, where the source, terrain, ground, and atmospheric conditions have been judged as equivalent.

L_{AE}: See Sound exposure level.

L_{Aeq}: See Equivalent sound level.

L_{AFmx} and L_{ASmx}: See Maximum sound level.

L_{den}: See Community-noise exposure level.

L_{dn}: See Day-night average sound level.

L_{90}: A statistical descriptor describing the sound level exceeded 90 percent of a measurement period.

LINE SOURCE: Multiple point sources moving in one direction radiating sound cylindrically. Note: Sound levels measured from a line source decrease at a rate of 3 dB per doubling of distance.

LOWER BOUND TO INSERTION LOSS: The value reported for insertion loss when background levels are not measured or are too high to determine the full attenuation potential of the barrier.

MAXIMUM SOUND LEVEL (MXFA or MXSA, denoted by the symbol L_{AFmx} or L_{ASmx}, respectively): The maximum, A-weighted sound level associated with a given event (See Figure 1). Fast-scale response (L_{AFmx}) and slow-scale response (L_{ASmx}) characteristics effectively damp a signal as if it were to pass through a low-pass filter with a time constant of 125 and 1000 milliseconds, respectively. See Section 3.1.3.4.4 for a more detailed discussion of exponential time-averaging.

NEAR FIELD: The sound field (between the source and the far field). The near field exists under optimal conditions at distances less than four times the largest sound source dimension.

NOISE: Any unwanted sound.

NOISE BARRIER: The structure, or structure together with other material, that potentially alters the noise at a site from a BEFORE condition to an AFTER condition.

NOISE CONTAMINATION: Any noise event, other than that which is intended for measurement. Contamination typically occurs when the background noise is within 10 dB of the noise produced by the source intended for measurement.*

---

* **Rule-of-Thumb**

NOISE DOSE: A measure of the noise exposure to which a person is subjected in the workplace. For the purposes of this document, the workplace is any highway-related environment.

NOISE REDUCTION COEFFICIENT (NRC): A single-number rating of the sound absorption properties of a material; it is the arithmetic mean of the Sabine absorption coefficients (See below) at 250, 500, 1000, and 2000 Hz, rounded to the nearest multiple of 0.05.

PINK NOISE: A random signal for which the spectrum density, i.e., narrow-band signal, varies as the inverse of frequency. In other words, one-third octave-band spectral analysis of pink noise yields a flat response across all frequency bands.

POINT SOURCE: Source that radiates sound spherically. Note: Sound levels measured from a point source decrease at a rate of 6 dB per doubling of distance.

SABINE ABSORPTION COEFFICIENT ("$_{Sab}$): Absorption coefficient obtained in a reverberation room by measuring the time rate of decay of the sound energy density with and without a patch of the sound-absorbing material under test laid on the floor. These measurements are performed in accordance with the American Society of Testing and Materials (ASTM) Standard C 423-90a.

SOFT GROUND: Any highly absorptive surface in which the phase of the sound energy is changed upon reflection; examples include terrain covered with dense vegetation or freshly fallen snow. (Note: at grazing angles greater than 20 degrees, which can commonly occur at short ranges, or in the case of elevated sources, soft ground becomes a good reflector and can be considered hard ground).*

SOUND ABSORPTION COEFFICIENT ("): (See also Sabine Absorption Coefficient) The ratio of the sound energy, as a function of frequency, absorbed by a surface, to the sound energy incident upon that surface.

SOUND EXPOSURE LEVEL (SEL, denoted by the symbol L_{AE}): Ten times the logarithm to the base 10 of the ratio of a given time integral of squared instantaneous A-weighted sound pressure to the squared reference sound pressure of 20 :Pa, the threshold of human hearing. The time interval must be long enough to include a majority of the sound source's acoustic energy. As a minimum, this interval should encompass the 10 dB down points (See Figure 1).

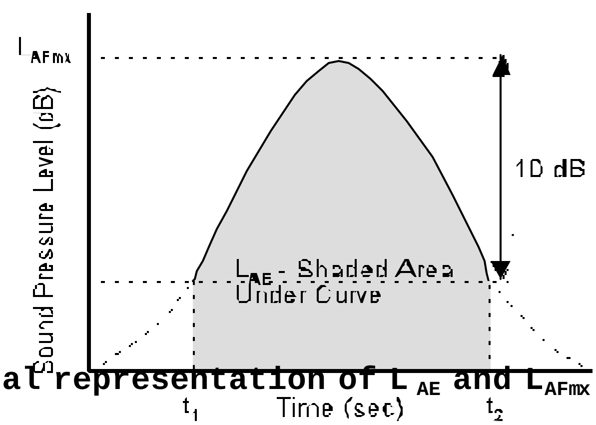


Figure 1. Graphical representation of L_{AE} and L_{AFmx} noise descriptors.

In addition, L_{AE} is related to L_{AeqT} by the following equation:

$$L_{AE} = L_{AeqT} + 10*\log_{10}(t_2-t_1) \qquad \text{(dB)}$$

where L_{AeqT} = Equivalent sound level in dB (See definition above).

*** Rule-of-Thumb**

SOUND PRESSURE LEVEL (SPL): Ten times the logarithm to the base 10 of the ratio of the time-mean-squared pressure of a sound, in a stated frequency band, to the square of the reference sound pressure of 20 :Pa, the threshold of human hearing.

SOUND TRANSMISSION CLASS (STC): A single-number rating used to compare the sound insulation properties of barriers.

SPECTRUM: A signal's resolution expressed in component frequencies or fractional octave bands.

3. INSTRUMENTATION

This section describes field measurement instrumentation, acoustic and otherwise. It also includes a list of instrumentation manufacturers.

3.1 ACOUSTIC INSTRUMENTATION

Figure 2 presents a generic, acoustic-measurement-instrumentation setup. Subsequent subsections address individual components of this generic setup.

All acoustic instrumentation should be calibrated annually by its manufacturer, or other certified laboratory to verify accuracy. Where applicable, all calibrations shall be traceable to the National Institute of Standards and Technology (NIST).

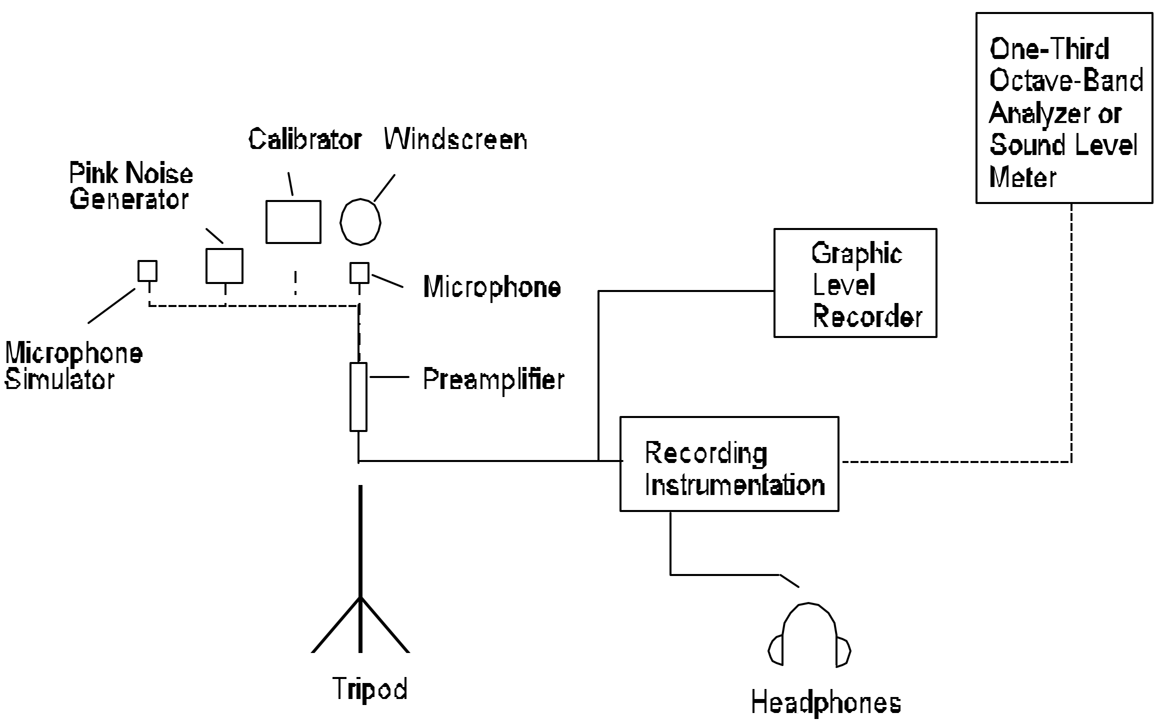


Figure 2. Generic measurement instrumentation setup.

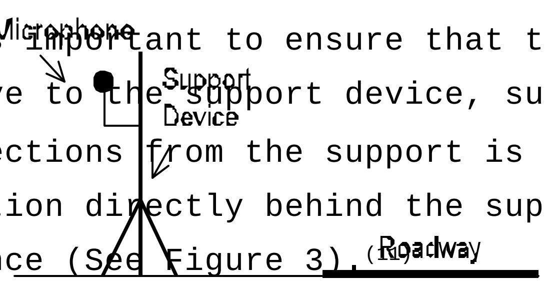
3.1.1 Microphone System (Microphone and Preamplifier)

A microphone transforms sound-pressure variations into electrical signals, that are in turn measured by instrumentation such as a sound level meter, a one-third octave-band spectrum analyzer, or a graphic level recorder. These electrical signals are also often recorded on tape for later off-line analysis. Microphone characteristics are further addressed in ANSI S1.4-1983.[9]

A compatible preamplifier, if not engineered as part of the microphone system, should also always be used. A preamplifier provides high-input impedance and constant, low-**noise*** amplification over a wide frequency range.[10] Also, depending upon the type of microphone being used (See Section 3.1.1.1), a preamplifier may also provide a polarization voltage to the microphone.

The microphone system (microphone and preamplifier) should be supported using a tripod or similar device, such as an anchored conduit. Care should be taken to isolate the microphone system from the support, especially if the support is made up of a metal composite. In certain environments, the support can act as an antenna, picking up errant radio frequency interference which can potentially contaminate data. Common isolation methods include encapsulating the microphone system in nonconductive material (e.g., nylon) prior to fastening it to the support.

In addition, it is important to ensure that the microphone system is positioned relative to the support device, such that **contamination** due to sound reflections from the support is minimized. Research has shown that a position directly behind the support device provides for minimum interference (See Figure 3).[11]



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* As previously noted, all terms defined in the Terminology section are highlighted when they first appear in the main body of the text of this document.

Figure 3. Recommended microphone position relative to support device.

Once supported appropriately, the microphone should be positioned as discussed in Section 3.1.1.3. The microphone system should then be connected to the measuring/recording instrumentation via an extension cable. At least 15 m (50 ft) of cable is recommended. Thus, any potential contamination of the measured data due to operator activity can be minimized.

3.1.1.1 Microphone Type

Condenser (or electrostatic or capacitor) microphones are recommended for a wide range of measurement purposes because of their high stability, reasonably high sensitivity, excellent response at high frequencies, and very low electrical noise characteristics. There are two types of condenser microphones: conventional and electret.

Conventional condenser microphones characterize magnitude changes in sound pressure in terms of variations in electrical capacitance. Sound pressure changes incident upon the diaphragm of a microphone change the spacing between the diaphragm and the microphone backplate. This dynamic change in the gap between the diaphragm and backplate translates to a change in electrical capacitance.

In the case of a conventional condenser microphone, a polarization voltage must be applied to the backplate. Typically, a polarization voltage of between 50 and 200 V is applied to the microphone backplate by the preamplifier. Due to the requirement that a polarization voltage be supplied from a source external to the microphone, i.e., the microphone is not a “closed” system, measurements made with a conventional condenser microphone are often adversely effected by atmospheric conditions, especially high humidity. High humidity can result in condensation between the microphone diaphragm and backplate. Condensation can cause arcing of the polarization voltage, rendering the measured data essentially useless.(8,12) To minimize condensation effects, the use of dehumidifying chambers, desiccants, and nonconductive back coating, such as quartz, can be used. Several manufacturers provide devices to minimize this often-overlooked potential problem.

Electret condenser microphones, on the other hand, use a thin plastic sheet with a conductive coating on one side as a backplate. This design allows the microphone to maintain its own polarization, i.e., often referred to as a “pre-polarized” design.(10) "Pre-polarization" allows the electret microphone to be essentially a “closed” system, eliminating the potential for condensation in high-humidity environments.

One drawback to electret microphones is they are often less sensitive at high frequencies. In addition, there are currently no electret microphones known to the authors which provide nearly flat response characteristics at grazing incidence, which is the incidence of choice for transportation-related noise measurements (See Section 3.1.1.3).

3.1.1.2 Microphone Size

The diameter of a microphone diaphragm directly affects its useable frequency range, **dynamic range** (or level sensitivity), and directivity. For example, as the microphone diameter becomes smaller, the useable frequency range increases; however, sensitivity decreases.[8,13] Thus, the selection of a microphone size often involves a compromise of these elements. Unless measurements at extremely low **sound pressure levels** (SPL) are required (e.g., below 20 dB SPL) a ½-in (1.27 cm) diameter microphone, or d-in (0.95 cm) microphone as characterized by some manufacturers, is suitable for most situations. For low-SPL measurements, a 1-in diameter microphone may be necessary.

3.1.1.3 Microphone Incidence

The sensitivity of a microphone varies with the angle of incidence between the sound waves and the microphone diaphragm. Two microphone system orientations and their specific applications are discussed below: normal and grazing incidence.

Normal incidence, also referred to as 0-degrees incidence, occurs when sound waves impinge at an angle perpendicular, or normal, to the microphone diaphragm (See Figure 4). It is best used for situations involving point-source measurements, in which the sound being measured is coming from a stationary, single, known direction (e.g., an idling automobile or a power generator).

Grazing incidence, also referred to as 90-degrees incidence, occurs when sound waves impinge at an angle that is parallel to, or grazing, the plane of the microphone diaphragm (See Figure 4). This orientation is preferred for moving, or line-source, measurements, since the microphone presents a constant incidence angle to any source located within the plane of the microphone diaphragm.[8]

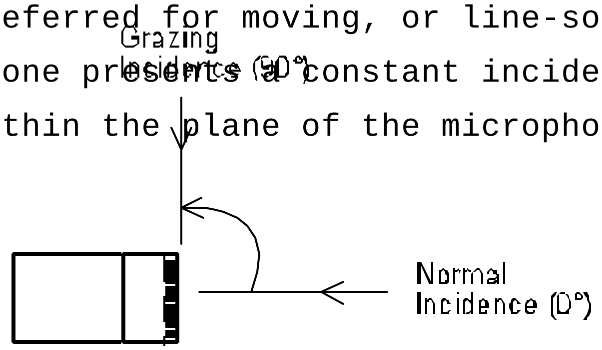

Figure 4. Microphone incidence.

Grazing incidence is commonly used for the measurement of highway, aircraft, and guided-transit noise. If other than grazing incidence is used for the measurement of moving noise sources, correction of the measured data in accordance with manufacturer-published response curves is required. This process can be quite complex because the incidence angle is continually changing, thus requiring continuously varying corrections. It is perfectly acceptable to position a microphone for grazing incidence even if it has its flattest frequency response characteristics in a normal incidence configuration, as long as the appropriate manufacturer-published corrections are applied, and as long as the required corrections do not exceed certain limits.(14) If the manufacturer does not provide the appropriate incidence corrections, testing must be performed in accordance with ANSI S1.10-1986.(15)

For the unique situation of measuring randomly occurring sounds, such as the case with **ambient noise** measurements, or existing-noise measurements where the location of the sound source can be arbitrary, microphone corrections should be based on random-incidence response curves.

3.1.2 Recording System

Components of the measurement system are discussed separately in Section 3.1.3, so as to make a distinction between the actual recorded data, as would be heard by the human ear, and the actual sound level data computed as a result of some form of electrical/ arithmetic process.

There are two basic types of tape recorders: analog and digital. Analog recorders store signals as continuous variations in the magnetic state of the particles on the tape. Digital recorders store signals as a combination of binary “1s” and “0s.” Most digital recorders represent a continually varying analog level using many discrete 16-bit words, i.e., a unique combination of 16 “1s” and “0s.” The number of 16-bit words depends upon the sampling rate of the particular recorder.

The sampling rate must be at least twice the highest frequency of interest, which is often 20 kHz for transportation-related measurements. In theory, this means that one second of continuously varying analog data is represented by at least 40,000 discrete 16-bit combinations of “1s” and “0s.” However, practically, due to the design limitations on **anti-alias filters** (anti-alias filters are described later in this section), a sampling rate of 44,000 to 48,000 is common, i.e., 44,000 to 48,000 discrete 16-bit combinations of “1s” and “0s.”

Not all field measurement systems will include a tape recorder. A recorder offers the unique capability of repeated playback of the measured noise source, thus allowing for more detailed analyses. The electrical characteristics of a tape recorder shall conform to the guidelines set in IEC 1265 and ANSI S1.13-1971 for frequency response and signal-to-noise ratio.[14,16]

The advantages of modern digital over analog recorders are numerous. Digital recorders typically have much wider frequency response characteristics, as well as a much larger dynamic range. About the only advantage analog recorders have is that they typically are less expensive, although the cost difference is decreasing.

When selecting a specific model of tape recorder, there are three important issues and/or differences associated with the use of digital versus analog recorders that require consideration. They are as follows:

- Anti-Alias Filters: An anti-alias filter is a low-pass filter applied to the input signal of a digital system prior to the digitization process. This filter, unique to digital systems, ensures that spurious signals (alias signals) resulting from the digitization process are not contributing components of the sampled signal. An anti-alias filter must have attenuation characteristics which ensure the contribution of aliased frequency components in the output are reduced to a negligible level.[17,18]

- System Overloads: The overload point in a digital system is a well-defined point controlled by the maximum size of the bit-register used in the digitization process. When the size of the bit-register is exceeded, "hard" limiting occurs, followed by instantaneous distortion. In most cases, the dynamic range of a digital recorder is specified from this "hard" limiting point, and the overload and full-scale indicators are referenced to it.

  In contrast, analog recorders have no clearly defined overload point and generally "soft" limiting (a gradual process) begins around 6 dB above the full scale (0 dB) on a volume unit (VU) meter, with the subsequent gradual increase in distortion.

  A safety margin of at least 10 dB, and preferably 20 dB, between the overload point and the expected maximum level of the data to be digitally recorded, including calibration data, should be maintained.

- Dynamic Range: A substantial advantage of digital recorders is that they offer an extended dynamic range, resulting in an extended operating range available. Dynamic range is typically specified from the "hard" overload point, and to guard against overload, a 10- to 20-dB safety margin is recommended, thus reducing the effective operating range by 10 to 20 dB. Additionally, the amplitude linearity error of a digital recorder increases as signal levels decrease, thus, reducing the effective operating range of the recorder. This is also true of analog recorders.

3.1.3 Measurement System

There are three general acoustic measurement systems discussed in this section: graphic level recorders (GLRs), sound level meters (SLMs), and one-third octave-band analyzers.

3.1.3.1 Graphic Level Recorder

A graphic level recorder (GLR) connected to the analog output of the measuring or recording instrumentation is typically used in the field to provide a visual, real-time history of the measured noise level. A GLR plot varies in level at a known, constant pen-speed rate and response time that may be adjusted to approximate exponential time-averaging, i.e., fast-scale and slow-scale response characteristics (See Section 3.1.3.4.4).[10] It is valuable in visually judging ambient levels and verifying the acoustic integrity of individual events.

3.1.3.2 Sound Level Meter

For the purposes of all measurements discussed herein, sound level meters (SLMs) should perform true numeric integration and averaging in accordance with ANSI S1.4-1983.[9] Components of an SLM include

(See Figure 5): a microphone with preamplifier, an amplifier, frequency weighting (See Section 3.1.3.4.2), input gain control (See Section 3.1.3.4.3), time-averaging (See Section 3.1.3.4.4), and an output indicator or display.[8] Selection of a specific model of sound level meter should be based upon cost and the level of accuracy desired.

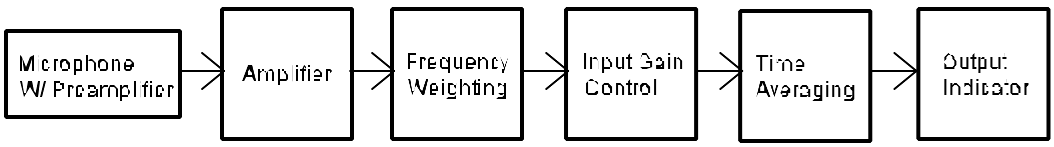

Figure 5. Components of a sound level meter.

The accuracy of an SLM is characterized by its "type." There are three types of sound level meters available: Types 0, 1, and 2. Type 0 sound level meters are used for laboratory reference purposes, where the highest precision is required. Type 1 sound level meters are designed for precision field measurements and research.[9] Either Type 1 or Type 2 sound level meters are acceptable for use in traffic noise analyses for Federal-aid highway projects.

3.1.3.3 One-Third Octave-Band Analyzer

When the frequency characteristics of the sound source being measured are of concern, a one-third octave-band analyzer should be employed. In most cases, such a unit would not be employed directly in the field, but would be used subsequent to field measurements in tandem with tape-recorded data (See Section 3.1.2). Such units can be employed to determine noise spectra, as well as compute various noise descriptors, such as L_{AeqT} and L_{AE}. If consistency with previously measured data is desired, one-third octave-band filters must be shown to comply with a Type 1-D Butterworth filter, as defined in ANSI S1.11-1986.[19] The Type 1-D Butterworth filter design has existed in analyzers for decades. However, manufacturers are now providing filter-shape algorithms which depart from the traditional Butter worth design, and more closely resemble “ideal” filters, which allow essentially no energy outside of the pass-band.

Use of octave-band analyzers is not precluded; however, one-third octave-band analysis is preferred.

3.1.3.4 Characteristics of the Measurement System

3.1.3.4.1 Bandwidth

The bandwidth of a measurement instrument refers to its frequency range of operation. Most measurement instrumentation of interest for readers of this document will accurately measure levels in the frequency range 20 Hz to 20 kHz, the audible range for humans. Typically, measurement of one-third octave-band data between 50 Hz and 10 kHz will satisfy the objectives of highway-related studies.

3.1.3.4.2 Frequency Weighting

Frequency weighting is used to account for changes in sensitivity of the human ear as a function of frequency. Three standard weighting networks, A, B, and C, are used to account for different responses to sound pressure levels (See Table 1 and Figure 6).[8,20] Note: The absence of frequency weighting is referred to as "flat" response.

C-weighting is essentially linear. B-weighting reflects the ear's response to sounds of moderate pressure level. **A-weighting** reflects the ear's response to sounds of lower pressure level.[20] A-weighting is the most widely used system for assessing transportation-related noise. In fact, unless otherwise stated, noise descriptors for transportation-related activity are assumed to be A-weighted. Most SLMs and one-third octave-band analyzers offer A- and C-weighting options. B-weighting has essentially become obsolete. Note: It is also important to note that the response for the A-, B-, and C-weighting curves are all referenced to a frequency of 1 kHz. In other words, the weighting at 1 kHz for all three curves is zero.

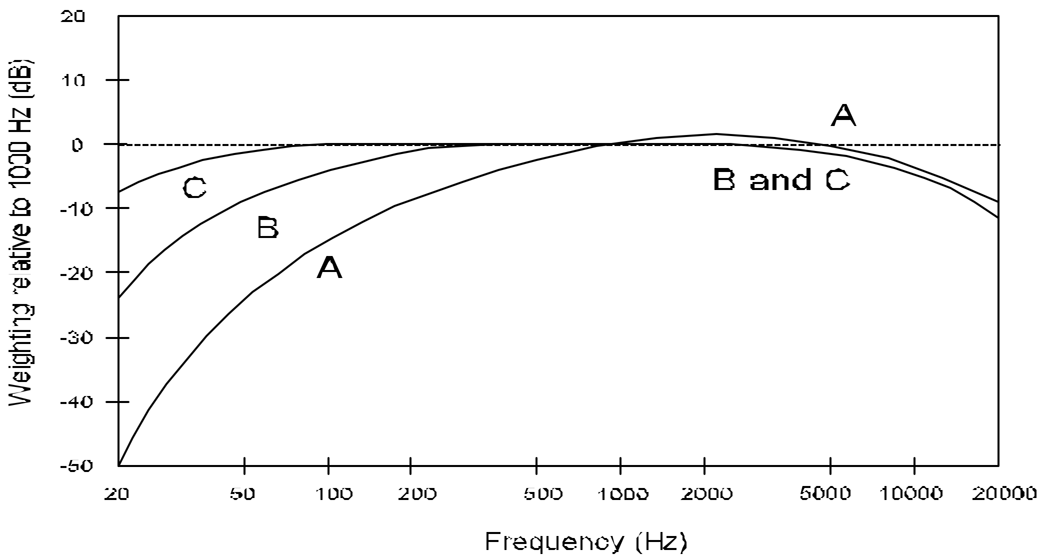

Figure 6. Frequency weighting.

Table 1. Frequency weighting.

One-Third Octave-Band Center Frequency	A	B	C
20	-50.4	-24.2	-6.2
25	-44.8	-20.5	-4.4
31.5	-39.5	-17.1	-3.0
40	-34.5	-14.1	-2.0
50	-30.3	-11.6	-1.3
63	-26.2	-9.4	-0.8
80	-22.4	-7.3	-0.5
100	-19.1	-5.6	-0.3
125	-16.2	-4.2	-0.2
160	-13.2	-2.9	-0.1
200	-10.8	-2.0	0
250	-8.7	-1.4	0
315	-6.6	-0.9	0
400	-4.8	-0.5	0
500	-3.2	-0.3	0
630	-1.9	-0.1	0
800	-0.8	0	0
1000	0	0	0
1250	0.6	0	0
1600	1.0	0	-0.1
2000	1.2	-0.1	-0.2
2500	1.3	-0.2	-0.3
3150	1.2	-0.4	-0.5
4000	1.0	-0.7	-0.8
5000	0.6	-1.2	-1.3
6300	-0.1	-1.9	-2.0
8000	-1.1	-2.9	-3.0
10000	-2.5	-4.3	-4.4
12500	-4.3	-6.1	-6.2
16000	-6.7	-8.5	-8.6
20000	-9.3	-11.2	-11.3

3.1.3.4.3 Input Gain Control

The input gain of a measurement system should be adjusted to provide for maximum dynamic range while preserving a modest safety factor to avoid overload. Dynamic range is the difference in **decibels** between the maximum and minimum levels that can be accurately measured. To avoid system overload, it is recommended that the gain be set such that the expected maximum level of the source being measured is between 10 and 20 decibels below overload. In the absence of a standard that addresses linear operating ranges for general field measurement studies, it is recommended that the linear operating range of the measurement system is in accordance with tolerances specified in IEC 1265, a standard specific to aircraft noise measurement.[14]

3.1.3.4.4 Exponential Time-Averaging

Exponential time-averaging is a method of stabilizing instrumentation response to signals with changing amplitudes over time using a low-pass filter with a known, electrical time constant. The time constant is defined as the time required for the output level to reach 67 percent of the input, assuming a step-function input. Also, the output level will typically reach 100 percent of an input-step-function after approximately five time constants.

The exponential time-averaged output produced by the low-pass filter is a running average dominated by the most recent value but smoothed out by the contribution of the preceding values. Two exponential time-averaging, response settings are applicable for this document: fast and slow, with time constants (J) of 0.125 and 1 second, respectively (See Figure 7).

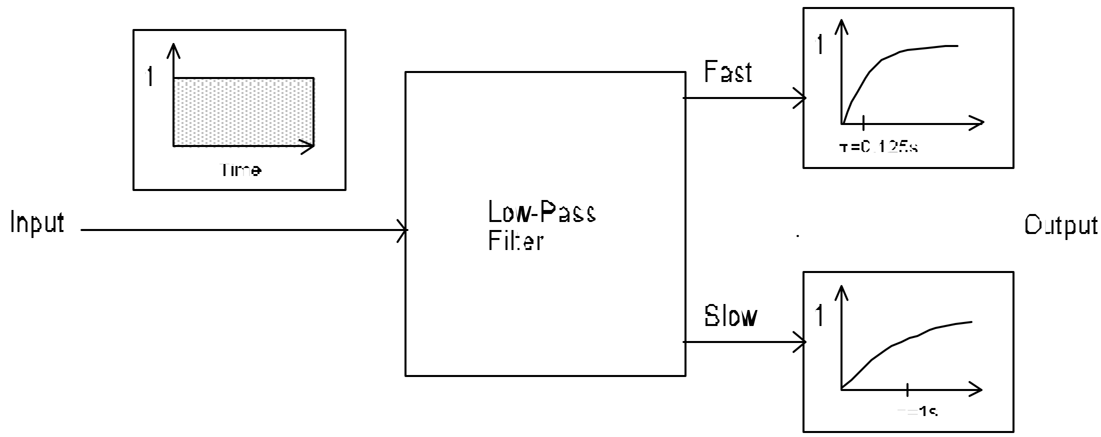

Figure 7. Exponential time-averaging.

Slow response is typically used for measurements of sound source levels which vary slowly as a function of time, such as aircraft. Fast response is typically used for measuring individual highway vehicle pass-bys (See Section 5). Slow response is recommended for the measurement of long-term impact due to highway noise, where impulsive noises are not dominant.

3.1.3.4.5 Temperature and Humidity Effects

Temperature and humidity can affect the sensitivity of many types of instrumentation, including microphones and spectrum analyzers. For example, most current-generation digital audio tape (DAT) recorders have a built-in dew sensor which monitors condensation, and will prevent operation under high-humidity situations. As discussed in Section 3.1.1.1, non-electret condenser microphones are subject to arcing under high-humidity conditions. Also, battery life is substantially shortened when subject to prolonged low temperatures. Manufacturers' recommendations for acceptable temperature and humidity ranges for equipment operation should be followed. Typically, these range from -10°C to 50°C (14°F to 122°F) and from 5 to 90 percent relative humidity.

3.1.4 Calibrator

An acoustic calibrator provides a means of checking the entire acoustic instrumentation system's (i.e., microphone, cables, and recording instrumentation) sensitivity by producing a known sound pressure level (referred to as the calibrator's reference level) at a known frequency, typically 94 or 114 dB at 1 kHz, or 124 dB at 250 Hz. The calibrator used for measurements described herein shall meet the Type 1L performance requirements of IEC 942.[21]

Calibration of acoustic instrumentation must be performed at least at the beginning and end of each measurement session, and before and after any changes are made to system configuration or components. In addition, it is strongly recommended that calibration be performed at hourly intervals throughout the session.

The following procedure should be used to determine calibration (CAL) adjustments prior to data analysis:

! If the final calibration of the acoustic instrumentation differs from the initial calibration by 1 dB or less, all data measured with that system during the time between calibrations should be adjusted by arithmetically adding to the data the following CAL adjustment:

$$\text{CAL adjustment} = \text{reference level} - [(\text{CAL}_{INITIAL} + \text{CAL}_{FINAL}) / 2]$$

For example:

• reference level = 114.0 dB
• initial calibration level = 114.1 dB
• final calibration level= 114.3 dB

Therefore:

CAL adjustment = 114.0-[(114.1+114.3)/2] = -0.2 dB

- If the final calibration of the acoustic instrumentation differs from the initial calibration by greater than 1 dB, all data measured with that system during the time between calibrations should be discarded and repeated; and the instrumentation should be thoroughly checked.

3.1.5 Microphone Simulator

In accordance with ANSI S1.13-1971,[16] the electronic noise floor of the entire acoustic instrumentation system should be established on a daily basis by substituting the measurement microphone with a passive microphone simulator (dummy microphone) and recording the noise floor for a period of at least 30 seconds.

A dummy microphone electrically simulates the actual microphone by providing a known fixed (i.e., passive) capacitance which is equivalent to the minimum capacitance the microphone is capable of providing. This allows for valid measurement of the system's electronic noise floor.

With the microphone removed and the simulator inserted in its place, all input channels of the instrumentation system should be monitored using headphones. Extraneous signals, such as radio interference or hum, can result when the system is located near antennae, power lines, transformers, or power generators. The system can be especially susceptible to such interference when using long cables which essentially act as antennae for such signals. Extraneous signals detected must be eliminated or reduced to a negligible level, i.e., at least 40 dB below the expected maximum level of the noise source being measured. This can usually be accomplished by re-orienting the instrumentation and/or cables, using shorter cable, checking and cleaning grounding contacts, or in a worst-case scenario, moving the instrumentation system away from the source of the interference, if the position of the source is known.

3.1.6 Pink Noise Generator

The frequency response characteristics of the entire acoustic instrumentation system should be established on a daily basis by measuring and storing 30 seconds of **pink noise**. Pink noise is a random signal for which the spectrum density, i.e., narrow-band signal, varies as the inverse of frequency. In other words, one-third octave-band spectral analysis of pink noise yields a flat response across all frequency bands.

3.1.7 Windscreen

Windscreens should be placed atop all microphones used in outdoor measurements. A windscreen is a porous sphere placed atop a microphone to reduce the effects of wind-generated noise on the microphone diaphragm. The windscreen should be clean, dry, and in good condition. A new windscreen is preferred.

Typically, the effect on the measured sound level due to the insertion of a windscreen into an acoustic instrumentation system can be neglected. As an example, Table 2 shows typical response corrections to be applied to the measured data to account for the insertion of a Brüel & Kjær Model 0237 windscreen, the most commonly used windscreen for transportation-related noise measurements, into an acoustic instrumentation system. These corrections should not be considered typical for other model windscreens. If a manufacturer does not provide corrections and high precision measurements are desired, tests in an anechoic chamber would be required.

Table 2. B&K Model 0237 windscreen typical response corrections.[12]

Incidence Angle (°)	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6130	8000	10000
0	-0.1	-0.2	-0.2	-0.3	-0.3	-0.5	-0.6	-0.6	-0.5	0	0	0.1	0.2	0.5
30	-0.2	-0.3	-0.3	-0.4	-0.4	-0.5	-0.5	-0.8	-0.6	0	0.2	0.1	0.5	0.6
60	0	-0.1	-0.2	-0.3	-0.3	-0.4	-0.6	-0.9	-0.8	-0.2	0.4	0.1	0.4	0.6
90	-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8	-0.8	-0.3	0.5	0.6	0.5	1
120	0	0	-0.1	-0.2	-0.3	-0.3	-0.5	-0.7	-0.6	0	0.7	0.5	0.9	1.2
150	0	0	0	0	-0.1	-0.2	-0.3	-0.4	-0.3	0	0.8	0.7	0.6	1.3
180	0	0	-0.1	-0.2	-0.3	-0.4	-0.5	-0.5	-0.4	0	0.5	0.9	0.8	1.4

3.2 METEOROLOGICAL INSTRUMENTATION

When performing any transportation-related noise study, proper documentation of meteorological conditions is essential. This section provides guidance in selecting instrumentation for measuring meteorological conditions.

3.2.1 Anemometer

Recent research has shown that wind speed and direction may affect measured noise levels in the vicinity of a highway.[22,23] These effects typically increase with increasing distance from the noise source.

An anemometer is an instrument used to measure wind speed. Anemometers shall meet the requirements of ANSI S12.18-1994.[7]

For general-purpose measurements at relatively close distances to a noise source, i.e., within 30 m (100 ft), a hand-held, wind-cup anemometer and an empirically observed estimation of wind direction are sufficient to document wind conditions. For research purposes or for measurements where the receiver(s) will be positioned at distances greater than 30 m (100 ft) from the noise source, a high-precision anemometer, capable of measuring wind conditions in three dimensions, integrated into an automated, data-logging weather station, should be used. For all types of measurements, the anemometer should be located at a relatively exposed position and at an elevation approximately equal to that of the highest receiver position.[6]

Except for research purposes, where the study of wind effects on measured data is an integral objective, measurements should not be made when wind speeds exceed 19 km/h (12 mi/h), regardless of direction. A previous study, in which wind data were carefully recorded and analyzed, concluded that wind speeds below 19 km/h have no apparent effect on measurements performed at a distance within 30 m of the noise source.[24]

Wind conditions are also important in judging equivalency for BEFORE and AFTER acoustical measurements -- e.g., during existing-noise measurements (See Section 4)-- and **barrier insertion loss** measurements (See Section 6). It is recommended that BEFORE and AFTER measurements be compared only if the wind class (See Table 3) remains unchanged and the vector components of the average wind velocity (vector wind speed, VWS) from the source to receiver do not differ by more than a certain limit. This limit depends on the accuracy desired and the distance from source to receiver.[6] VWS is computed as follows (Note: A negative VWS indicates the wind is blowing from receiver to source): VWS = COS(Wind Direction) * Wind Speed.

Table 3. Classes of wind conditions.

Wind Class	Vector Component of Wind Velocity (m/s)
upwind	-1 to -5
calm	-1 to +1
downwind	+1 to +5

* Note: 1 m/s = 2.2 mi/h

Specifically, to keep the error due to wind conditions to less than ±1 dB and distances less than 70 m (230 ft), this limit should be 1.0 m/s (2.2 mi/h). If it is desired to keep the acoustical error within ±0.5 dB and distances less than 70 m, at least four BEFORE and four AFTER measurements should be made within the limit of 1.0 m/s (2.2 mi/h). However, these 1.0 m/s (2.2 mi/h) limits are not applicable for a calm wind class when strong winds with a small vector component in the direction of propagation exist. In other words, BEFORE/AFTER measurements in such instances should be avoided.[25]

3.2.2 Thermometer, Hygrometer, and Psychrometer

A thermometer for measuring ambient temperature and a hygrometer for measuring relative humidity should be used in conjunction with all noise measurement studies. An alternative is to use a psychrometer which is capable of measuring both dry and wet bulb temperature. Dry and wet bulb temperatures can then be used to compute relative humidity (See Appendix A).

For general purpose measurements, use of a sling psychrometer is recommended. For research purposes, a high-precision system may be needed, such as an automated, fast-response, data-logging weather station.

The thermometer or other temperature sensor should have an accuracy of ±5 percent or better at full scale. All temperature sensors should be shielded from direct solar radiation. In addition, a variable-height support-device may be necessary for the measurement of temperature profiles.[6]

Temperature and humidity can affect measured sound levels, typically to a much lesser degree than wind. In the case where the noise source is on pavement, such as vehicle emissions (See Section 5), measurements should not be made unless the pavement is dry; emission levels may be influenced by up to 2 dB by moisture on road surfaces.[26]

In addition, atmospheric absorption can substantially reduce measured sound levels, especially at high frequencies in a low temperature, low-humidity environment. As such, it is important to use caution comparing measured data taken under substantially different temperature and humidity conditions, especially when the distance from source to receiver is quite large, or when the sound source is dominated primarily by higher frequencies. It is very difficult to provide general rules-of-thumb, or guidance for quantifying atmospheric absorption because of the many parameters involved; however, there are several standards which provide algorithms for computing such effects.[27,28,29]

3.3 VEHICLE-SPEED DETECTION UNIT

Measured sound levels of transportation-related vehicles are a direct function of vehicle speed. This section discusses various instruments for measuring vehicle speed.

3.3.1 Doppler-Radar Gun

A **Doppler**-radar gun may be used to measure vehicle speed. When using a radar gun, it should be placed at least 120 m (400 ft) upstream of traffic flow, relative to the noise measurement microphone, and directed toward the vehicles as they approach the microphone. This placement has been shown to minimize effects on traffic flow resulting from driver curiosity.[4]

The radar gun should be positioned at a distance of no greater than 10 m (31 ft) from the centerline of the path of the vehicle being measured. This will ensure that the angle subtended by the axis of the radar antenna and the direction of travel of the vehicle will be less than 5 degrees, when the vehicle is at the microphone pass-by point, assuming the 120 m offset distance mentioned above is maintained. The resulting uncertainty in vehicle speed readings, due to angular effects on Doppler accuracy, will not exceed 0.5 km/h (0.28 mi/h) over a speed range from 15 to 110 km/h (10 to 70 mi/h).[30]

Some manufacturers now offer speed guns which are based on laser technology. Such units would also be appropriate for determining vehicle speed.

3.3.2 Stopwatch

A stopwatch may be used to determine vehicle speed. Cones or observers at known distances from one another should be positioned along the roadway. A separation distance of at least 15 m (50 ft) should be maintained. Start/stop the stopwatch at the instants the vehicle reaches the pass-by points. The vehicle's speed is simply determined by dividing the distance by the measured time period. A similar method for determining vehicle speed could also be used in conjunction with a video camera processing a time-synchronized display.

3.3.3 Light Sensor

Light sensors may also be used to determine vehicle speed. Position the light sensors at known distances from one another along the roadway. A separation distance of at least 15 m (50 ft) should be maintained. The light sensors are triggered at the instants the vehicle reaches the pass-by points. The triggering of the sensors typically results in a signal being sent to some type of electronic detector, which in turn is programmed to read and store time of day, or compute elapsed time between pulses from a computer or other time base. Light sensor systems are commercially available at most electronic stores. The signal detector system may also by used to trigger the start and stop of acoustic data collection.

3.3.4 Pneumatic Line

Pneumatic lines may also be positioned at known locations from one another along the roadway to determine vehicle speed. The pressure in the pneumatic line increases when a vehicle passes over it, causing a mechanical switch to close. The vehicle's speed is determined by dividing the known distance by the measured time period. The mechanical switches may also be used to trigger the start and stop of acoustic data collection.

3.4 TRAFFIC-COUNTING DEVICE

For many transportation-related measurements, the collection of traffic data, including the logging of vehicle types, as defined in Section 5.1.3, vehicle-type volumes, and average vehicle speed may be required for: (1) determination of site equivalence (See Existing-Noise Measurements in Section 4 and Barrier Insertion Loss Measurements in Section 6); or (2) input into a highway traffic noise prediction model. This section discusses various instruments for the counting and classification of roadway traffic, including the use of a video camera, counting board, or pneumatic line. If none of these instruments is available, meticulous pencil/paper tabulation should be used.

3.4.1 Video Camera

A video camera can be used to record traffic in the field and perform counts off-line at a later time. This approach, however, would require strict time synchronization between the acoustic instrumentation and the camera.

3.4.2 Counting Board

A counting board is simply a board with three or more incrementing devices, depending on the number of vehicle types. Each device is manually triggered to increment for a given type of vehicle pass-by.

3.4.3 Pneumatic Line

A pneumatic line may also be used to determine traffic counts. The pressure in the line increases when a vehicle passes over it, causing a mechanical switch to close. The mechanical switch triggers an internal counting mechanism to increment. The disadvantage of using a pneumatic line is that the specific vehicle mix, i.e., automobiles versus trucks, as well as other vehicle types, is not preserved.

3.5 SPECIAL PURPOSE INSTRUMENTATION

3.5.1 Tachometer

A tachometer indicates or measures the revolutions per minute of a revolving shaft. A tachometer may be used to more completely characterize noise sources, primarily for the purpose of research. A tachometer may also be used for the measurement of special equipment, e.g., power generators.

3.5.2 Artificial Noise Source

A fixed, **artificial noise source**, such as a loudspeaker, may be used in place of the actual noise source, usually when the actual source is not available, such as might be the case for building noise-reduction measurements (See Section 8). Where measurements using a loudspeaker source are to be directly compared with measurements made using the actual noise source, a high-powered omnidirectional loudspeaker system is recommended to properly simulate the direct and reflected sounds of the source.[31]

The loudspeaker should produce signals of random noise filtered in one-third octave-bands. Loudspeaker directional characteristics shall be such that at 2000 Hz, the free-field radiated signal out to an angle of 45 degrees shall drop no more than 6 dB relative to the on-axis signal. In addition, the loudspeaker must supply sufficient output for measurements within the band range of 100 to 4000 Hz.[32]

3.5.3 Noise Dosimeter

In accordance with ANSI S1.25-1991[33] and the U.S. Occupational Safety and Health Administration (OSHA), a noise dosimeter is a small device that integrates sound pressure over time to determine a subject’s **noise dose**, as a percentage of a manually set maximum criterion determined by OSHA.[8]

Similar to a sound level meter (See Figure 5 in Section 3.1.3.2), components of a noise dosimeter include: a microphone with preamplifier, an amplifier, A-weighting (See Section 3.1.3.4.2), a squaring device, slow exponential time-averaging (See Section 3.1.3.4.4), an **exchange rate** of 5 dB, and an output indicator or display.

3.6 SUPPORT INSTRUMENTATION

Care should be taken to ensure that all support instrumentation is compatible with the acoustic instrumentation. For example, headphones should have an input impedance suitable for the recording instrumentation's output impedance. In addition, for maximum power transfer and minimum distortion, cables used with this equipment should have a matching impedance. Finally, sufficient back-up equipment, such as batteries, chargers, data sheets, floppy diskettes, etc., should always be available.

3.7 MANUFACTURERS AND VENDORS

The following is a suggested list of sources for the instrumentation discussed in Section 3.[34] It is not an endorsement by the FHWA, nor is it meant to be complete, but is intended solely as a guide for readers.

3.7.1 Acoustic Instrumentation

3.7.1.1 Microphone System

- ACO Pacific, Inc., 2604 Read Avenue, Belmont, CA 94002, (415) 595-8588.
- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Cirrus Research p/c, Acoustic House, Bridlington Road, Hunmanby, Y014 OPH UK, 44-1723-891655.
- Hewlett-Packard Company, P.O. Box 95052-8059, Santa Clara, CA 95052, (800) 333-1917.
- Ivie Technologies, Inc., 1366 West Center Street, Orem, UT 84043, (801) 224-1800.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.
- Lucas CEL Instruments, 1 Westchester Drive, Milford, NH 03055, (800) 366-2966.
- Metrosonics, Inc., P.O. Box 23075, Rochester, NY 14692, (716) 334-7300.
- Ono Sokki Technology, Inc., 2171 Executive Drive, Suite 400, Addison, IL 60101, (708) 627-9700.
- Quest Technologies, 510 South Worthington Street, Oconomowoc, WI 53066, (414) 567-9157.
- Scantek, Inc., 916 Gist Avenue, Silver Spring, MD 20910, (301) 495-7738.
- Zonic Corporation, 50 West Technecenter Drive, Milford, OH 45150, (513) 248-1911.

3.7.1.2 Recording System

- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Hewlett-Packard Company, P.O. Box 95052-8059, Santa Clara, CA 95052, (800) 333-1917.
- JVC Company of America, 41 Slater Drive, Elmwood Park, NJ 07407, (201) 794-3900.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.

- Lucas CEL Instruments, 1 Westchester Drive, Milford, NH 03055, (800) 366-2966.
- Metrosonics, Inc., P.O. Box 23075, Rochester, NY 14692, (716) 334-7300.
- Quest Technologies, 510 South Worthington Street, Oconomowoc, WI 53066, (800) 245-0779.
- Racal Recorders, Inc., 15375 Barranca Parkway, Suite H-101, Irvine, CA 92718, (714) 727-3444.
- Scantek, Inc., 916 Gist Avenue, Silver Spring, MD 20910, (301) 495-7738.
- Sony Electronics Inc., 3300 Zanker Road, San Jose, CA 95134, (408) 432-1600.
- TEAC, 7733 Telegraph Road, Montebello, CA 90640, (213) 726-0303.
- Technics, Panasonic East, 50 Meadowlands Parkway, Secaucus, NJ 07094, (201) 348-7250.
- Tritek, Inc., 155 Middlesex Turnpike, Burlington, MA 01803, (617) 272-4550.
- Zonic Corporation, 50 West Technecenter Drive, Milford, OH 45150, (513) 248-1911.

3.7.1.3 Measurement System

3.7.1.3.1 Graphic Level Recorder

- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Hewlett-Packard Company, P.O. Box 95052-8059, Santa Clara, CA 95052, (800) 333-1917.

3.7.1.3.2 Sound Level Meter

- ACO Pacific, Inc., 2604 Read Avenue, Belmont, CA 94002, (415) 595-8588.
- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Cirrus Research p/c, Acoustic House, Bridlington Road, Hunmanby, Y014 OPH UK, 44-1723-891655.

- Hewlett-Packard Company, P.O. Box 95052-8059, Santa Clara, CA 95052, (800) 333-1917.
- Ivie Technologies, Inc., 1366 West Center Street, Orem, UT 84043, (801) 224-1800.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.
- Lucas CEL Instruments, 1 Westchester Drive, Milford, NH 03055, (800) 366-2966.
- Metrosonics, Inc., P.O. Box 23075, Rochester, NY 14692, (716) 334-7300.
- Ono Sokki Technology, Inc., 2171 Executive Drive, Suite 400, Addison, IL 60101, (708) 627-9700.
- Quest Technologies, 510 South Worthington Street, Oconomowoc, WI 53066, (800) 245-0779.
- Scantek, Inc., 916 Gist Avenue, Silver Spring, MD 20910, (301) 495-7738.
- Tritek, Inc., 155 Middlesex Turnpike, Burlington, MA 01803, (617) 272-4550.
- Zonic Corporation, 50 West Technecenter Drive, Milford, OH 45150, (513) 248-1911.

3.7.1.3.3 One-Third Octave-Band Analyzer

- ACO Pacific, Inc., 2604 Read Avenue, Belmont, CA 94002, (415) 595-8588.
- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Cirrus Research p/c, Acoustic House, Bridlington Road, Hunmanby, Y014 OPH UK, 44-1723-891655.
- Computational Systems, Inc., 835 Innovation Drive, Knoxville, TN 37932, (423) 675-2400.
- GW Instruments, 35 Medford Street, Somerville, MA 02143, (617) 625-4096.
- Hewlett-Packard Company, P.O. Box 95052-8059, Santa Clara, CA 95052, (800) 333-1917.
- Ivie Technologies, Inc., 1366 West Center Street, Orem, UT 84043, (801) 224-1800.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.

- Lucas CEL Instruments, 1 Westchester Drive, Milford, NH 03055, (800) 366-2966.
- Metrosonics, Inc., P.O. Box 23075, Rochester, NY 14692, (716) 334-7300.
- Ono Sokki Technology, Inc., 2171 Executive Drive, Suite 400, Addison, IL 60101, (708) 627-9700.
- Quest Technologies, 510 South Worthington Street, Oconomowoc, WI 53066, (800) 245-0779.
- Scantek, Inc., 916 Gist Avenue, Silver Spring, MD 20910, (301) 495-7738.
- Tektronix, Inc., P.O. Box 500, Beaverton, OR 97077, (503) 627-7111.
- Tritek, Inc., 155 Middlesex Turnpike, Burlington, MA 01803, (617) 272-4550.
- Zonic Corporation, 50 West Technecenter Drive, Milford, OH 45150, (513) 248-1911.

3.7.1.4 Calibrator

- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Cirrus Research p/c, Acoustic House, Bridlington Road, Hunmanby, Y014 OPH UK, 44-1723-891655.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.
- Metrosonics, Inc., P.O. Box 23075, Rochester, NY 14692, (716) 334-7300.
- Scantek, Inc., 916 Gist Avenue, Silver Spring, MD 20910, (301) 495-7738.

3.7.1.5 Microphone Simulator

- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.

3.7.1.6 Pink Noise Generator

- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.

- Ivie Technologies, Inc., 1366 West Center Street, Orem, UT 84043, (801) 224-1800.

3.7.1.7 Windscreen

- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.

3.7.2 Meteorological Instrumentation

- Climatronics Corp., 1324 Motor Parkway, Hauppauge, NY 11787, (516) 567-7300.
- Edmund Scientific, Order Dept., Edscorp Bldg., Barrington, NJ 08007-1380, (609) 573-6250.
- Industrial Instruments & Supplies, P.O. Box 416, County Line Industrial Park, Southampton, PA 18966, (215) 396-0822.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.
- R.M Young Company, 2801 Aero-Park Drive, Traverse City, MI 49686, (616) 946-3980.
- Robert E. White Instruments, 34 Commercial Wharf, Boston, MA 02110, (617) 742-3045.
- Viking Instruments, 525 Main Street, S. Weymouth, MA 02190, (800) 325-0360.

3.7.3 Vehicle-Speed Detection Unit

- Applied Concepts, 717 Sherman, Suite 300, Richardson, TX 75081, (214) 578-5100.
- CMI Inc., 316 East Ninth Street, Owensboro, KY 42301, (502) 685-6545.
- Decatur Electronics, Inc., 715 Bright Street, Decatur, IL 62522, (217) 428-4315.
- Kustom Signals, Inc., 9325 Pflumm, Lenexa, KS 66215, (913) 492-1400.
- Laser Technology, Inc., 7399 South Tucson Way, Garden Level B, Inglewood, CO 80112, (303) 649-9707.

- Tribar Inc., 1655 Flint Road, Downsview, Ontario, Canada M3J2W8, (416) 736-9600.

3.7.4 Traffic-Counting Device

3.7.4.1 Video Camera

- HB Communications Inc., 15 Corporate Drive, P.O. Box 689, North Haven, CT 06473-0689, (203) 234-9246.
- JVC, 14 Slater Drive, Elmwood Park, NJ 07407, (201) 794-3900.
- Panasonic, One Panasonic Way, Secaucus, NJ 07094, (201) 348-7000.
- Sony, One Sony Drive, Park Ridge, NJ 07656, (941) 768-7669.

3.7.5 Special Purpose Instrumentation

3.7.5.1 Tachometer

- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.

3.7.5.2 Artificial Noise Source

- CTS of Brownsville Inc., 3555 East 14th Street, Brownsville, TX 78521, (210) 546-5184.
- ESS, 9613 Oates Drive, Sacramento, CA 95827.
- HB Communications Inc., 15 Corporate Drive, P.O. Box 689, North Haven, CT 06473-0689, (203) 234-9246.
- Infinity, 9409 Owensmouth Avenue, Chatsworth, CA 91311, (818) 407-0228.
- Jamo, 425 Huehl Road, Bldg 8, Northbrook, IL 60062, (847) 498-4648.
- JBL, 240 Crossways Park W., WoodBury, NY 11797, (516) 496-3400.
- Motorola, Sheumburg, IL, (312) 397-1000.
- OHM Acoustics, 241 Taaffe Place, Brooklyn, NY 11205, (718) 783-1111.
- Panasonic, One Panasonic Way, Secaucus, NJ 07094, (201) 348-7000.

- Phase Technology, 6400 Yougerman Circle, Jacksonville, FL 32244, (904) 777-0700.
- Pioneer, 737 Fargo Avenue, Elk Grove Village, IL 60007, (312) 593-2960.
- Shure Brothers Inc., 222 Hartrey Avenue, Evanston, IL 60204.
- Sonance, 961 Calle Negocio, San Clemente, CA 92672, (800) 582-7777.
- VMPS, Itone, 3429 Morningside Drive, El Sobrante, CA 94803, (415) 222-4276.

3.7.5.3 Noise Dosimeter

- Brüel & Kjær Instruments, Inc., 2364 Park Central Blvd., Decatur, GA 30035, (800) 332-2040.
- Cirrus Research p/c, Acoustic House, Bridlington Road, Hunmanby, Y014 OPH UK, 44-1723-891655.
- Larson Davis Laboratories, 1681 West 820 North, Provo, UT 84601, (801) 375-0177.
- Scantek, Inc., 916 Gist Avenue, Silver Spring, MD 20910, (301) 495-7738.

4. EXISTING-NOISE MEASUREMENTS IN THE VICINITY OF HIGHWAYS

This section describes recommended procedures for performing existing-noise measurements in the vicinity of highways. Existing-noise measurements include measurements made either prior to a highway project, including the construction of a new highway or the expansion of an existing one (BEFORE), measurements made subsequent to project completion (AFTER), or measurements of both the BEFORE-project and AFTER-project condition. This section does not address the assessment of highway **noise barrier** performance, which is covered separately in Section 6. The difference in sound levels BEFORE a highway project is started and AFTER it is completed, combined with the overall level associated with the completed project, gives an indication of the expected noise impact.[35]

4.1 SITE SELECTION

Site selection should be guided by the location of noise-sensitive receivers.

4.1.1 Site Characteristics

Site characteristics depend on the purpose of the existing-noise measurements: (1) establishing an overall sound level for the purpose of assessing noise impact of a nearby highway; and (2) establishing a change in sound level prior to a highway project relative to the sound level upon project completion.

4.1.1.1 Overall Sound Level Measurements

Land-use maps and field reconnaissance should be used to identify potential noise-sensitive areas. Schools, hospitals, and churches are especially sensitive to noise impacts since they require very low levels to facilitate activity. Noise-sensitive residential areas should also be included in a noise-impact assessment. When selecting potential representative sites for overall sound level measurements, keep in mind, that the site should exhibit typical conditions (e.g., ambient, roadway, and meteorological) for the entire community. It is recommended that good engineering judgment be used to select sites, keeping in mind the objectives of the study.

4.1.1.2 Change in Sound Level Measurements

For valid comparison of BEFORE and AFTER sound levels, equivalence in site geometry, meteorological, and traffic conditions must be established.

Equivalence in site geometry entails similar terrain characteristics and **ground impedance** within an angular sector of 120 degrees from all receivers looking towards the noise source. For research purposes, equivalence in ground impedance may be determined by performing measurements in accordance with the ANSI Standard for measuring ground impedance, scheduled for publication in the second half of 1996.[37] For more empirical studies, or if measurements are not feasible, then the ground for BEFORE and AFTER measurements may be judged equivalent if general ground surface type and conditions, e.g., surface water content, are similar.

Equivalence in meteorological conditions includes wind, temperature, humidity, and cloud cover. Wind conditions may be judged equivalent for BEFORE and AFTER measurements if the wind class (See Table 3 in Section 3.2.1) remains unchanged and the vector components of the average wind velocity from source to receiver do not differ by more than a certain limit, which is defined as follows: (1) for an acoustical error within ±1.0 dB and distances less than 70 m (230 ft), this limit is 1.0 m/s (2 mi/h); (2) for an acoustical error within ±0.5 dB and distances less than 70 m (230 ft), at least four BEFORE and AFTER measurements should be made within the limit of 1.0

m/s (2 mi/h). However, these 1.0 m/s limits are not applicable for a calm wind class when strong winds with a small vector component in the direction of propagation exist. In other words, BEFORE/AFTER measurements in such instances should be avoided.[25]

Average temperatures during BEFORE and AFTER measurements may be judged equivalent if they are within 14° C of each other. In certain conditions, dry air produces substantial changes in sound attenuation at high frequencies. Therefore, for a predominantly high-frequency source (most sound energy over 3000 Hz), the absolute humidity for BEFORE and AFTER measurements should be similar.

The BEFORE and AFTER acoustical measurements should be made under the same class of cloud cover, as determined from Table 4.

Table 4. Classes of cloud cover.[6]

Class	Description
1	Heavily overcast
2	Lightly overcast (either with continuous sun or the sun obscured intermittently by clouds 20 to 80% of the time)
3	Sunny (sun essentially unobscured by clouds at least 80% of the time)
4	Clear night (less than 50% cloud cover)
5	Overcast night (50% or more cloud cover)

Equivalence in traffic conditions includes the volume and mix of roadway traffic, as well as spectral content, directivity, and spatial and temporal patterns of the individual vehicles. To a certain degree, non-equivalence in traffic conditions can be factored out through the use of a reference microphone (See Section 4.1.2.1).

4.1.2 Microphone Location

When performing measurements to establish the change in sound level, it is important to remember that microphone locations relative to the sound source in the BEFORE and AFTER cases should be as close to identical as possible.

4.1.2.1 Reference Microphone

The use of a reference microphone is strongly recommended for all existing-noise measurements. Use of a reference microphone allows for a calibration of measured levels, which accounts for variations in the characteristics of the noise source, e.g., traffic speeds, volumes, and mixes.

Typically, the reference microphone is positioned at a height of 1.5 m (5 ft), and located within 30 m (100 ft) of the centerline of the near travel lane at a position which is minimally influenced by **ground attenuation** and atmospheric effects (See Section 3.2).

However, the specific location of the reference microphone may be defined by the location(s) of any noise-sensitive receiver(s) (See Section 4.1.2.2).

4.1.2.2 Receiver

In most situations, study objectives will dictate specific microphone locations. As such, this section presents a generic discussion of microphone locations, and assumes no specific study objectives have been identified.

Sometimes a single, typical residential area near the existing or proposed highway route can be used to represent other similar areas. If traffic conditions or topography vary greatly from one residential area to the next, receivers at many locations may be required.

In terms of microphone height, 1.5 m (5 ft) is the preferred position. However, microphone height(s) should be chosen to represent all noise-sensitive receivers of interest, i.e., if multistory structures are of interest, including microphones at heights of 4.5 m and 7.5 m (15 ft and 25 ft) may be helpful.

Note: For receiver distances greater than 100 m (300 ft) from the source, atmospheric effects have a much greater influence on measured sound levels.[8,38] In such instances, precise meteorological data will be needed to ensure BEFORE and AFTER equivalence of meteorological conditions (See Section 3.2).

4.2 NOISE DESCRIPTORS

The **equivalent sound level (L_{Aeq})** should be used to describe continuous sounds, such as relatively dense highway traffic. The **sound exposure level (L_{AE})**, or the **maximum A-weighted sound level** with fast time response characteristics **(L_{AFmx})** should be used to describe the sound of single events, such as individual vehicle pass-bys. The **day-night average sound level (L_{dn})** and the **community-noise exposure level (L_{den})** may be used to describe long-term noise environments (typically greater than 24 hours), particularly for land-use planning. Note: Once the L_{Aeq} and L_{AE} noise descriptors are established, other descriptors can be computed using the mathematical relationships presented in Section 2.

4.3 INSTRUMENTATION (See Section 3)

- Microphone system (microphone and preamplifier)
- Graphic level recorder (optional)
- Measurement/recording instrumentation
- Calibrator
- Microphone simulator
- Pink noise generator
- Windscreen
- Tripod
- Cabling
- Meteorological instrumentation
- Vehicle-speed detection unit
- Traffic-counting device

4.4 SAMPLING PERIOD

Different sound sources require different sampling periods. For multiple-source conditions, a longer sampling period is needed to obtain a representative sample, averaged over all conditions. Typical sampling periods range from 2 to 30 minutes. In special instances where the temporal nature is expected to vary substantially, longer sampling periods, such as 1 hr or 24 hr, may be necessary. Measurement repetitions at all receiver positions are required to ensure statistical reliability of measurement results. A minimum of 3 repetitions for like conditions is recommended, with 6 repetitions being preferred. Table 5 presents suggested measurement sampling periods based on the temporal nature and the range in sound level fluctuations of the noise source. Guidance on judgment of the temporal nature of the source may also be found in ANSI S1.13-1971 and ANSI S12.9-1988.[16,47]

Table 5. Sampling periods.

Temporal nature[16]	Greatest anticipated range		
	10 dB	10-30 dB	>30 dB
Steady *	2 minutes	N/A	N/A
Nonsteady fluctuating	5 minutes	15 minutes	30 minutes
Nonsteady intermittent	For at least 10 events	For at least 10 events	For at least 10 events
Nonsteady, impulsive isolated bursts	For at least 10 events	For at least 10 events	For at least 10 events
Nonsteady, impulsive-quasi-steady	3 cycles of on/off	3 cycles of on/off	3 cycles of on/off

* A minimum of three repetitions is recommended, with 6 repetitions being preferred.

4.5 MEASUREMENT PROCEDURES

1. Prior to initial data collection, at hourly intervals thereafter, and at the end of the measurement day, the entire acoustic instrumentation system should be calibrated. Meteorological conditions (wind speed and direction, temperature, humidity, and cloud cover) should be documented prior to data collection, at a minimum of 15-minute intervals, and whenever substantial changes in conditions are noted.

2. The electronic noise floor of the acoustic instrumentation system should be established daily by substituting the measurement microphone with a dummy microphone (See Section 3.1.5). The frequency response characteristics of the system

should also be determined on a daily basis by measuring and storing 30 seconds of pink noise from a random-noise generator (See Section 3.1.6).

3. Ambient levels should be measured and/or recorded by sampling the sound level at each receiver and at the reference microphone, with the sound source quieted or removed from the site. A minimum of 10 seconds should be sampled. Note: If the study sound source cannot be quieted or removed, an upper limit to the ambient level using a statistical descriptor, such as L_{90}, may be used. Such upper limit ambient levels should be reported as "assumed." Note: Most sound level meters have the built-in capability to determine this descriptor.

4. Sound levels should be measured and/or recorded simultaneously with the collection of traffic data, including the logging of vehicle types, as defined in Section 5.1.3, vehicle-type volumes, and the average vehicle speed. It is often easier to videotape traffic in the field and perform counts at a later time. This approach, of course, requires strict time synchronization between the acoustic instrumentation and the video camera.

(Note: Appendix B provides example field-data log sheets.)

4.6 DATA ANALYSIS

4.6.1 Overall Sound Level Measurement Analysis

1. Adjust measured levels for calibration drift (See Section 3.1.4).

2. Adjust measured levels for ambient (See Section 4.6.3).

3. Compute the mean sound level for each receiver by arithmetically averaging the levels from individual sampling periods.

4. Perform an assessment of the averaged sound levels based on study objectives.

4.6.2 Change in Sound Level Measurement Analysis

1. Adjust measured levels for calibration drift (See Section 3.1.4).

2. Adjust measured levels for ambient (See Section 4.6.3).

3. For each measurement repetition of each BEFORE-AFTER receiver pair, the noise level difference should be determined by subtracting the difference in adjusted reference and receiver levels for the BEFORE case from the difference in adjusted reference and receiver levels for the AFTER case:

$$Difference_i = (L_{Aref} - L_{Arec}) - (L_{Bref} - L_{Brec}) \qquad \text{(dB)}$$

where: $Difference_i$ is the noise level difference at the *i*th receiver;
L_{Brec} and L_{Arec} are, respectively, the BEFORE and AFTER adjusted source levels at the *i*th receiver; and
L_{Bref} and L_{Aref} are, respectively, the BEFORE and AFTER adjusted reference levels.

4. Compute the mean sound level for each receiver by arithmetically averaging the levels from individual sampling periods.

5. Perform an assessment of the averaged sound levels based on study objectives.

4.6.3 Ambient Adjustments

If measured levels do not exceed ambient levels by 4 dB or more, i.e., they are masked, or if the levels at the reference microphone do not exceed those at the receivers, then those data should be omitted from data analysis.

If measured levels exceed the ambient levels by between 4 and 10 dB, and if the levels at the reference microphone exceed those at the receivers, then correct the measured levels for ambient as follows (Note: For source levels which exceed ambient levels by greater than 10 dB, ambient contribution becomes essentially negligible and no correction is necessary):

$$L_{adj} = 10 * \log_{10}(10^{0.1L_c} - 10^{0.1L_a}) \quad \text{(dB)}$$

where: L_{adj} is the ambient-adjusted measured level;
L_c is the measured level with source and ambient combined; and
L_a is the ambient level alone.

For example:

- L_c = 55.0 dB
- L_a = 47.0 dB

Therefore:

L_{adj} = $10*\log_{10}(10^{(0.1*55.0)}-10^{(0.1*47.0)})$ = 54.3 dB

5. VEHICLE NOISE EMISSION LEVEL MEASUREMENTS FOR HIGHWAY NOISE PREDICTION MODELS

This section describes recommended procedures for the measurement of vehicle noise emission levels. Among other purposes, emission levels are required to input user-defined vehicles in the FHWA Traffic Noise Model (FHWA TNM®).[3] The TNM is used to predict sound levels in the vicinity of highways and to design highway noise barriers. The procedures described below are consistent with the methodology used during the development of the Reference Energy Mean Emission Level (REMEL) Data Base for the FHWA TNM.[4,36]

5.1 SITE SELECTION

5.1.1 Site Characteristics

To minimize site specific effects associated with vehicle-noise emission level measurements, it is recommended that between five and ten unique sites be selected. These sites should possess the following geometric characteristics:

- A flat open space free of large reflecting surfaces, such as parked vehicles, signboards, buildings, or hillsides, located within 30 m (100 ft) of either the vehicle path or the microphone(s) (See Figure 8).

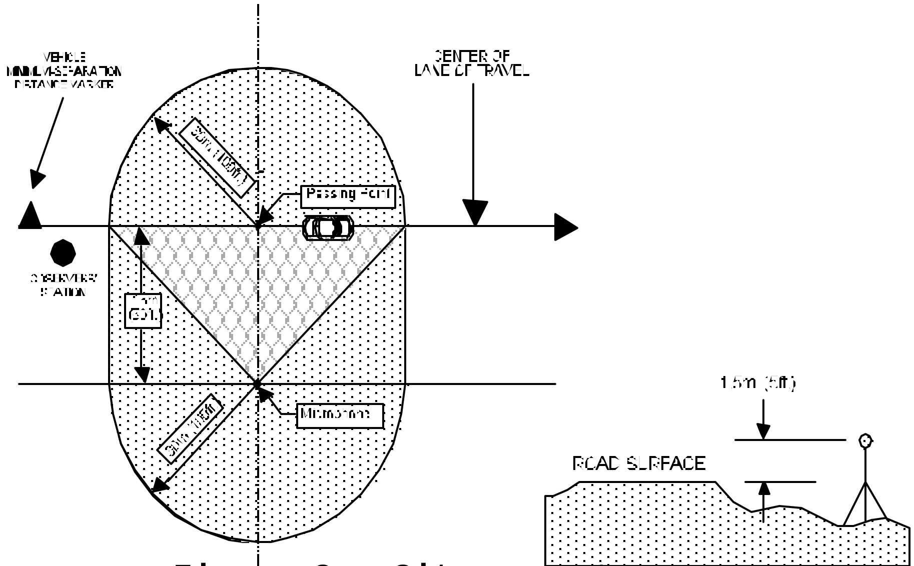

Figure 8. Site geometry.

- Ground surface within the measurement area is free of snow and representative of acoustically hard, e.g., pavement, or acoustically soft, e.g., grass, terrain.
- Line-of-sight from the microphone(s) to the roadway is unobscured within an arc of 150 degrees.
- Vehicle path, i.e., roadway lane, is smooth, dry concrete, dense-graded asphalt, or open-graded asphalt, and free of extraneous material, such as gravel or road debris.
- A predominant, ambient level at the measurement site is low enough to enable the measurement of uncontaminated vehicle pass-by sound levels. Specifically, the difference between the lowest-anticipated, vehicle pass-by, maximum A-weighted sound-pressure level (L_{AFmx}) and the A-weighted ambient level, as measured at the 15-m (50-ft) microphone, should be at least 10 dB.
- Site is to be located away from known noise sources, such as airports, construction sites, rail yards, or other heavily traveled roadways.

- Site is to exhibit constant-speed roadway traffic operating under cruise conditions at speeds between 15 and 110 km/h (10 to 70 mi/h) and located away from intersections, lane merges or any other features that would cause traffic to accelerate or decelerate, unless, of course, noise emission levels are being measured for vehicles subject to interrupted-flow traffic or roadway grade conditions.

The above characteristics and parameters are presented for vehicle noise emission level measurements in general; Section 5.6.1 presents specific requirements and measurement parameters associated with inputting user-defined vehicles in the TNM.

5.1.2 Microphone Location

The microphone system should be placed 15 m (50 ft) from the center of the near travel lane, with the microphone diaphragm positioned for grazing incidence, 1.5 m (5 ft) above the plane of the pavement (See Figure 8). Additionally, systems may be optimally positioned at other offset distances, e.g., 7.5 and 30 m (25 and 100 ft), for the purpose of characterizing measurement-site drop-off rate.

5.1.3 Vehicle Types

Roadway vehicles are typically grouped into five acoustically significant types, i.e., vehicles within each type exhibit statistically similar acoustical characteristics. These vehicle types are consistent with the FHWA TNM, and are defined as follows:

- <u>Automobiles (A)</u>: All vehicles having two axles and four tires and designated primarily for transportation of nine or fewer passengers, i.e., automobiles, or for transportation of cargo, i.e., light trucks. Generally, the gross vehicle weight is less than 4500 kg (9900 lb).

- Medium Trucks (MT): All cargo vehicles having two axles and six tires. Generally, the gross vehicle weight is greater than 4500 kg (9900 lb) but less than 12,000 kg (26,400 lb).
- Heavy Trucks (HT): All cargo vehicles having three or more axles. Generally, the gross vehicle weight is greater than 12,000 kg (26,400 lb).
- Buses (B): All vehicles having two or three axles and designated for transportation of nine or more passengers.
- Motorcycles (MC): All vehicles having two or three tires with an open-air driver and/or passenger compartment.

One of the primary purposes for performing REMEL measurements is for the purpose of characterizing user-defined vehicle types (See Section 5.6.1). Such types may include motor homes or electric cars.

5.2 NOISE DESCRIPTORS

The maximum, A-weighted sound-pressure level with fast exponential time-averaging (L_{AFmx}) should be used for the development of vehicle noise emission level relationships. Additionally, spectral data, although not required, may be useful during analysis. Specifically, since TNM computations are performed in one-third octave-bands, it may be helpful to verify consistency with the spectral data currently in the model.[4]

5.3 INSTRUMENTATION (See Section 3)

Microphone system (microphone and preamplifier)
Graphic level recorder (optional)
Measurement/recording instrumentation
Calibrator
Microphone simulator
Pink noise generator
Windscreen

Tripod
Cabling
Meteorological instrumentation
Vehicle-speed detection unit

5.4 SAMPLING PERIOD

The sampling period for each vehicle pass-by will vary, but should be chosen to encompass a time period such that a minimum rise and fall in the noise-level time-history trace of 6 dB is achieved, with 10 dB being preferred (See Section 5.4.1). Rise and fall are defined, respectively, as the difference between L_{AFmx} and the minimum measured level associated with either the start or end of a given pass-by (whichever difference is smaller). This criterion ensures acoustic quality of the pass-by event, and may be determined by (1) observing the display of the sound level meter; or (2) examining the time-history chart produced by a Graphic Level Recorder (GLR). A GLR is the preferred instrument for establishing event quality.

5.4.1 Event Quality

The event quality for each pass-by should be determined during data measurement and prior to data analysis. Event quality is characterized by three type designations (Type 2, 1, or 0).

Events with a rise and fall of the optimum 10 dB or greater are designated as Type 2, the highest quality event. Events with a rise and fall of between 6 and 10 dB are designated as Type 1. Events with a rise and fall of between 3 and 6 dB are designated as Type 0, and in most cases should not be used. Events with less than a 3 dB rise and fall should be discarded.

In special situations, events in which the ambient is less than 10 dB below the L_{AFmx} and events designated as Type 0 may be used in the analysis. More specifically, it may be necessary to relax the 10-dB ambient requirement, discussed in Section 5.1.1, to 6-dB. This situation may occur, for example, during the measurement of low-speed automobiles or during the measurement of hard-to-find vehicle types, e.g., buses. The L_{AFmx} for these events may be corrected for ambient via energy-subtraction before data analysis as follows:

$$L_{adj} = 10*\log_{10}(10^{0.1L_c} - 10^{0.1L_a}) \quad \text{(dB)}$$

where: L_{adj} is the ambient-adjusted measured level;
L_c is the measured level with vehicle and ambient combined;
and L_a is the ambient level alone.

For example:

- L_c = 55.0 dB
- L_a = 47.0 dB

Therefore:

L_{adj} = $10*\log_{10}(10^{(0.1*55.0)}-10^{(0.1*47.0)})$ = 54.3 B

Furthermore, it may be necessary to use events designated as Type 0. These events may be corrected only if the 10 dB-ambient requirement is maintained, and as such, the rise and fall of these events can be attributed entirely to nearby vehicles. This correction is to be performed by subtracting from the measured L_{AFmx}, the sound energy due to "contaminating" vehicle(s) as follows:

$$L_{adj} = 10*\log_{10}(10^{0.1L_c} - 10^{0.1L_a}) \quad \text{(dB)}$$

where: L_{adj} is the adjusted measured level;
L_c is the measured level with vehicle and contaminating vehicle(s) combined;
and L_a is the level due to contaminating vehicle(s) alone.

This method is only viable if a time-history trace is available. In such instances, the sound due entirely to a contaminating vehicle can be estimated through linear extrapolation (See Figure 9).

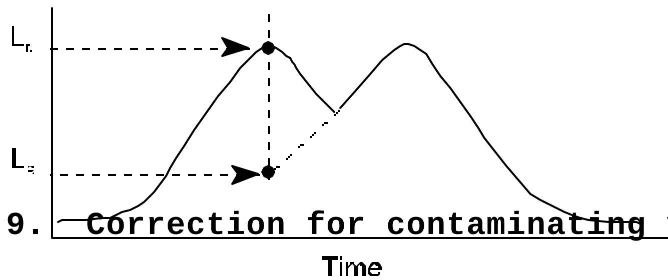

Figure 9. Correction for contaminating vehicles.

5.4.2 Minimum Separation-Distance

To ensure negligible contamination from vehicles other than the subject vehicle, a minimum separation-distance between vehicles should be used during the process of event selection in the field. A previous study(35) has shown that a minimum of 120 m (400 ft) between similar vehicles is required to insure that the contamination from nearby vehicles is less than 0.5 dB. In the case of sequential pass-bys of unlike vehicles, such as an automobile followed by a heavy truck, a minimum of 300 m (985 ft) is required (See Appendix C for further details).

5.4.3 Recommended Number of Samples

While, the number of samples is somewhat arbitrary and often a function of budgetary constraints, a larger number of samples will result in higher precision and a greater degree of statistical confidence in the final emission levels. Table 6 provides, as a function of speed, the recommended minimum number of samples. These numbers should be considered an absolute minimum for characterizing automobiles, medium trucks, and heavy trucks. However, for more obscure vehicle types, such as buses, motorcycles, or motor homes, it may not be practical to obtain such a significant number of samples. As a point of relative comparison, 2825 autos, 765 medium trucks, 2986 heavy trucks, 355 buses, and 39 motorcycles were sampled for the development of the TNM.

Table 6. Recommended minimum number of samples.

Speed	Minimum Number of Samples
0-10	10
11-20	10
21-30	20
31-40	30
41-50	100
51-60	200
61-70	100

5.5 MEASUREMENT PROCEDURES

1. The instrumentation should be deployed as shown in Figure 10.

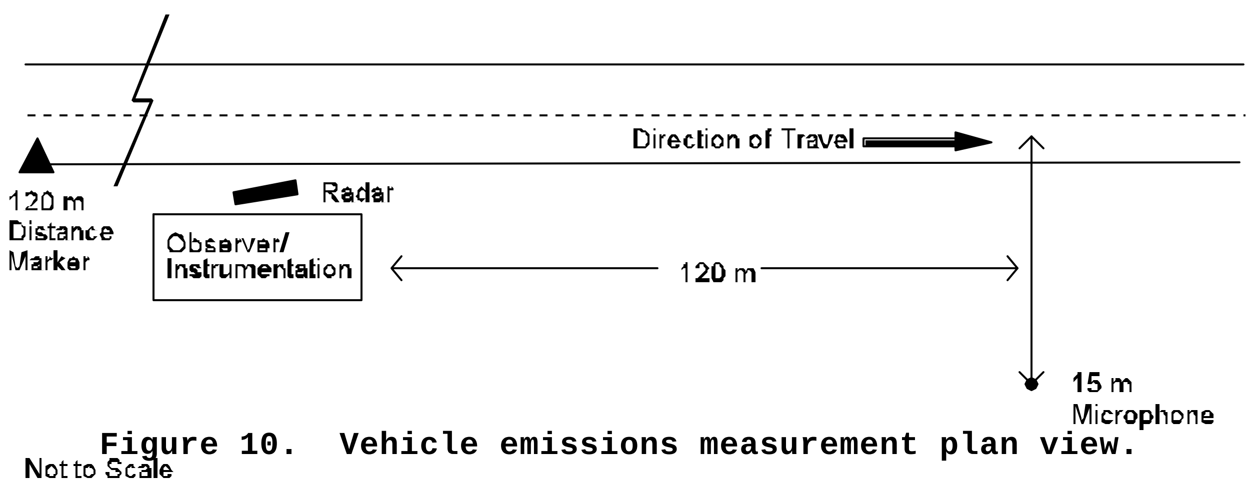

Figure 10. Vehicle emissions measurement plan view.

2. Prior to initial data collection, at hourly intervals thereafter, and at the end of the measurement day, the entire acoustic instrumentation system should be calibrated. Meteorological conditions (wind speed and direction, temperature, humidity, and cloud cover) should be documented prior to data collection, at a minimum of 15-minute intervals, and whenever substantial changes in conditions are noted.

3. The electronic noise floor of the acoustic instrumentation system should be established daily by substituting the measurement microphone with a dummy microphone (See Section 3.1.5). The frequency response characteristics of the system (if applicable) should also be determined on a daily basis by measuring and storing 30 seconds of pink noise from a random-noise generator (See Section 3.1.6).

4. If applicable, calibration of the Doppler radar should be periodically checked in the field for accuracy and functionality, using a calibrated tuning fork, and the unit's "internal circuit test" capability, if available.

5. Ambient levels should be measured and/or recorded by sampling the sound level at each receiver with the sound source quieted or removed from the site. A minimum of 10 seconds should be sampled. Note: If the study sound source cannot be quieted or removed, an upper limit to the ambient level using a statistical descriptor, such as L_{90}, may be used. Such upper limit ambient levels should be reported as “assumed.” Note: Most sound level meters have the built-in capability to determine this descriptor.

6. A minimum of two operators are necessary for logging all field data: a vehicle observer and an acoustic observer. For each pass-by event the following data should be logged: site number, event number, vehicle class, vehicle speed, maximum A-weighted sound level (L_{AFmx}), spectral data (if desired), meteorological conditions, and any observed anomalies or extraneous sounds.

   A potential pass-by event is identified when the vehicle observer confirms that the minimum separation-distance criterion is met. Note: Orange highway cones may be positioned

120 m (394 ft) upstream from the observers’ station to aid in identifying potentially acceptable events.

7. After the vehicle passes the observers' station, the acoustic observer should begin data capture.

8. After the vehicle passes the microphones and before subsequent vehicles approach, the acoustic observer should end data capture. Note: If the subject vehicle's speed varied by more than ±3 km/h (2 mi/h) and/or acoustic contamination was observed, the pass-by event should be omitted from later data analysis.

(Note: Appendix B provides example field-data log sheets.)

5.6 DATA ANALYSIS

1. Adjust L_{AFmx} for calibration drift (See Section 3.1.4).

2. Merge L_{AFmx} data and corresponding vehicle information, including speed data, into a single file for subsequent analysis, and development of REMEL regression equations. A spreadsheet-compatible file is recommended. Note: It is extremely important not to exclude samples which appear to be outliers (e.g., samples measured for extremely loud vehicles) in the data set. Due to the nature of the field measurement procedures, specifically the use of the minimum separation-distance criteria, the data collected are truly representative of a random sample.

5.6.1 Development of REMEL Regression Equations

The FHWA's Traffic Noise Model (FHWA TNM®) used for noise prediction and barrier analysis and design allows the user to input user-defined vehicles. However, it is anticipated that the capability to input user-defined vehicles in the FHWA TNM will not be used for entering state-specific emission levels. Based on work performed by the Volpe Center,[(40] there is no indication of a need or justification for developing state-specific REMELs at this time. Until the design of highway vehicles change incrementally, or regulatory requirements warrant lower noise emission levels, development of state-specific REMELs is unnecessary.

However, the user-defined-vehicle capability in the FHWA TNM is intended for describing vehicles which differ significantly from automobiles, medium trucks, heavy trucks, buses, or motorcycles (e.g., motor homes or electric cars). Unique vehicles should be measured under the following reference conditions: constant-flow roadway traffic; level grade; and dense-graded asphaltic concrete or Portland-cement concrete.

The first step in defining a user-defined vehicle is to develop the level-mean emission level equation. To develop the equation, the measured L_{AFmx} data should be regressed as a function of vehicle speed for each vehicle type. This can be done with any commercially available statistical analysis program. The functional form of the regression equation is as follows:

$$\begin{aligned} L(s) &= C + [A*\log_{10}s + B] \\ &= 10*\log_{10}[10^{C/10} + 10^{(A*\log s+B)/10}] \\ &= 10*\log_{10}[10^{C/10} + s^{A/10}10^{B/10}] \qquad \text{(dB)} \end{aligned}$$

For example:

- C = 50.128316
- s = 65 km/h
- A = 41.740807
- B = 1.148546

Therefore:

$L(65\ km/h) = 10*\log_{10}(10^{(50.128/10)}+65^{(41.741/10)}*10^{(1.149/10)}) = 76.8$ dB

In the above equation, L(s) is expressed in terms of the logarithm to the base 10 of the coefficient, C, (the engine/ exhaust coefficient, which is independent of vehicle speed); and, $A*\log_{10}(s) + B$ (the tire/pavement-term, which increases with increasing speed, s). The graphical form on a logarithmic plot of L(s) is illustrated in Figure 11 below.

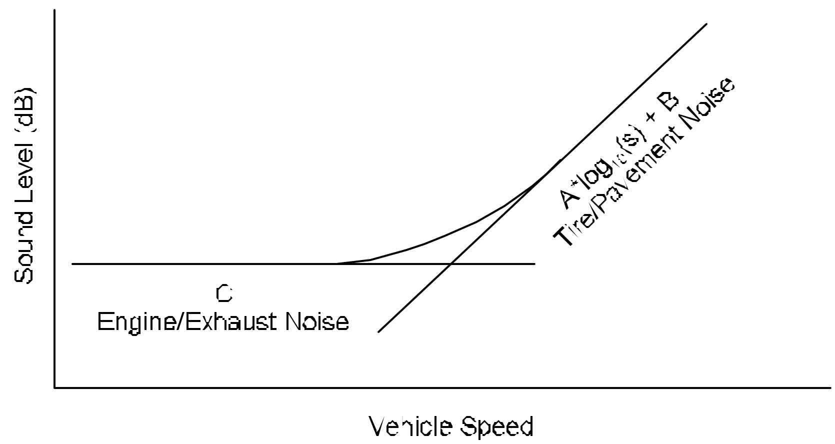

Figure 11. Graphical form of the FHWA TNM regression equation.

The level-mean emission level equation is then adjusted upward by a fixed value, which is a function of the relationship between the level-mean regression and the individual L_{AFmx} values, to develop the energy-mean emission level equation. In previous REMEL studies, the adjustment from level-mean to energy-mean was computed using $0.115\sigma^2$, where σ is the standard error of the regression. However, due to the potentially non-Gaussian distribution of the level-mean data about its level-mean regression (the $0.115\sigma^2$ adjustment assumes a Gaussian distribution), the following equation is used to compute the level-mean to energy-mean adjustment factor:

$$\Delta E = 10*\log_{10}[(1/n)\Sigma RE_i] - (1/n)\Sigma RL_i \qquad \text{(dB)}$$

For example:

- n = 327
- ΣRE_i (i=1 to n) = $RE_1 + RE_2 + ... + RE_{327}$ = 378.768351

• ΣRL_i (i=1 to n) $= RL_1 + RL_2 + ... + RL_{327} = -3.761481$

Therefore:

$\Delta E = 10*\log_{10}[(1/n)\Sigma RE] - (1/n)\Sigma RL = 0.649762$

In the above, the RL_i values represent the level residuals, which are equivalent to the value of each data point, i, at its corresponding speed, s, minus the value of regression at s; RE_i values represent the energy residuals, which are equivalent to $10^{(RL_i/10)}$; and n represents the total number of data samples.

This ΔE adjustment is then added to both the engine/exhaust term and the tire/pavement term of the L(s) equation, i.e., the C and B coefficients, as follows:

$$L_E(s) = 10*\log_{10}[10^{(C+\Delta E)/10} + s^{A/10}10^{(B+\Delta E)/10}] \qquad \text{(dB)}$$

From the above energy-mean emission-level regression equation, four input parameters are required to specify a user-defined vehicle type in the FHWA TNM: (1) a minimum level (the C coefficient plus ΔE); (2) a reference level (the emission level at 80 km/h or 50 mi/h); (3) the slope (the A coefficient); and (4) a like vehicle type. A like vehicle type is the FHWA TNM vehicle type to which the user-defined type is most similar. In determining a like vehicle type, the factors to be considered are listed in order of importance as follows: estimated subsource heights; estimated acceleration characteristics; and estimated, one-third octave-band frequency spectrum.[(3,4)]

6. HIGHWAY BARRIER INSERTION LOSS MEASUREMENTS

This section describes recommended procedures for the measurement of highway noise barrier insertion loss. Insertion loss is defined as the difference in sound level at a receiver location with and without the presence of a noise barrier, assuming no change in the sound level of the source.

The procedures described in this section are in accordance with ANSI S12.8-1987,[6] which provides three methods to determine the field insertion loss of noise barriers: (1) "direct" BEFORE/AFTER measurement; (2) "indirect" BEFORE measurement at an equivalent site; and (3) "indirect" predictions of BEFORE levels.

The "direct" BEFORE/AFTER method requires performing measurements at a site before the barrier has been constructed to determine "BEFORE" levels, and another set of measurements at the same site after construction to determine "AFTER" levels. The advantage of using this method is that it insures identical site geometric characteristics. However, the disadvantages are that equivalent meteorological and traffic conditions may not be reproducible.

The "indirect" BEFORE method requires performing measurements at a site with a barrier to determine "AFTER" levels, and another set of measurements at an "equivalent" site without a barrier to determine equivalent "BEFORE" levels.

A site may be judged equivalent if geometric, atmospheric, and traffic conditions are determined to be essentially identical for the BEFORE case as compared with the AFTER case. Geometric equivalence refers to the terrain characteristics and ground impedance at the site. Atmospheric equivalence refers to temperature, humidity, and wind speed and direction (See Section 6.1.1). Traffic equivalence refers to vehicle type and mix.

The BEFORE and AFTER cases for the “indirect” BEFORE method should be studied simultaneously, if possible. In other words, the ideal situation is to make BEFORE and AFTER measurements simultaneously at adjacent locations. The primary advantage to using this method is that it insures essentially the same meteorological and traffic conditions. The difficulty is that an adjacent equivalent site may not always be available. If an adjacent equivalent site is available, then this method is preferred.

The "indirect" prediction method requires performing measurements at a site with a barrier to determine AFTER levels, and using a highway-traffic, noise-prediction model, such as the Federal Highway Administration's Traffic Noise Model (FHWA TNM®), to predict sound levels at an equivalent site without a barrier. This method is inherently the least accurate of the three methods presented herein.

6.1 SITE SELECTION

Site selection for all three measurement methods is guided by site geometry, and the location of noise-sensitive receivers.

6.1.1 Site Characteristics

For valid comparison of BEFORE and AFTER sound levels, equivalence in site geometry, meteorological, and traffic conditions must be established.

Equivalence in site geometry entails similar terrain characteristics and ground impedance within an angular sector of 120 degrees from all receivers looking towards the noise source. For research purposes, equivalence in ground impedance may be determined by performing measurements in accordance with the ANSI Standard for measuring ground impedance scheduled for publication in the second half of

1996.[37] For more empirical studies, or if measurements are not feasible, then the ground for BEFORE and AFTER measurements may be judged equivalent if general ground surface type and conditions, e.g., surface water content, are similar.

Equivalence in meteorological conditions includes wind, temperature, humidity, and cloud cover. Wind conditions may be judged equivalent for BEFORE and AFTER measurements if the wind class (See Table 3 in Section 3.2.1) remains unchanged and the vector components of the average wind velocity from source to receiver do not differ by more than a certain limit, which is defined as follows: (1) for an acoustical error within ±1.0 dB and distances less than 70 m (230 ft), this limit is 1.0 m/s (2 mi/h); (2) for an acoustical error within ±0.5 dB and distances less than 70 m (230 ft), at least four BEFORE and AFTER measurements should be made within the limit of 1.0 m/s (2 mi/h). However, these 1.0 m/s limits is not applicable for a calm wind class when strong winds with a small vector component in the direction of propagation exist. In other words, BEFORE/AFTER measurements in such instances should be avoided.[25]

Average temperatures during BEFORE and AFTER measurements may be judged equivalent if they are within 14° C of each other. Also, in certain conditions, dry air produces substantial changes in sound attenuation at high frequencies. Therefore, for a predominantly high-frequency source (most sound energy over 3000 Hz), the absolute humidity for BEFORE and AFTER measurements should be similar.

The BEFORE and AFTER acoustical measurements should be made under the same class of cloud cover (See Table 4 in Section 4.1.1.2).

Equivalence in traffic conditions includes the number and mix of roadway traffic, as well as spectral content, directivity, and spatial and temporal patterns of the individual vehicles. To a certain degree, non-equivalence in traffic conditions can be factored out through the use of a reference microphone (See Section 6.1.2.1).

6.1.2 Microphone Location

6.1.2.1 Reference Microphone

The use of a reference microphone is strongly recommended for all barrier insertion loss measurements. Use of a reference microphone allows for a calibration of measured levels, which accounts for variations in the characteristics of the noise source, e.g., traffic speeds, volumes, and mixes. In most cases, a reference microphone is placed between the noise source and other measurement microphones at a height of 1.5 m (5 ft) directly above the barrier (See Figure 12), and at a distance from the sound source sufficient to minimize **near-field** effects. Typically, a minimum, standard distance of 15 m (50 ft) from the noise source is used. If the barrier is located less than 15 m from the source, the reference microphone should be placed at a distance of 15 m from the noise source, but at a height such that the line of sight between the microphone and the ground plane beneath the source is at least 10° (See Figure 13). This location should remain the same for all measurements, including measurements at the equivalent site, where the barrier is not present.

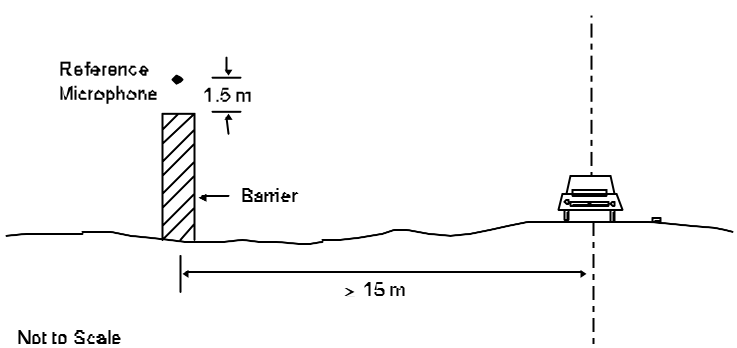

Figure 12. Reference microphone-position 1.

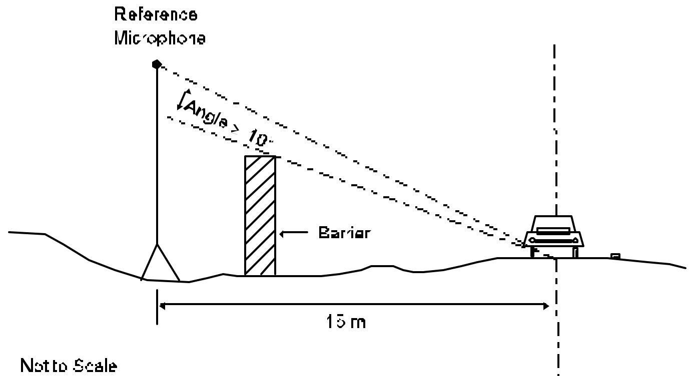

Figure 13. Reference microphone-position 2.

6.1.2.2 Receiver

In most situations, study objectives will dictate specific microphone locations. As such, this section presents a very generic discussion of microphone locations, and assumes no specific study objectives have been identified.

Generally, it is useful to position microphones at offset distances from the barrier which corresponds to incremental doublings of distances (e.g., 15, 30, and 60 m [50, 100, and 200 ft]). Often times measurement sites are characterized by drop-off rates as a function of distance doubling.

In terms of microphone height, 1.5 m (5 ft) is the preferred position. If multi-story structures are of interest, including microphones at heights of 3 m and 6 m (10 ft and 20 ft) may be helpful. Microphone heights should be chosen to encompass all noise-sensitive receivers of interest (See Figure 14).

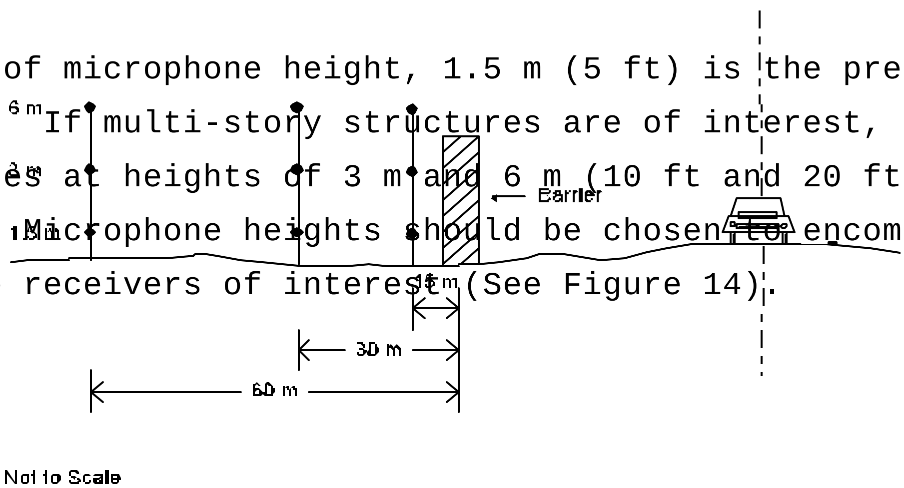

Figure 14. Receiver positions.

For the purpose of determining barrier insertion loss, it is important to remember that microphone locations relative to the sound source in the BEFORE and AFTER cases must be identical. There may be instances when receivers are placed on the lawns of homes within the community adjacent to a noise barrier.

Note: For receiver distances greater than 100 m (300 ft) from the source, atmospheric effects have a much greater influence on measured sound levels.[8,38] In such instances, precise meteorological data will be needed to ensure BEFORE and AFTER equivalence of the meteorological conditions (See Section 3.2).

6.2 NOISE DESCRIPTORS

The equivalent sound level (L_{Aeq}) should be used to describe continuous sounds, such as relatively dense highway traffic. The sound exposure level (L_{AE}), or the maximum A-weighted sound level with fast time response characteristics (L_{AFmx}), should be used to describe the sound of single events, such as individual vehicle pass-bys. The day-night average sound level (L_{dn}) and the community-noise exposure level (L_{den}) may be used to describe long-term noise environments (typically greater than 24 hours), particularly for land-use planning. Note: Once the L_{Aeq} and L_{AE} noise descriptors are established, other descriptors can be computed using the mathematical relationships presented in Section 2.

6.3 INSTRUMENTATION (See Section 3)

- Microphone system (microphone and preamplifier)
- Graphic level recorder (optional)
- Measurement/recording instrumentation
- Calibrator
- Microphone simulator
- Pink noise generator
- Windscreen
- Tripod
- Cabling
- Meteorological instrumentation
- Vehicle-speed detection unit
- Traffic-counting device

6.4 SAMPLING PERIODS

Different sound sources require different sampling periods. For multiple-source conditions, a longer sampling period is needed to obtain a representative sample, averaged over all conditions. Typical sampling periods are 15 minutes, 1 hr and 24 hr. Measurement repetitions at all receiver positions are required to ensure statistical reliability of measurement results. A minimum of three repetitions for like conditions is recommended, with six repetitions being preferred. Table 5 in Section 4.4 presents suggested measurement sampling periods based on the temporal nature and the range in sound level fluctuations of the noise source. Guidance on judgment of the temporal nature of the source may also be found in ANSI S1.13-1971 and ANSI S12.9-1988.[16,47]

6.5 MEASUREMENT PROCEDURES

The following steps apply for all methods except the BEFORE predictions for the "indirect predicted" method, which is discussed separately in Section 6.5.1.

1. Prior to initial data collection, at hourly intervals thereafter, and at the end of the measurement day, the entire acoustic instrumentation system should be calibrated. Meteorological conditions (wind speed and direction, temperature, humidity, and cloud cover) should be documented prior to data collection, at a minimum of 15-minute intervals, and whenever substantial changes in conditions are noted.

2. The electronic noise floor of the acoustic instrumentation system should be established daily by substituting the measurement microphone with a dummy microphone (See Section 3.1.5). The frequency response characteristics of the system should also be determined on a daily basis by measuring and storing 30 seconds of pink noise from a random-noise generator (See Section 3.1.6)

3. Ambient levels should be measured and/or recorded by sampling the sound level at each receiver and at the reference microphone with the sound source quieted or removed from the site. A minimum of 10 seconds should be sampled. Note: If the study sound source cannot be quieted or removed, an upper limit to the ambient level using a statistical descriptor, such as L_{90},may be used. Such upper limit ambient levels should be reported as “assumed.” Note: Most sound level meters have the built-in capability to determine this descriptor.

4. Sound levels should be measured and/or recorded simultaneously with the collection of traffic data, including the logging of vehicle types, as defined in Section 5.1.3, vehicle-type volumes, and the average vehicle speed. It is often easier to videotape traffic in the field and perform counts at a later time. This approach, of course, requires strict time

synchronization between the acoustic instrumentation and the video camera.

(Note: Appendix B provides example field-data log sheets.)

6.5.1 Predicted BEFORE levels for the "Indirect Predicted" Method

1. Perform the data collection for the AFTER case according to Section 6.5.

2. Using the measured traffic data and the observed site data, input the necessary information into a highway-noise prediction model, such as the FHWA TNM, to compute BEFORE levels at the reference position and at each receiver position. It is possible that modeled levels at the reference position may differ substantially in the BEFORE case, as compared with the measured AFTER case. In such instances, the difference observed at the reference microphone shall be used as a calibration factor for all other measurement positions (See Section 6.6).

6.6 DATA ANALYSIS

1. For valid comparisons of BEFORE and AFTER measured levels, the equivalence of meteorological conditions, i.e., wind, temperature, humidity, and cloud cover, should be established (See Section 6.1.1). It is assumed that equivalence of site parameters, such as terrain characteristics and ground impedance, were established prior to performing measurements. Sampling periods in which equivalence cannot be established should be excluded from subsequent analysis.

2. Adjust measured levels for calibration drift (See Section 3.1.4).

3. Adjust measured levels for ambient (See Section 6.6.1).

4. Adjust measured levels for the reflection and/or edge-**diffraction** bias adjustment (See Section 6.6.2).

5. Compute the barrier insertion loss or lower-bound to insertion loss for each source-receiver pair (See Section 6.6.3).

6. Compute the mean barrier insertion loss by arithmetically averaging the insertion loss values from individual sampling periods.

7. Perform an assessment of mean insertion loss values based on study objectives.

6.6.1 Ambient Adjustments

If measured levels do not exceed ambient levels by 4 dB or more, or if the levels at the reference microphone do not exceed those at the receivers, then the barrier insertion loss cannot be determined.

If measured levels exceed the ambient levels by between 4 and 10 dB, and if the levels at the reference microphone exceed those at the receivers, then measured levels must be corrected for ambient as follows (Note: For sound levels which exceed ambient levels by greater than 10 dB, ambient contribution becomes essentially negligible and no correction is necessary):

$$L_{adj}=10*\log_{10}(10^{0.1L_c}-10^{0.1L_a}) \qquad \text{(dB)}$$

where: L_{adj} is the ambient-adjusted measured level;
L_c is the measured level with source and ambient combined; and
L_a is the ambient level alone.

For example:

- L_c = 55.0 dB
- L_a = 47.0 dB

Therefore:

$L_{adj} = 10*\log_{10}(10^{(0.1*55.0)}-10^{(0.1*47.0)}) = 54.3$ dB

6.6.2 Reflections and/or Edge-Diffraction Bias Adjustment

Due to multiple reflections between source and barrier and/or edge diffraction at the top of a barrier, a 0.5 dB correction factor to reference microphone sound levels in the AFTER case may be applied. Good engineering judgment, based on repeatability through measurements, should be used to determine the magnitude and necessity of this correction. For example, if for several runs (i.e., greater than six), a consistent repeatable difference at the reference microphone position in the BEFORE and AFTER case occurs, and it can be proven that the traffic during both cases were equivalent, then the difference can be attributed to edge diffraction effects. The edge diffraction correction factor will be a negative value which is added directly to the sound level measured at the reference microphone in the AFTER case (See Section 6.6.3).[22,31] Note: Larger corrections due to parallel barriers may be necessary.

6.6.3 Insertion Loss

For each measurement repetition and each BEFORE/AFTER pair, the insertion loss, or its **lower bound**, should be determined by subtracting the difference in adjusted reference and receiver levels for the BEFORE case from the difference in adjusted reference and receiver levels for the AFTER case:

$$IL_i = (L_{Aref} + L_{edge} - L_{Arec}) - (L_{Bref} - L_{Brec}) \qquad \text{(dB)}$$

where: IL_i is the insertion loss at the *i*th receiver;
L_{Bref} and L_{Aref} are, respectively, the BEFORE and AFTER adjusted reference levels;
L_{edge} is the edge diffraction correction factor (See Section 6.6.2);
L_{Brec} and L_{Arec} are, respectively, the BEFORE and AFTER adjusted source levels at the *i*th receiver.

For example:
- L_{Aref} = 78.2 dB
- L_{edge} = -0.5 dB
- L_{Arec} at receiver 1= 56.3 dB
- L_{Bref} = 77.7 dB
- L_{Brec} at receiver 1= 65.0 dB

Therefore:

IL_1 = (78.2-0.5-56.2)-(77.7-65.0) = 21.5-(12.7) = 8.8 dB

The lower bound to barrier insertion loss is the value reported when ambient levels are not directly measured without the sound source, i.e., “assumed” ambient.

*Note: There are several useful rules-of-thumb for estimating noise barrier insertion loss. If the line-of-sight is broken by the barrier between the source and the receiver, barrier insertion loss is typically 5 dB. For each additional 1 m (3 ft) of barrier height beyond the line-of-sight blockage, an increase in barrier insertion loss of 1.5 dB can be considered typical. Noise barriers are usually

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* **Rule-of-Thumb**

designed with an insertion loss goal of 10 dB in mind. Actual barrier insertion losses of between 6 and 8 dB are quite common.

*In addition, insertion loss due to buildings is dependent on the amount of gap, or opening, between buildings in the same row. Typically, 4.5 dB attenuation is attainable for the first row of buildings, and an additional 1.5 dB for each subsequent row, up to a maximum of about 10 dB.

Also, to achieve any substantial amount of attenuation due to foliage, such as trees and bushes, foliage must be at least 30 m (100 ft) deep and dense enough to block the line-of-sight. Typically, as much as 5 dB attenuation is attainable.[20,39]

6.7 PARALLEL NOISE BARRIERS

One of the consequences of noise barrier construction on one side of a roadway, is the possibility of noise reflecting to the opposite side of the roadway. Increases in sound level due to a single reflection can practically range from 0.5 to 1.5 dB, with a theoretical increase of 3 dB when 100 percent of the sound energy is reflected. A 3 dB increase is generally just slightly perceptible to the human ear.

Although the overall sound level increase due to reflections off a single barrier may not be readily perceptible, the frequency of the reflected sound may alter the signature of the source as perceived by residents on the opposite side of the road. This change in the general character of the sound may be perceptible, although no conclusive research has been done in this area.

However, construction of barriers on both sides of the highway may not solve this potential problem. Sound reflected between both barriers may cause degradations in each barrier’s performance anywhere from 2 to as much as 6 dB, i.e., a single reflective barrier with an insertion loss of 10 dB may only realize an effective reduction of 4 to 8 dB if another reflective barrier is placed parallel to it on the opposite side of the highway.

There are several methods used to minimize the reflections from single barriers and reflections between parallel barriers:

- For parallel barriers, ensure that the distance (width) between the two barriers is at least 10 times their average height relative to the roadway elevation (width-to-height ratio or w/h ratio).

  In recent studies,[22,25] it was determined that as the w/h ratio increases, the insertion loss degradation tends to decrease. This decrease was attributed to: (1) the decrease in the number of reflections between the barriers; and (2) the weakening of the reflections due to geometrical spreading and atmospheric absorption. Table 7 provides a guideline of three, general w/h ratio ranges and the corresponding barrier insertion-loss degradation ($)_{IL}$) that can be expected.

Table 7. Guideline for categorizing parallel barrier sites based on the width-to-height ratio.

w/h Ratio	Maximum $)_{IL}$ in dB(A)	Recommendation
Less than 10:1	3 or greater	Action required to minimize degradation
10:1 to 20:1	0 to 3	Degradation acceptable in most instances
Greater than 20:1	No measurable degradation	No action required

- Apply acoustically absorptive material on either one or both barrier facades. Absorptive treatment may be categorized by the amount of incident sound that a barrier absorbs. Currently, the **Noise Reduction Coefficient** (NRC) is the measure of choice. NRC is defined as the arithmetic average of the **Sabine absorption coefficients**, "$_{Sab}$, at 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. Measurements to determine the "$_{Sab}$ of a facade should be made in accordance with the American Society of Testing and Materials (ASTM) Recommended Practice C 423-90a (Reverberation Room Method).(40) An alternative method for computing the NRC is to determine the absorption coefficients using ASTM Recommended Practice C384-95a (Impedance Tube Method).(41) The Reverberation Room method provides a measure of material absorption for randomly incident sound while the Impedance Tube method provides a measure of absorption for normal incident sound. Typically, the reverberation room method is used for determining NRC.

  NRC values theoretically range from 0 to 1, where 0 indicates that the barrier will reflect all the incident sound, and 1 indicates that the barrier will absorb all the incident sound. However, very often when a material is tested in a reverberation room (ASTM C423-90a), NRC values higher than 1 may be computed. This is the result of an anomaly in the test procedure. To correct for this anomaly, and, in turn, obtain a meaningful NRC, the four absorption coefficients should first be normalized such that the highest one is equivalent to 1.0, and the factor that was applied to the highest one should then, in turn, be applied to the remaining three coefficients. Typical NRC values for an absorptive barrier range from 0.6 to 0.9.

- Tilt one of the barriers outward away from the road. Previous research has shown that an angle as small as 7 degrees is quite effective at minimizing degradations.[31] Note: This method must consider structures higher than the opposite barrier. High structures may be adversely affected by the reflected sound.

6.8 NOISE BARRIER SOUND TRANSMISSION CLASS

A barrier may be described by the amount of noise it transmits, i.e., its **Sound Transmission Class** (STC). Measurements to determine the STC of a section of a barrier should be made in accordance with ASTM Recommended Practice E 413-87.[42]

Usually it is assumed that the sound transmitted through a barrier is negligible relative to that which is diffracted over the top, i.e., the sound transmitted is at least 20 dB below that diffracted. Most state transportation agencies specify a minimum STC for barriers constructed within their state.

7. CONSTRUCTION EQUIPMENT NOISE MEASUREMENTS FOR HIGHWAY-RELATED PROJECTS

This section describes recommended procedures for the measurement of highway construction equipment noise. The results of these measurements can be used to assess the potential noise impact of a construction site associated with a highway-related project.

Highway construction site activity consists of several generic phases, including mobilization, clearing and grading, earthwork, foundations, bridge construction, base preparation, paving, and cleanup. Thus, any noise impact due to a construction site is actually composed of contributions from each of these phases.[43]

The noise level associated with a particular construction phase is determined by first measuring the levels of individual equipment, then summing the individual contributions over a particular time period. The types and numbers of construction equipment, and the amount of time specific equipment operate in different modes are a direct function of the construction phase.

For the procedures described herein, each type of construction equipment will be characterized by up to four modes of operation as appropriate: (1) the equipment is stationary in a passive operation mode (STATIONARY-PASSIVE, e.g., a bulldozer at idle); (2) the equipment is stationary in an active operation mode (STATIONARY-ACTIVE, e.g., a bulldozer lifting earth, debris, etc.); (3) the equipment is moving to another area within a site but is not actively performing project-related activities (MOBILE-PASSIVE); and (4) the equipment is mobile in an active operation mode (MOBILE-ACTIVE, e.g., a bulldozer moving while pushing earth, debris, etc).

7.1 SITE SELECTION

7.1.1 Site Characteristics

In determining overall noise levels associated with a particular construction site, the first step is to establish reference noise emission levels for each type of construction equipment operating in each of the above four modes. As such, the general site characteristics for determining reference noise emission levels for construction equipment are somewhat similar to those presented in Section 5.1.1 for determining noise emissions for highway vehicles. These characteristics are as follows:

- A flat open space free of large reflecting surfaces, such as parked vehicles, signboards, buildings, or hillsides, located within 30 m (100 ft) of either the construction equipment's path (if measurements of mobile operations are being performed), its stationary position (if appropriate), or the microphone(s).
- The ground surface within the measurement area is free of snow and representative of acoustically hard, e.g., pavement, or acoustically soft, e.g., grass, terrain.
- The line-of-sight from the microphone(s) to the construction equipment being measured unobscured within an arc of 150 degrees.
- A predominant, ambient level at the measurement site low enough to enable the measurement of uncontaminated vehicle pass-by sound levels. Specifically, the difference between the lowest-anticipated, vehicle pass-by, maximum A-weighted sound-pressure level (L_{AFmx}) and the A-weighted ambient level, as measured at the 15-m (50-ft) microphone, should be at least 10 dB.
- The site to be located away from known noise sources, such as airports, construction sites, rail yards, or heavily traveled roadways, if possible.

7.1.2 Microphone Location

Microphones should be positioned at a height of 1.5 m (5 ft) above ground level (AGL), and placed at a distance of 15 m (50 ft) perpendicular to the equipment's typical operating location (for STATIONARY-PASSIVE and STATIONARY-ACTIVE operating modes), and typical operating path (for MOBILE-PASSIVE and MOBILE-ACTIVE operating modes). For stationary noise sources, measurements should be made at each of 4 positions around each piece of construction equipment, each position representing azimuth angles separated by 90 degrees (See Figure 15).[44] For mobile noise sources, measurements should be made with each piece of equipment passing by in a left-to-right and a right-to-left direction (See Figure 15).[44,45] For all measurements, a minimum of three measurement repetitions, and preferably six, should be made.

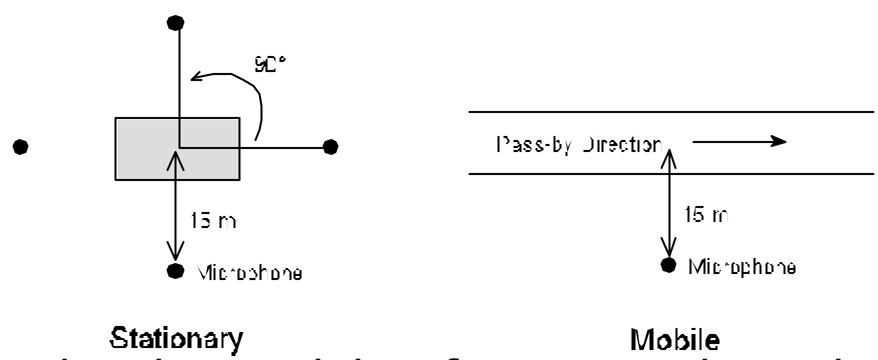

Figure 15. Microphone positions for construction equipment noise measurements.

7.2 NOISE DESCRIPTORS

For stationary noise sources, a 30-second L_{Aeq} should be measured at each of the four azimuth angles. If a 30-second measurement is not possible, shorter durations can be used if the sound level is relatively steady as a function of time. For mobile noise sources, the L_{AFmx} should be measured. The individual reference levels and the number and type of each piece of construction equipment are then, ultimately, used to compute the total equivalent sound level,

$L_{Aeq,total}$, for a typical work day during a particular construction phase. Note: Once the L_{Aeq} descriptor has been established for a typical work day and construction phase, other descriptors can be computed using the mathematical relationships presented in Section 2. The L_{Aeq} descriptor may be more useful in assessing potential noise impact due to construction-related activity.

7.3 INSTRUMENTATION (See Section 3)

Microphone system (microphone and preamplifier)
Graphic level recorder (optional)
Measurement/recording instrumentation
Calibrator
Microphone simulator
Pink noise generator
Windscreen
Tripod
Cabling
Meteorological instrumentation
Tachometer (optional)

7.4 SAMPLING PERIOD

For each type of construction equipment, the sampling period will vary depending upon the operating mode (STATIONARY-PASSIVE, STATIONARY-ACTIVE, MOBILE-PASSIVE, and MOBILE-ACTIVE). For each mode, the construction equipment should be operated in a manner which is considered typical for the work period associated with a particular mode. Due to the expected abundance of activity at a construction site, the sampling period may be based entirely on good engineering judgment; and it will be up to the person performing the measurements to ensure that representative high-quality data are obtained.

7.5 MEASUREMENT PROCEDURE

1. The instrumentation should be deployed as shown in Figure 15.

2. Prior to initial data collection, at hourly intervals thereafter, and at the end of the measurement day, the entire acoustic instrumentation system should be calibrated. Meteorological conditions (wind speed and direction, temperature, humidity, and cloud cover) should be documented prior to data collection, at a minimum of 15-minute intervals, and whenever substantial changes in conditions are noted.

3. The electronic noise floor of the acoustic instrumentation system should be established daily by substituting the measurement microphone with a dummy microphone (See Section 3.1.5). The frequency response characteristics of the system should also be determined on a daily basis by measuring and storing 30 seconds of pink noise from a random-noise generator (See Section 3.1.6).

4. Ambient levels should be measured and/or recorded by sampling the sound level at each receiver with the sound source quieted or removed from the site. A minimum of 10 seconds should be sampled. Note: If the study sound source cannot be quieted or removed, an upper limit to the ambient level using a statistical descriptor, such as L_{90}, may be used. Such upper limit ambient levels should be reported as "assumed." Note: Most sound level meters have the built-in capability to determine this descriptor.

5. For each mode, the construction equipment should be operated in a manner which is considered typical for the work period and the particular mode.

6. For each equipment type and operating mode, record the L_{AFmx} or L_{Aeq30s}, as appropriate.

(Note: Appendix B provides example field-data log sheets.)

7.6 DATA ANALYSIS

1. Adjust measured levels for calibration drift (See Section 3.1.4).

2. Adjust measured levels for ambient (See Section 7.6.1).

3. Calculate an energy-averaged level ($L_{AVG,j}$) of the L_{Aeq30s} values obtained for each azimuth angle and each measurement repetition of each equipment type in each stationary mode of operation, j (See Section 7.4).

4. Calculate an energy-averaged level ($L_{AVG,j}$) of the L_{AFmx} values obtained for each measurement repetition of each equipment type in each mobile mode of operation, j (See Section 7.4).

5. Calculate the $L_{Aeq,i}$ for each equipment type, i (See Section 7.6.2).

6. When all equipment measurements used for a particular phase are complete, compute the $L_{Aeq,total}$ for a typical workday during that phase (See Section 7.6.3).

7. Perform an assessment of noise impact due to construction equipment activity based on study objectives. In most instances, the $L_{Aeq,total}$ computed above will be used in Environmental Analyses to compare the potential impact of different construction phases. If a particular noise-sensitive

receiver is a primary concern in the study, it is suggested that long-term existing-noise measurements be made at that location, in accordance with the recommendations in Section 4.

7.6.1 Ambient Adjustments

If measured levels do not exceed ambient levels by 4 dB or more, i.e., they are masked, then those data should be omitted from data analysis.

If measured levels exceed the ambient levels by between 4 and 10 dB, then correct the measured levels for ambient as follows (Note: For source levels which exceed ambient levels by greater than 10 dB, ambient contribution becomes essentially negligible and no correction is necessary):

$$L_{adj} = 10 * \log_{10}(10^{0.1L_c} - 10^{0.1L_a}) \quad \text{(dB)}$$

where: L_{adj} is the ambient-adjusted measured level;
L_c is the measured level with source and ambient combined; and
L_a is the ambient level alone.

For example:

- L_c = 55.0 dB
- L_a = 47.0 dB

Therefore:

L_{adj} = $10*\log_{10}(10^{(0.1*55.0)}-10^{(0.1*47.0)})$ = 54.3 dB

7.6.2 Determination of the Equivalent Sound Level for Each Type of Construction Equipment

The equivalent sound level for a particular type, i, of construction equipment is computed as follows:

$$L_{Aeq,i} = 10*\log_{10}\sum_{j=1}^{4}\left[10^{\frac{L_{Avg,j}}{10}*(T_j)} * \frac{T_j}{T_{total}} * N_j\right]$$

(dB)

where: $L_{Aeq,i}$ is the equivalent sound level for equipment type i;

j is the operating mode, where up to four modes are applicable for each type of equipment;

$L_{AVG,j}$ is energy-averaged level obtained in operating mode j;

T is the operating mode duration, in seconds; and

N is the number of pieces of equipment type i operating in mode j.

For example:

- $L_{AVG,1}$ = 65.5 dB for T_1 = 600 seconds and N = 3 pieces
- $L_{AVG,2}$ = 86.7 dB for T_2 = 5500 seconds and N = 2 pieces
- $L_{AVG,3}$ = 71.0 dB for T_3 = 350 seconds and N = 2 pieces
- $L_{AVG,4}$ = Not applicable

Therefore:

$$L_{Aeq,1} = 10\log_{10}\left[\left(10^{\frac{65.5}{10}} * \frac{600}{6450} * 3\right) + \left(10^{\frac{86.7}{10}} * \frac{5500}{6450} * 2\right) + \left(10^{\frac{71.0}{10}} * \frac{350}{6450} *\right.\right.$$

= 89.0 dB

7.6.3 Determination of the Total Equivalent Sound Level

The total equivalent sound level for a typical work day during a particular construction phase is computed as follows:

$$L_{Aeq,total} = 10*\log_{10}\sum_{i=1}^{k}\left[10^{\frac{L_{Aeq,i}}{10}}\right] \quad \text{(dB)}$$

where: $L_{Aeq,total}$ is the total equivalent sound level for a typical work day during a particular construction period;

k is the number of different types of equipment; and

$L_{Aeq,i}$ is the equivalent sound level for equipment type i.

For example:

- $L_{Aeq,1}$ = 89.0 dB
- $L_{Aeq,2}$ = 81.7 dB
- $L_{Aeq,3}$ = 79.0 dB
- $L_{Aeq,4}$ = 80.5 dB

Therefore:

$$L_{Aeq,total} = 10\log_{10}\left[10^{\frac{89.0}{10}} + 10^{\frac{81.7}{10}} + 10^{\frac{79.0}{10}} + 10^{\frac{80.5}{10}}\right]$$

$$= 90.6 \text{ dB}$$

8. BUILDING NOISE REDUCTION MEASUREMENTS IN THE VICINITY OF A HIGHWAY

This section describes recommended procedures for the measurement of building noise reduction, i.e., the effectiveness of a building structure in insulating residents from outside noise sources, in this case, highways. In contrast, these procedures may also be used to determine how effectively a structure contains internal noise, especially where the external environment is quieter than the noise environment within the building.[20] The following procedures are in accordance with the American Society of Testing and Materials (ASTM) Standard E966-84.[32]

Two sets of measurements are recommended: (1) exterior measurements of the roadway noise. (Note: If a traffic noise source is not available, a fixed, artificial noise source, such as a loudspeaker, may be used); and (2) interior measurements of the roadway noise within the building itself. The difference between the exterior and interior measured sound levels is the resulting noise reduction performance for that building, or commonly referred to as the "outdoor-indoor noise reduction."

8.1 SITE SELECTION

8.1.1 Site Characteristics

8.1.1.2 Interior Measurements

The interior location should be a completely enclosed space with, preferably, its largest dimension no greater than twice its smallest. During measurements, all other noise-generating activities in the room should be quieted. In addition, the interior ambient level should be at least 10 dB below the lowest-anticipated, vehicle pass-by, maximum A-weighted sound-pressure level (L_{AFmx}).

8.1.1.2 Exterior Measurements

Exterior measurement sites should have the following geometric characteristics:

- A flat open space relatively free of large reflecting surfaces, such as parked vehicles, signboards, hillsides, or buildings other than the subject building, located within 30 m (100 ft) of either the vehicle path or the microphones.
- A predominant, ambient level at the measurement site low enough to enable the measurement of vehicle pass-by sound levels. Specifically, the difference between the lowest-anticipated, vehicle pass-by, maximum A-weighted sound-pressure level (L_{AFmx}) and the A-weighted ambient level, as measured at the exterior microphone, should be at least 10 dB.
- The line-of-sight from microphone positions to the roadway unobscured within an arc of 150 degrees.
- The site to be located away from known noise sources, such as airports, construction sites, or rail yards.

8.1.2 Microphone Location

8.1.2.1 Interior Measurements

Microphones are placed at 1.5 m (5 ft) above the floor of the interior location and at least 1 m (3 ft) from any walls (See Figure 16). Measurements at several different heights and locations in the room are strongly recommended to achieve statistical precision.

8.1.2.2 Exterior Measurements

There are two potential locations for the placement of the exterior microphone as shown in Figure 16:

<u>Position 1</u>: At least 3 m (10 ft) from the side of the building, at the same distance from the road as the front wall, at a height of 1.5 m (5 ft) AGL. This position must be carefully selected such that the microphone is not shielded from the road by the building, or

influenced by noise sources behind the building. This positioning essentially eliminates influences on the measured levels due to reflections. As such, this is the preferred position.

Position 2: Not greater than 2 m (6.6 ft) from the facade, located on the roadway side of the building, at a point opposite the middle of the facade, at a height of 1.5 m (5 ft) AGL. This setup is not recommended if the roadway facade of the building is within 7.5 m (25 ft) of the centerline of the near lane of traffic.

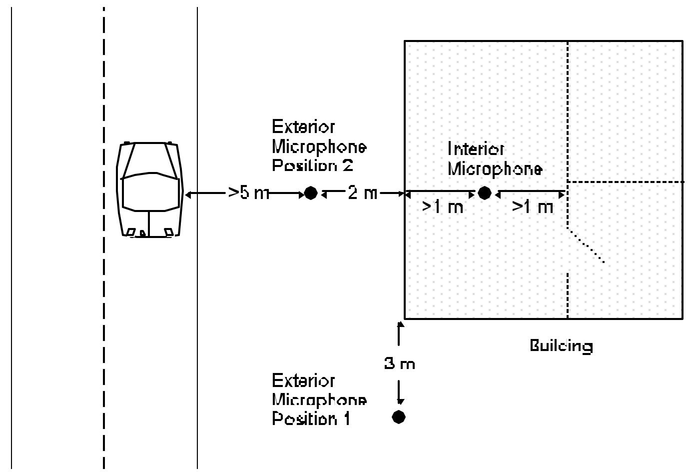

Figure 16. Microphone positions for building noise reduction measurements.

8.1.3 Artificial Noise Source Position

If a loudspeaker is used, it should be located at a distance from the building facade such that the ratio of the distances from the loudspeaker to the farthest (D1) and nearest (D2) edges of the facade is no greater than two, i.e., D1/D2 # 2. The loudspeaker should be angled at an incidence within the range of 15 and 60 degrees, preferably at an angle of 45 degrees (See Figure 17). This angle, 2 ,is determined by the perpendicular to the facade midpoint and the line joining the loudspeaker to the midpoint.

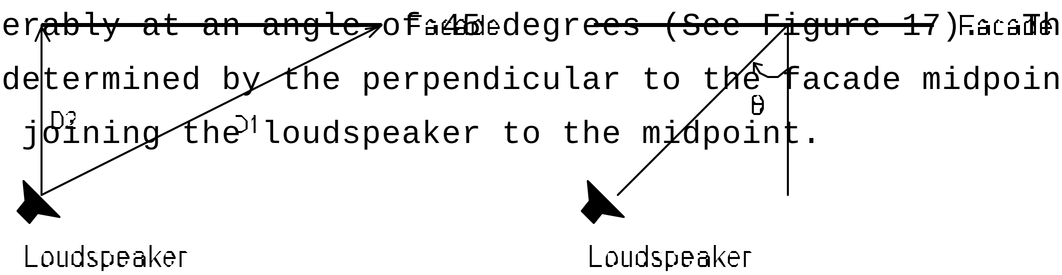

Figure 17. Loudspeaker position.

8.2 NOISE DESCRIPTORS

The equivalent sound level (L_{Aeq}) should be used to describe continuous sounds, such as relatively dense highway traffic. The sound exposure level (L_{AE}), or the maximum A-weighted sound level with fast time response characteristics (L_{AFmx}), should be used to describe the sound of single events, such as individual vehicle pass-bys. The day-night average sound level (L_{dn}) and the community-noise exposure level (L_{den}) may be used to describe long-term noise environments (typically greater than 24 hours), particularly for land-use planning. Note: Once the L_{Aeq} and L_{AE} noise descriptors are established, other descriptors can be computed using the mathematical relationships presented in Section 2. Ultimately, the particular descriptor chosen is of little importance since the objective of these measurements is to obtain a change in sound level.

8.3 INSTRUMENTATION (See Section 3)

- Microphone system (microphone and preamplifier)
- Graphic level recorder (optional)
- Measurement/recording instrumentation
- Calibrator
- Microphone simulator
- Pink noise generator
- Windscreen
- Tripod
- Cabling

Meteorological instrumentation
Vehicle-speed detection unit
Traffic-counting device
Artificial noise source (if applicable)

8.4 SAMPLING PERIOD

Different sources may require different measurement periods. For multiple-source conditions, a longer sampling period is needed to obtain a representative sample averaged over all conditions. Typical sampling periods are 15 minutes, 1 hr and 24 hr. Measurement repetitions at all receiver positions are required to ensure statistical reliability of measurement results. A minimum of 3 repetitions for like conditions is recommended, with 6 repetitions being preferred. Table 5 in Section 4.4 presents suggested measurement sampling periods based on the temporal nature and the range in sound level fluctuations of the noise source. Guidance on judgment of the temporal nature of the source may be found in ANSI S1.13-1971.[16]

8.5 MEASUREMENT PROCEDURE

1. Prior to initial data collection, at hourly intervals thereafter, and at the end of the measurement day, the entire acoustic instrumentation system should be calibrated. Meteorological conditions (wind speed and direction, temperature, humidity, and cloud cover) should be documented prior to data collection, at a minimum of 15-minute intervals, and whenever substantial changes in conditions are noted.

2. The electronic noise floor of the acoustic instrumentation system should be established daily by substituting the measurement microphone with a dummy microphone (See Section 3.1.5). The frequency response characteristics of the system should also be determined on a daily basis by measuring and

storing 30 seconds of pink noise from a random-noise generator (See Section 3.1.6)

3. Ambient levels should be measured and/or recorded by sampling the sound level at each receiver and at the reference microphone with the sound source quieted or removed from the site. A minimum of 10 seconds should be sampled. Note: If the study sound source cannot be quieted or removed, an upper limit to the ambient level using a statistical descriptor, such as L_{90}, may be used. Such upper limit ambient levels should be reported as "assumed." Note: Most sound level meters have the built-in capability to determine this descriptor.

4. The interior and exterior measurements should then be performed simultaneously; and the characteristics of the source should be carefully documented (e.g., if actual highway traffic is being used, the volume, speed, and mix should be recorded).

(Note: Appendix B provides example field-data log sheets.)

8.6 DATA ANALYSIS

1. Adjust measured levels for calibration drift (See Section 3.1.4).

2. Adjust measured levels for ambient (See Section 8.6.1).

3. Compute the building noise reduction (NR) as follows:
   For exterior microphone at Position 1:

$$NR = L_{exterior} - L_{interior} \quad \text{(dB)}$$

   For exterior microphone at Position 2:*

---

* At distances greater than ¼-wavelength from the facade of the building, the incident and reflected waves result in a level 3 dB higher than would be measured due to the incident wave alone. Thus the 3-dB correction for the 2-m exterior microphone position is acceptable down to about 50 Hz.

$$NR = L_{exterior} - L_{interior} - 3 \qquad \text{(dB)}$$

For example:

- $L_{exterior}$ = 77.0 dB for microphone-position 2
- $L_{interior}$ = 65.0 dB

Therefore:

NR = 77-65-3 = 9 dB

8.6.1 Ambient Adjustments

If measured levels do not exceed ambient levels by 4 dB or more, i.e., they are masked, then those data should be omitted from data analysis.

If measured levels exceed the ambient levels by between 4 and 10 dB, then correct the measured levels for ambient as follows (Note: For source levels which exceed ambient levels by greater than 10 dB, ambient contribution becomes essentially negligible and no correction is necessary):

$$L_{adj} = 10*\log_{10}(10^{0.1L_c} - 10^{0.1L_a}) \qquad \text{(dB)}$$

where: L_{adj} is the ambient-adjusted measured level;
L_c is the measured level with source and ambient combined; and
L_a is the ambient level alone.

For example:

- L_c = 55.0 dB
- L_a = 47.0 dB

Therefore:

L_{adj} = $10*\log_{10}(10^{(0.1*55.0)}-10^{(0.1*47.0)})$ = 54.3 dB

9. HIGHWAY-RELATED OCCUPATIONAL NOISE EXPOSURE MEASUREMENTS

This section describes recommended procedures for the measurement of highway-related occupational noise exposure. Highway toll plaza and tunnel employees, highway maintenance and repair crews, and highway inspectors may be exposed to sound levels hazardous to hearing. Occupational noise exposure was developed to rate a person's susceptibility to hearing loss and to study noise environments that may be hazardous to hearing.[8] The following procedures are in accordance with ANSI S12.19-1996.[47]

For occupational noise exposures greater than 90 dB(A) in an 8-hour workday, the Occupational Safety and Health Administration (OSHA) requires mandatory hearing-conservation measures, such as audiometric testing or hearing protectors. OSHA defines a 90-dB(A) noise exposure as the criterion sound level, denoted herein by the symbol, LC; OSHA defines an 8-hour workday as the criterion duration, denoted herein by the symbol, TC.[48] A continuous criterion sound level over an entire criterion duration would result in 100 percent of an employee's allowable noise exposure. In addition, for exposures greater than 90 dB(A), some type of noise abatement action, such as machinery noise reduction via redesign or replacement, source/receiver isolation/enclosure, or employee exposure time limits, must be initiated.

For varying exposure durations, OSHA limits may be adjusted accordingly by the use of an exchange rate. For occupational noise exposure studies, OSHA requires the use of a 5-dB(A) exchange rate. In other words, for each additional 5 dB(A) of noise exposure up to 115 dB(A), the permitted duration is halved; for each reduction of 5 dB(A), the permitted duration is doubled. For example, if the noise exposure is 95 dB(A), a duration of 4 hours is permissible according to OSHA.

In addition, OSHA states that “exposure to impulsive or impact noise level should not exceed 140 dB.” However, the regulations do not define what constitutes an impulsive or impact sound, nor do they address frequency weighting (See Section 3.1.3.4.2) of the measuring instrument, or whether the measurement uses one or none of the standard exponential time-averagings (See Section 3.1.3.4.4).[8] For the purposes of this document, it is recommended that the maximum A-weighted sound level, L_{AFmx}, be used to ensure the 140 dB criterion is met.

9.1 SITE SELECTION

For the purposes of noise exposure measurements, a noise dosimeter or a sound level meter can be used. To a certain degree, the particular instrument chosen will dictate the site-selection process.

9.1.1 Noise Dosimeter

The noise dosimeter should be worn by the employee during his/ her daily work routine. Its accompanying microphone should, preferably, be located on the employee's shoulder. If the employee is consistently exposed to noise from one particular side, the microphone should be placed on the associated side. The microphone cable, which connects to the dosimeter, should be routed and fastened such that it does not interfere with the employee's safety or performance. The main body of the dosimeter may be located/attached to the employee's clothing at any convenient location. If the employee works at only one particular station, or if the employee will not be present during measurements, the dosimeter may be placed on a tripod at a representative position within the area.

9.1.2 Sound Level Meter

Because of their larger size as compared with noise dosimeters, and due to the fact that they often do not have readily detachable microphones, sound level meters are often not logistically feasible to be worn directly by an employee. Consequently, they are typically positioned on a tripod within the work area. Specifically, the microphone should be positioned at a height approximately equal to that of the employee's head and as close as possible to the his/her ear. ANSI 12.19-1996 recommends a distance of 0.1 m (4 in) from the employee's ear, if feasible. In addition, the microphone should be placed such that shielding by the employee or other objects is avoided. If the employee works at only one particular station, or if the employee will not be present during measurements, the microphone and sound level meter may be placed on a tripod at a representative position within the area.

9.2 NOISE DESCRIPTORS

The equivalent sound level, L_{Aeq}, and the duration of each measurement period should be recorded. The L_{Aeq} and the duration are then used to compute noise dose, which is, in turn, used to compute the time-weighted average sound level ($L_{TWA(TC)}$), i.e., the employee's "noise exposure." As stated earlier, TC is the OSHA criterion duration of 8 hours. In addition, the maximum A-weighted sound level, L_{AFmx}, should be recorded to ensure that the employee is not subjected to impulsive or impact noise levels greater than 140 dB(A).

9.3 INSTRUMENTATION (See Section 3)

Microphone system (microphone and preamplifier)
Graphic level recorder (optional)
Noise dosimeter or sound level meter
Calibrator
Microphone simulator

Windscreen (if the employee's primary work area is outdoors)
Tripod
Cabling
Meteorological instrumentation (if the employee's primary work area is outdoors)

9.4 SAMPLING PERIOD

The measurement duration should be sufficiently long, such that the resulting noise exposure is representative of the noise exposure associated with each task/location. For continually varying sound environments (sound level fluctuations greater ± 2.5 dB(A)), a longer sampling period is recommended. In most cases, noise exposure measurements are performed over a typical 8-hour work day.

9.5 MEASUREMENT PROCEDURES

1. Prior to initial data collection, after data collection is complete, and at convenient times throughout the measurement day, calibrate the noise dosimeter or sound level meter.

2. Record the L_{Aeq} and the associated duration in addition to the L_{AFmx} for each measurement period. Note: For a measurement to be considered valid:
   a. The microphone should not be moved from its original position during the measurement period.
   b. The employee should not speak directly into the microphone.
   c. The unit should be periodically checked for proper use.

(Note: Appendix B provides example field-data log sheets.)

9.6 DATA ANALYSIS

1. Adjust measured levels for calibration drift (See Section 3.1.4).

2. Calculate the noise dose for a typical workday (See Section 9.6.1).

3. Calculate the noise exposure for a typical workday (See Section 9.6.2).

4. Perform an assessment of noise impact based on the calculated noise exposure. The maximum recorded sound levels for each task/location should also be considered in the assessment. The overall objective of any assessment should be to determine the necessity to implement hearing-conservation measures, or some type of noise abatement action.

9.6.1 Determination of Noise Dose

The total noise dose for a typical workday is a summation of the individual task/location noise doses and is computed as follows:

$$D = 100\left[\sum_{i=1}^{n}\left(\frac{C_i}{T_i}\right)\right] = 100\left[\frac{C_1}{T_1}+\frac{C_2}{T_2}+\ \dots\ \frac{C_n}{T_n}\right] \qquad (\%)$$

where:

$$T_i = \frac{TC}{2^{[(L_{Aeq,i} - LC)/Q]}}$$

The variables in the above equations are defined as follows:

D	=	Noise dose, expressed as a percentage;
C_i	=	Measurement duration at task/location i;
T_i	=	Permissible duration at task/location i;
$L_{Aeq,i}$	=	Equivalent sound level measured during task/ location, i (Note: If the $L_{Aeq,i}$ for a specific measurement period

is below the OSHA-defined threshold level of 80 dB(A), it is not considered in the noise dose computation);

LC = OSHA criterion level of 90 dB(A);

Q = OSHA exchange rate of 5 dB(A); and

TC = OSHA criterion duration of 8 hours;

For example:

- $L_{Aeq,1}$ = 88.0 dB, C1 = 0.33 hours, ˆ T_1 = 10.6
- $L_{Aeq,2}$ = 73.0 dB, C1 = 0.33 hours, ˆ T_1 = 4
- $L_{Aeq,3}$ = 90.0 dB, C1 = 2.6 hours, ˆ T_1 = 8.00
- $L_{Aeq,4}$ = 105.0 dB, C1 = 3.5 hours, ˆ T_1 = 1.00
- $L_{Aeq,5}$ = 108.0 dB, C1 = 1.24 hours, ˆ T_1 = 0.66
- $L_{Aeq,6}$ = 95.0 dB, C1 = 2.00 hours, ˆ T_1 = 4.00

Therefore:

$$D = 100\left[\frac{0.33}{10.6}+\frac{0.33}{\infty}+\frac{2.6}{8.0}+\frac{3.5}{1.0}+\frac{1.24}{0.66}+\frac{2.0}{4.0}\right] = 623.5\ \%$$

9.6.2 Determination of Noise Exposure

The total noise exposure for a typical workday is computed as follows:

$$L_{TWA(TC)} = \left[\frac{Q}{\log_{10}(2)}\right]\left[\log_{10}\left(\frac{D}{100}\right)\right] + LC \qquad \text{(dB)}$$

The variables in the above equation are defined as follows:

$L_{TWA(TC)}$ = Noise exposure (time-weighted average sound level);

Q = OSHA exchange rate of 5 dB(A);

D = Noise dose, expressed as a percentage; and

LC = OSHA criterion level of 90 dB(A).

For example:

- D = 623.5%

Therefore:

$$L_{TWA(8)} = \left[\frac{5}{\log_{10}(2)}\right]\left[\log_{10}\left(\frac{623.5}{100}\right)\right] + 90 = 103.2\ \text{dB}$$

10. REPORT DOCUMENTATION

This section details the information to be documented in the field measurement report. It is general enough to be applicable to all sections discussed herein. Report documentation shall include all procedures in sufficient detail such that the measurement results can be repeated. It shall include clearly stated measurement objectives, field measurement equipment and detailed field measurement procedures, a description of the noise source, the descriptors used, and detailed data analyses and results, including detailed meteorological conditions.(6,8,49) A sample computation of experimental error is also recommended. Note: A sample report has been provided in Appendix D.

10.1 SITE SKETCHES

10.1.1 Plan View

A plan view illustrates the site as if looking down upon it from above. The plan view should include the location of the source(s), receiver(s), and any notable geographical objects, such as trees, bodies of water, hills, buildings, and signs. Relative distances of all objects should also be indicated (See Figure 18).

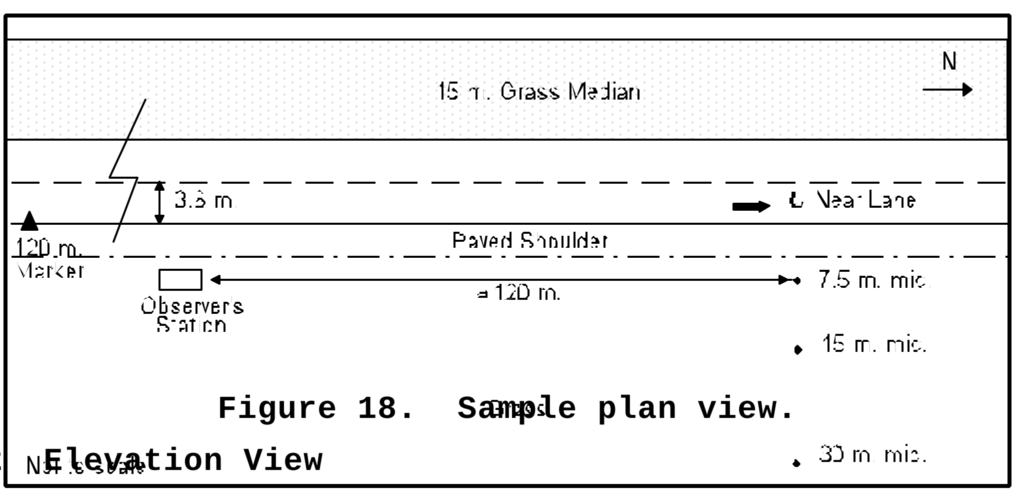

Figure 18. Sample plan view.

10.1.2 Elevation View

An elevation view illustrates the site from a viewpoint normal to the ground plane, cutting across or slicing the cross-section. It should include the relative slopes and elevations of the source, receiver, terrain, buildings, and other objects at that site for a given source-receiver pair (See Figure 19).

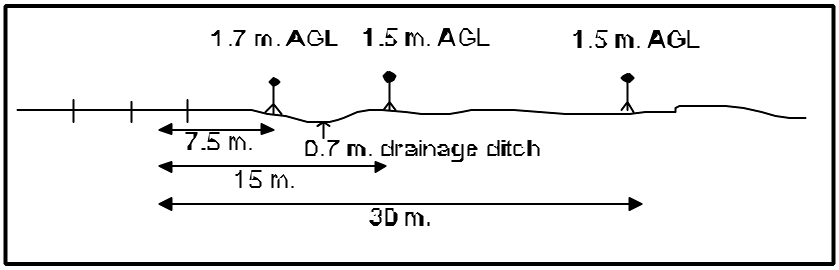

Figure 19. Sample elevation view.

10.2 SOURCE DESCRIPTION

A detailed description of the source should be provided. If applicable, this may include information regarding make, model, type, speed, etc., if an individual noise source; or volume and speed, if a fleet of vehicles.

10.3 INSTRUMENTATION DESCRIPTION

The manufacturer, model number, serial number, and parameter settings, including gain settings, for all instrumentation should be documented. A block diagram of the measurement and analysis systems should also be included. Calibration, frequency response, and noise floor data should all be provided.

10.4 METEOROLOGICAL DATA

Weather conditions should be documented at a minimum of 15-minute intervals, and whenever substantial changes in conditions are noted. These conditions include wind speed, wind direction, temperature, humidity, cloud cover, and time-of-day when these data were measured.

10.5 GROUND SURFACE CHARACTERIZATION

The ground characteristics for both the sources and receivers should also be documented, e.g., **hard** or **soft ground** (See Section 2).

10.6 BARRIER CHARACTERISTICS

For barrier insertion loss measurements, the following barrier characteristics need to be documented: barrier height, length, location, material, Noise Reduction Coefficient, Sound Transmission Class, and tilt angle (if applicable).

10.7 MEASUREMENT PROCEDURES

All field measurement procedures should be documented. These procedures should be detailed such that the measurement results are able to be repeated by other individuals.

10.8 ACOUSTICAL DATA

Data acquired from field measurements and analyses, as well as the procedures used, should be documented fully. Also to be recorded are all adjustments applied to the data due to calibration drift, ambient influences, and instrumentation non-linearities.

10.9 INCIDENTAL OBSERVATIONS AND CONCLUSIONS

A discussion of any unforeseen events during the measurements should be included. Any situations that suggest modifications to the experiment for improved results should be documented. Any relevant subjective judgments or interpretations may appear in this section of the measurement report.

APPENDIX A

RELATIVE HUMIDITY COMPUTATION

This appendix presents the procedures for converting measured dry and wet bulb temperatures into relative humidity expressed in percent.

1. Convert Dry Bulb temperature from °F to °C:

$$\text{Dry, °C} = \frac{[(Dry, °F) - 32]}{1.8}$$

2. Convert Dry Bulb temperature from °C to °K:

$$\text{Dry, °K} = (\text{Dry,°C}) + 273.15$$

3. Repeat steps 1 and 2 to convert Wet Bulb temperature (Wet) to °K.

4. Compute the Saturation Pressure, assuming standard-day ambient atmosphere pressure, for the Dry Bulb temperature (DrySatPres):

$$\text{DrySatPres} = e^{\left[19.163 - \frac{\left(4063.2 + \frac{184089.0}{Dry}\right)}{Dry}\right]}$$

5. Repeat step 4 to compute the Saturation Pressure for the Wet Bulb temperature (WetSatPres).

6. Compute the Relative Humidity (RH) in percent:

$$\text{RH, \%} = 100 * \left[\frac{WetSatPres}{DrySatPres}\right]$$

APPENDIX B
SAMPLE DATA LOG SHEETS

This appendix contains sample field-data log sheets for use with the measurement procedures described within the main body of the document.

Table 8. Sample instrumentation log.

Site #: 1	Date: 5/1/96	Location: I-95 S	
Item #:	Quantity:	Instrument Type:	Serial #:
1	1	Brüel & Kjær 4155 Microphone	43515
2	1	Brüel & Kjær 4155 Microphone	43516
3	1	Larson Davis 820 Sound Level Meter	33768
4	1	Larson Davis 820 Sound Level Meter	33769
5	1	Cetec Ivie Random Noise Generator	501
6	2	Microphone Simulators	N/A
7	3	Brüel & Kjær 0237 Windscreens	N/A
8	1	Wind-Cup Anemometer	N/A
9	1	Sling Psychrometer	N/A
10	1	100-Ft Tape Measure	N/A
11	10	9-Volt Batteries	N/A
12	1	Flashlight	N/A
13	10	D-Cell Batteries	N/A

Table 9. Blank instrumentation log.

Site #:	Date:	Location:	
Item #:	Quantity:	Instrument Type:	Serial #:

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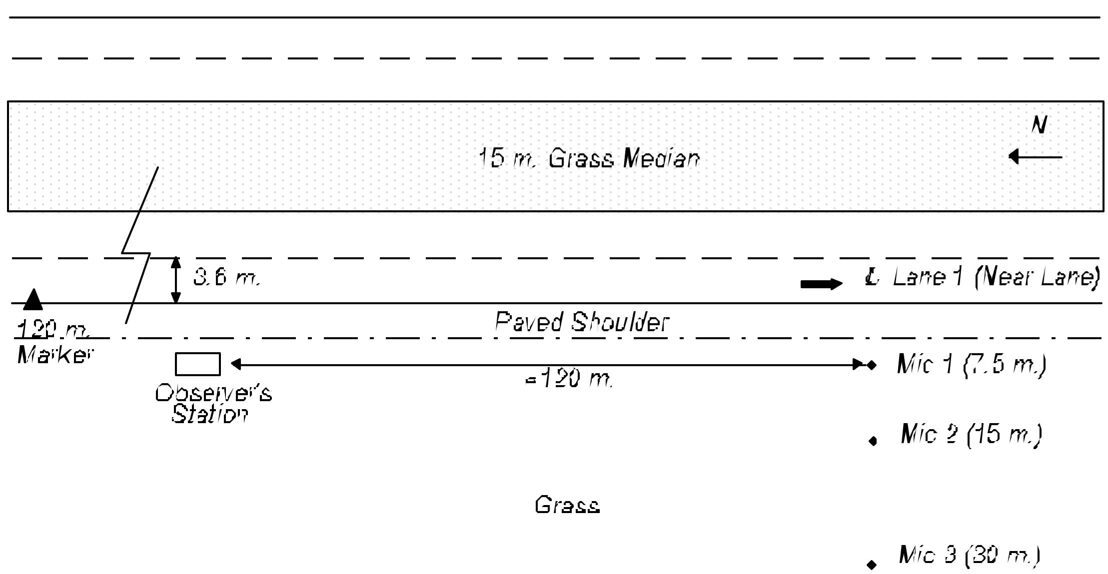
Table 10. Sample site data log.

Site #: 1	Date: 5/1/96	Location: I-95 S	Observer: Joe
Lane Dir: South	Site Surface: Soft	Nearby Landmark: I-495 Junction	
Grade: 0%	Pavement Type: Concrete	Distance to Landmark: 0.25 km	

Plan View:



Elevation View:

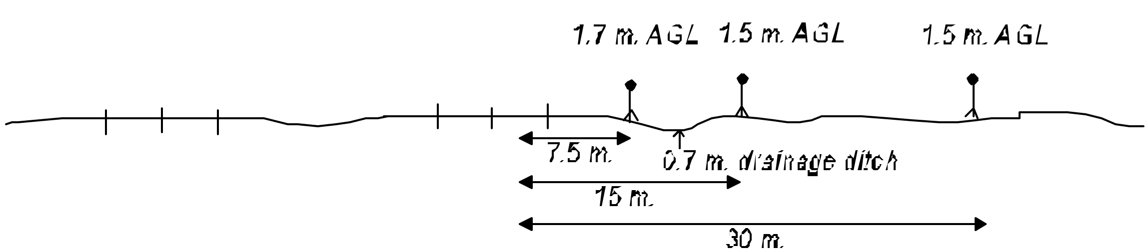


Table 11. Blank site data log.

Site #:	Date:	Location:	Observer:
Lane Dir:	Site Surface:	Nearby Landmark:	
Grade:	Pavement Type:	Distance to Landmark:	
Plan View:			
Elevation View:			

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Table 12. Sample meteorological data log.

Site #: 1	Date: 5/1/96	Location: I-95 S		Observer: Joe		
Time:	Temperature, °C (dry bulb):	Temperature, °C (wet bulb):*	Relative Humidity (%):	Wind Speed (km/h):	Wind Dir	Cloud Cover Class
8:00	15	13	89.8	5	W-E	2
8:15	16	13	86.6	5	W-E	2
8:30	16	14	86.7	5-7	W-E	2
8:45	16	14	86.7	5-7	W-E	2
9:00	16	14	86.7	5	W-E	3
9:15	16	15	91.5	5	W-E	3
9:30	17	15	89.9	0	N/A	3
9:45	17	16	89.9	0	N/A	3
10:00	18	16	83.9	0-5	W-E	3
10:15	19	16	83.3	0-5	W-E	3
10:30	19	16	83.3	0-5	W-E	3
10:45	19	16	83.3	4	W-E	3
11:00	20	16	79.7	4	W-E	3
11:15	20	16	79.7	4	W-E	3

* See Appendix A to convert Dry-Wet bulb temperature readings to Relative Humidity.

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Table 13. Blank meteorological data log.

Site #:	Date:	Location:		Observer:		
Time:	Temperature, °C (dry bulb):	Temperature, °C (wet bulb):*	Relative Humidity (%):	Wind Speed (km/h):	Wind Dir	Cloud Cover Class

* See Appendix A to convert Dry-Wet bulb temperature readings to Relative Humidity.

**Table 14. Existing-noise measurements
Sample acoustic data log.**

Site #: 1	Date: 5/1/96	Location: I-95 S	Observer: Joe

Site Type (Check one):	Overall Sound Level	Change in Sound Level		Mic Type (Check one):	Reference	Receiver	Mic #: 1	Mic Location: 7.5 m. offset
		BEFORE	AFTER			T		
		T						

Event #:	Time:	Duration (sec):	Sound Level (dB):	Gain Setting:	Comments:
PreCal	8:00:31	25.0	N/A	0	
Cal	8:05:24	20.125	N/A		Reset SLM
Dummy	8:09:01	30.125	N/A		
Pink	8:15:00	31.625	N/A		
PreCal	8:45:23	22.0	N/A		
Cal	8:55:15	20.25	N/A		
1	9:05:00	300.0	56.4	+20	
2	9:10:00	300.0	65.7		

Table 15. Existing-noise measurements
Blank acoustic data log.

Site #:	Date:	Location:					Observer:	
Site Type (Check one):	Overall Sound Level	Change in Sound Level		Mic Type (Check one):	Reference	Receiver	Mic #:	Mic Location:
		BEFORE	AFTER					
Event #:	Time:	Duration (sec):	Sound Level (dB):	Gain Setting:	Comments:			

**Table 16. Existing-noise measurements
Sample vehicle data log.**

Site #: 1	Date: 5/1/96	Location (Traffic Direction/Lane, etc.): I-95 (Southbound on Lane 1)						Observer: Joe	
Event #:	Time:	Predominant Vehicle Speed (km/h):	Auto:	Medium Truck:	Heavy Truck:	Bus:	Motor-cycle:	Other:	Comments:
1	9:05:00	80	𝍸𝍸 𝍸𝍸 𝍸	𝍸𝍸	𝍸𝍸 𝍸𝍸 𝍷𝍷𝍷𝍷	𝍷𝍷𝍷𝍷			
2	9:10:00	85	𝍸𝍸 𝍸𝍸 𝍷𝍷	𝍸𝍷𝍷𝍷	𝍸𝍸 𝍸𝍸	𝍷𝍷	𝍷		

**Table 17. Existing-noise measurements
Blank vehicle data log.**

Site #:	Date:	Location (Traffic Direction/Lane, etc.):						Observer:	
Event #:	Time:	Predominant Vehicle Speed (km/h):	Auto:	Mediu m Truck:	Heavy Truck:	Bus:	Motor-cycle:	Other:	Comments:

**Table 18. Vehicle emission level measurements
Sample acoustic data log.**

Site #: 1	Date: 5/1/96	Location: I-95 S				Observer: Joe
Mic #: 1	Mic Location: 7.5 m. offset					
Event #:	Time:	Duration (sec):	L_{AFmx}:	Event Quality:	Gain Setting:	Comments:
PreCal	8:00:31	25.0	N/A	N/A	0	
Cal	8:05:24	20.125	N/A	N/A		Reset SLM
Dummy	8:09:01	30.125	N/A	N/A		
Pink	8:15:00	31.625	N/A	N/A		
PreCal	8:45:23	22.0	N/A	N/A		
Cal	8:55:15	20.25	N/A	N/A		
1	9:05:12	8.0	56.4	1	+20	
2	9:09:15	10.875	65.7	2		
3	9:15:09	18.9	79.0	2		
4	9:21:54	4.375	58.9	NG		No good - jet overhead
5	9:34:56	7.25	65.0	1		

**Table 19. Vehicle emission level measurements
Blank acoustic data log.**

Site #:	Date:	Location:				Observer:
Mic #:	Mic Location:					
Event #:	Time:	Duration (sec):	L_{AFmx}:	Event Quality:	Gain Setting:	Comments:

Table 20. Vehicle emission level measurements
Sample vehicle data log.

Site #: 1	Date: 5/1/96	Location (Traffic Direction/Lane, etc.): I-95 (Southbound on Lane 1)						Observer: Joe	
Event #:	Time:	Vehicle Speed (km/h):	Auto:	Medium Truck:	Heavy Truck:	Bus:	Motor-cycle:	Other:	Comments:
1	9:05:12	80			T				5 axle
2	9:09:15	85		T					
3	9:15:09	75			T				3 axle
4	9:21:54	88	T						
5	9:34:56	90	T						

**Table 21. Vehicle emission level measurements
Blank vehicle data log.**

Site #:	Date:	Location (Traffic Direction/Lane, etc.):						Observer:	
Event #:	Time:	Vehicle Speed (km/h):	Auto:	Mediu m Truck:	Heavy Truck:	Bus:	Motor- cycle:	Other:	Comments:

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Table 22. Barrier insertion loss measurements
Sample acoustic data log.

Site #: 1	Date: 5/1/96	Location: I-95 S					Observer: Joe	
Site Type (Check one):	BEFORE	Equiv. BEFORE	AFTER	Mic Type (Check one):	Reference	Receiver	Mic #: 1	Mic Location: 7.5 m. offset
	T					T		

Event #:	Time:	Duration (sec):	Sound Level (dB):	Event Quality (if applicable):	Gain Setting:	Comments:
PreCal	8:00:31	25.0	N/A	N/A	0	
Cal	8:05:24	20.125	N/A	N/A		Reset SLM
Dummy	8:09:01	30.125	N/A	N/A		
Pink	8:15:00	31.625	N/A	N/A		
PreCal	8:45:23	22.0	N/A	N/A		
Cal	8:55:15	20.25	N/A	N/A		
1	9:15:00	300.0	56.4	N/A	+20	
2	9:20:00	300.0	65.7	N/A		

Table 23. Barrier insertion loss measurements
Blank acoustic data log.

Site #:	Date:	Location:					Observer:	
Site Type (Check one):	BEFORE	Equiv. BEFORE	AFTER	Mic Type (Check one):	Reference	Receiver	Mic #:	Mic Location:
Event #:	Time:	Duration (sec):	Sound Level (dB):	Event Quality (if applicable):	Gain Setting:	Comments:		

Table 24. Barrier insertion loss measurements
Sample vehicle data log.

Site #: 1	Date: 5/1/96	Location (Traffic Direction/Lane, etc.): I-95 (Southbound on Lane 1)						Observer: Joe	
Event #:	Time:	Predominant Vehicle Speed (km/h):	Auto:	Medium Truck:	Heavy Truck:	Bus:	Motor-cycle:	Other:	Comments:
1	9:15:00	80	卌 卌 卌 卌 卌	卌 卌	卌 卌 卌 卌 ||||	||||			
2	9:20:00	85	卌 卌 卌 卌 ||	卌 |||	卌 卌 卌 卌	||	|		

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Table 25. Barrier insertion loss measurements
Blank vehicle data log.

Site #:	Date:	Location (Traffic Direction/Lane, etc.):						Observer:	
Event #:	Time:	Predominant Vehicle Speed (km/h):	Auto:	Mediu m Truck:	Heavy Truck:	Bus:	Motor-cycle:	Other:	Comments:

Table 26. Construction equipment noise measurements
Sample acoustic data log.

Site #: 1	Date: 5/1/96	Location/Construction Phase: I-95 S /Earthwork				Observer: Joe	
Operating Mode (Check one):	Stationary-Passive	Stationary-Active	Mobile-Passive	Mobile-Active	Equipment Type: Bulldozer	Mic #: 1	Mic Location: 15 m. offset
			T				
Event #:	Time:	Duration (sec):	Sound Level (dB):	Equipment Speed (km/h):	Gain Setting:	Comments:	
PreCal	8:00:31	25.0	N/A	N/A	0		
Cal	8:05:24	20.125	N/A	N/A		Reset SLM	
Dummy	8:09:01	30.125	N/A	N/A			
Pink	8:15:00	31.625	N/A	N/A			
PreCal	9:15:23	22.0	N/A	N/A			
Cal	9:20:15	20.25	N/A	N/A			
1	10:00:07	8.0	56.4	5	+20		
2	10:05:15	10.875	65.7	6			
3	10:09:56	18.9	79.0	5			
4	10:14:37	4.375	58.9	7		No good - dogs barking	
5	10:21:21	7.25	65.0	5			

**Table 27. Construction equipment noise measurements
Blank acoustic data log.**

Site #:	Date:	Location/Construction Phase:				Observer:	
Operating Mode (Check one):	Stationary-Passive	Stationary-Active	Mobile-Passive	Mobile-Active	Equipment Type:	Mic #:	Mic Location:
Event #:	Time:	Duration (sec):	Sound Level (dB):	Equipment Speed (km/h):	Gain Setting:	Comments:	

**Table 28. Building noise reduction measurements
Sample acoustic data log.**

Site #: 1	Date: 5/1/96	Location: 55 Broadway Street off I-95 S				Observer: Joe
Site Type (Check one):	Interior	Exterior				
		T				
Event #:	Time:	Duration (sec):	Sound Level (dB):	Event Quality (if applicable):	Gain Setting:	Comments:
PreCal	8:00:31	25.0	N/A	N/A	0	
Cal	8:05:24	20.125	N/A	N/A		Reset SLM
Dummy	8:09:01	30.125	N/A	N/A		
Pink	8:15:00	31.625	N/A	N/A		
PreCal	8:45:23	22.0	N/A	N/A		
Cal	8:55:15	20.25	N/A	N/A		
1	9:30:01	8.0	56.4	1	+20	
2	9:36:15	10.875	65.7	2		

**Table 29. Building noise reduction measurements
Blank acoustic data log.**

Site #:	Date:	Location:				Observer:
Site Type (Check one):	Interior	Exterior				
Event #:	Time:	Duration (sec):	Sound Level (dB):	Event Quality (if applicable):	Gain Setting:	Comments:

**Table 30. Building noise reduction measurements
Sample vehicle data log.**

Site #: 1	Date: 5/1/96	Location (Traffic Direction/Lane, etc.): I-95 (Southbound on Lane 1)						Observer: Joe	
Event #:	Time:	Predominant Vehicle Speed (km/h):	Auto:	Medium Truck:	Heavy Truck:	Bus:	Motor-cycle:	Other:	Comments:
1	9:30:01	80	25	10	24	4			
2	9:36:15	85	22	8	20	2	1		

**Table 31. Building noise reduction measurements
Blank vehicle data log.**

Site #:	Date:	Location (Traffic Direction/Lane, etc.):						Observer:	
Event #:	Time:	Predominant Vehicle Speed (km/h):	Auto:	Mediu m Truck:	Heavy Truck:	Bus:	Motor-cycle:	Other:	Comments:

Table 32. Sample occupational noise exposure data log.

Site #: 1	Date: 5/1/96	Task/Location: I-95 S Toll booth at Exit 19				Employee/Observer: Joe/Fred
Instrumentation (Check one):	Noise Dosimeter	Sound Level Meter				Mic Location: Shoulder
	T					
Event #:	Time:	Duration (hour):	L_{Aeq} (dB):	L_{AFmx} (dB):	Gain Setting:	Comments:
PreCal	7:00:31	25.0 sec	N/A		0	
Cal	7:05:24	20.125 sec	N/A		↓	Reset SLM
Dummy	7:09:01	30.125 sec	N/A		↓	
Pink	7:15:00	31.625 sec	N/A		↓	
PreCal	7:45:23	22.0 sec	N/A		↓	
Cal	7:55:15	20.25 sec	N/A		↓	
1	8:07:12	0.33	88.0	90.1	+20	
2	8:30:15	0.33	73.0	77.9		
3	8:52:09	2.60	90.0	90.9		
4	11:15:12	3.50	105.0	105.1		
5	15:08:15	1.24	108.0	109.0		
6	16:25:09	2.00	95.0	96.9		

Table 33. Blank occupational noise exposure data log.

Site #:	Date:	Task/Location:				Employee/Observer:
Instrumentation (Check one):	Noise Dosimeter	Sound Level Meter				Mic Location:
Event #:	Time:	Duration (min):	L_{Aeq} (dB):	L_{AFmx} (dB):	Gain Setting:	Comments:

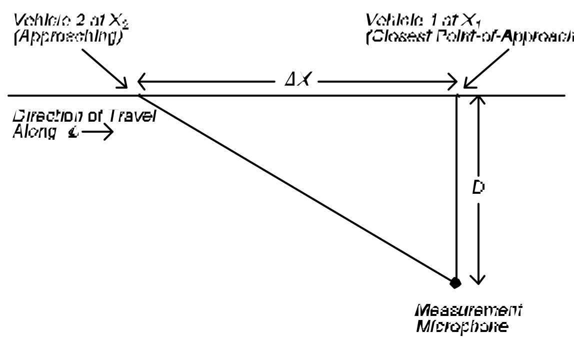
APPENDIX C
MINIMUM SEPARATION-DISTANCE CRITERIA FOR NOISE EMISSION LEVEL MEASUREMENTS

The minimum separation-distance criteria were based on Caltrans' California REMEL study.[24]

In the Caltrans study, the following assumptions were made: (1) the vehicle behaves as a **point source**, i.e., spherical **divergence** is assumed; and (2) there is no ground attenuation of the emission level. In addition, the ambient level was at least 10 dB less than the L_{AFmx} of the observed vehicle.

In general, when a vehicle approaches a measurement microphone at a constant speed, the observed sound level at the microphone is related to the vehicle position as follows:

$$L_2 = L_1 - 20 * Log_{10} \frac{\sqrt{\Delta X^2 + D^2}}{D}$$



where: L_2 is the contribution to the measured emission level of the subject vehicle, Vehicle 1 at X_1, due to a subsequent vehicle, Vehicle 2, at X_2;

L_1 is the contribution to the measured emission level of the subject vehicle, Vehicle 1, due entirely to Vehicle 1 at X_1;

)X is the distance between X_1 and X_2, or the minimum separation distance to be determined; and

D is the distance from the microphone to X_1, or 15 m in this case.

If other vehicles are in proximity of the subject vehicle to be measured, the measured sound level at the microphone for the subject vehicle may increase due to contamination. A maximum of 0.5 dB contamination is considered allowable.

Based on the 0.5-dB criterion, the next step is to determine the associated separation-distance criteria. Potential sources of contamination include contamination due to ambient noise, as well as contamination due to other vehicles in proximity of the subject vehicle (See Figure 20 on the following page).

The maximum contamination due to ambient noise was determined to be 0.4 dB, assuming the ambient level is 10 dB less than the L_{AFmx} of observed vehicles. Consequently, a maximum 0.1-dB contamination due to subsequent vehicles, based on the 0.5-dB contamination criterion, is allowed.

To ensure no more than 0.1-dB contamination due to subsequent vehicles, it was determined that the emission level due to a subsequent vehicle, Vehicle 2 in the case of Figure 20, must be at least 15.9 dB below that of the subject vehicle, Vehicle 1. The next step was to determine the separation distance associated with the 15.9-dB requirement.

Using the above equation and substituting the following values:

$$L_2 = L_{AFmx} - 15.9$$

$$D = 15 \text{ m},$$

)X was solved for.

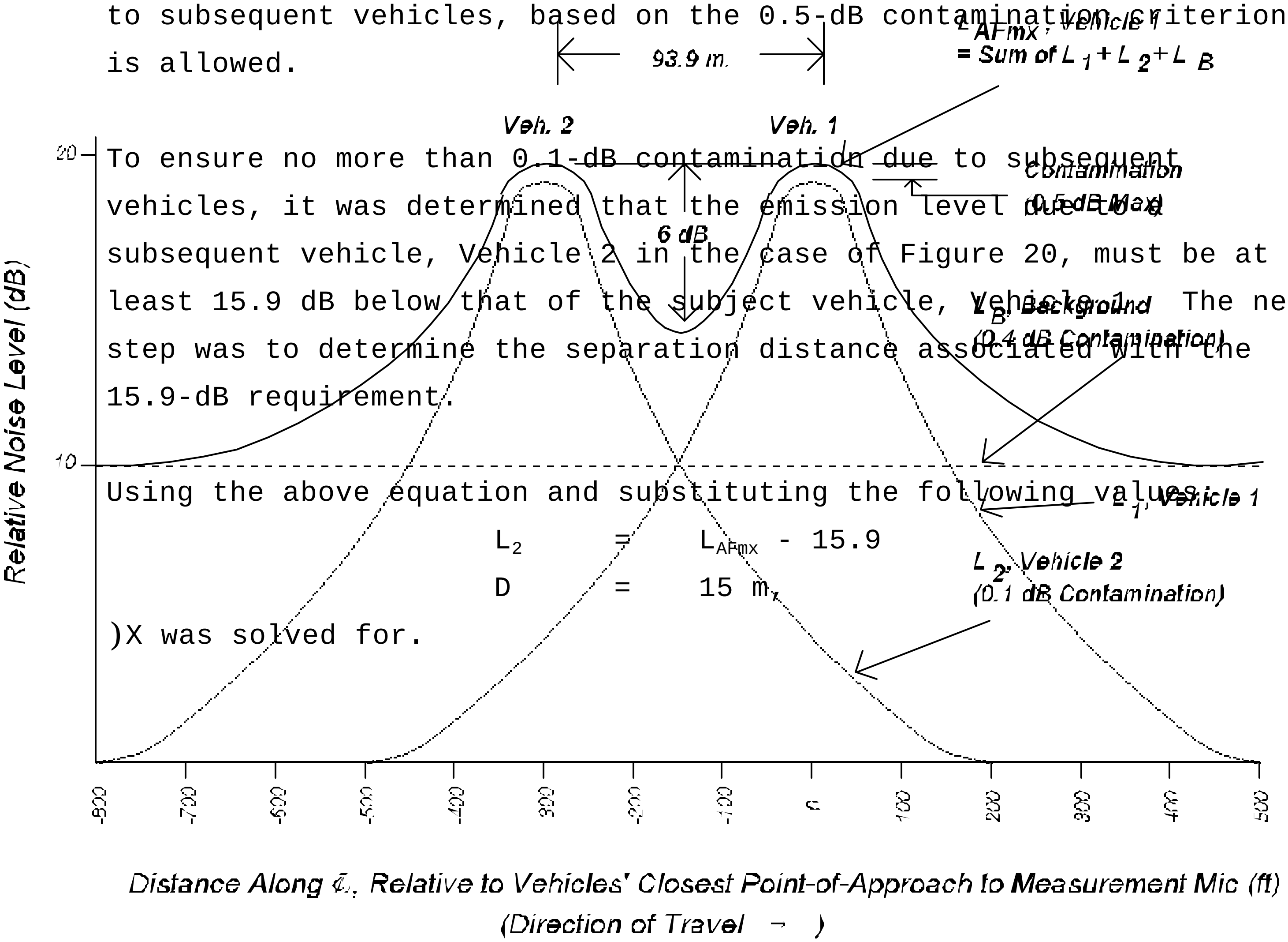


Figure 20. Minimum separation distance between two similar vehicles.

For REMELs measured at 15 m (50 ft), a minimum separation distance of 93.9 m (308 ft) between similar vehicles was required to ensure that the total contamination was not greater than 0.5 dB. For automobiles in the vicinity of heavy trucks, a minimum separation distance of 300.2 m (985 ft) between the automobile and heavy truck was required, assuming a heavy truck is 10 dB louder than an automobile at comparable speeds.

APPENDIX D
SAMPLE REPORT DOCUMENTATION

The objective of this appendix is to exemplify the types of information to be documented in a field measurement report. For the purposes of this appendix, assume existing-noise measurements were performed (See Section 4).

D.1 Site Sketches

The measurement site was located on Route 95 (a 2-lane highway) 0.8 km past Exit 21. A reference microphone was attached to a mast, placed at a height of 1.5 m above the roadway pavement, and located at a 15 m offset position from the centerline of the near travel lane. Another portable mast was fitted with three microphones, placed at heights of 1.5 m (low), 4.5 m (middle), and 7.5 m (high), and located at a 30-m offset position. When referring to microphone heights, the high, middle, and low convention will be used for the remainder of this report. Figures D1 and D2 present the plan and elevation views, respectively.

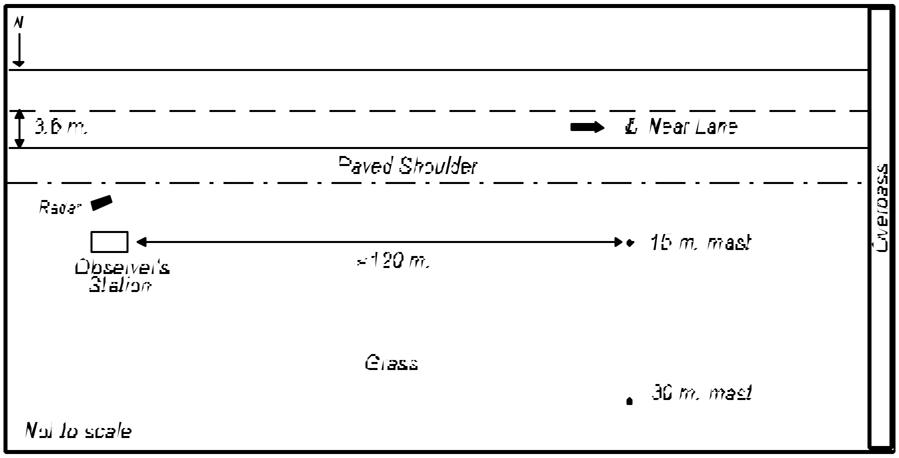


Figure D1. Measurement site plan view.

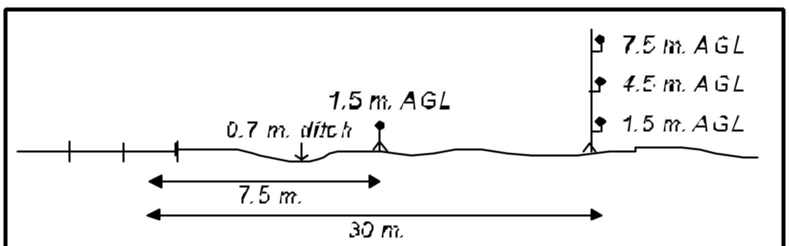


Figure D2. Measurement site elevation view.

D.2 Source Description

The source was constant free-flowing traffic traveling on Route 95. Traffic volume and mix were recorded on video cassette and used to obtain vehicle counts. Vehicles were counted and classified in three categories: automobiles (A); medium trucks (MT); and heavy trucks (HT). Vehicles were further grouped by direction (eastbound and westbound). Vehicle counts and average speed for each test run are presented in Table D1.

Table D1. 5-minute vehicle count and average speed data.

Test Run #	Start Time	Westbound A	Westbound MT	Westbound HT	Eastbound A	Eastbound MT	Eastbound HT	Avg Speed (km/h)	Std Deviation (F)
1	9:00	407	7	31	322	9	38	96.7	3.4
2	9:10	351	8	36	348	12	26	97.3	3.4
3	9:20	319	8	20	340	10	29	96.4	3.7
4	9:30	317	16	25	338	10	37	96.7	3.2
5	9:40	335	14	25	342	12	39	94.8	3.1
6	9:50	363	8	32	335	6	38	93.6	3.3
7	10:00	332	8	20	375	8	35	94.0	3.8
8	10:10	340	11	22	320	11	33	93.8	3.9
9	10:20	291	10	23	354	7	28	96.7	3.5
10	10:30	374	10	25	404	12	40	94.9	3.5
11	11:00	370	3	41	428	7	55	90.7	4.3
12	11:10	364	3	47	422	11	42	91.6	5.7
13	11:20	352	4	48	375	4	41	93.8	5.0
14	11:30	397	2	38	426	4	39	90.1	4.1
15	11:40	416	4	39	384	6	47	90.7	4.6
16	11:50	397	3	34	411	5	49	94.8	3.6
17	12:00	424	3	49	377	6	44	92.5	3.3
18	12:10	408	2	28	364	2	39	91.4	2.7
19	12:20	-	-	-	-	-	-	-	-
20	12:30	346	3	37	342	8	30	93.6	5.0
21	13:30	385	8	49	427	11	33	93.6	3.8
22	13:40	391	4	40	459	5	42	94.3	3.6
23	13:50	409	1	39	463	14	30	94.4	3.1
24	14:00	-	-	-	-	-	-	-	-
25	14:10	-	-	-	-	-	-	-	-
26	14:20	-	-	-	-	-	-	-	-
27	14:30	426	3	33	499	10	33	92.2	4.1
28	14:40	500	3	39	699	5	51	90.6	4.5
29	14:50	507	3	17	678	7	32	94.9	4.0
30	15:00	476	7	32	704	9	39	92.7	2.3

(-) Denotes test run was removed from the population of events to be analyzed (See Section D.7 for an explanation).

D.3 Instrumentation Description

Note: A list of instrumentation is presented in Table D2. Each noise measurement system consisted of a General Radio Model 1962-9610 random-incidence electret microphone, connected to a Larson Davis Model 827-0V preamplifier. The microphone/ preamplifier system was mounted in an insulated nylon holder and connected via cable to a Larson Davis Model 820 Type 1 Precision Integrating Sound Level Meter/Environmental Noise Analyzer (LD820). The microphone/preamplifier combination was positioned 0.3 m from the mast and placed in its shadow as viewed from the roadway. This position insured minimum errors due to reflections from the mast structure.(11) Brüel & Kjær Model UA0237 windscreens were placed atop each microphone to reduce the effects of wind-generated noise on the microphone diaphragm.

Pre-processing and storage of the measured noise level data were accomplished by the LD820. Each unit was programmed to continually measure, energy average, and store A-weighted noise levels with fast-exponential response characteristics at a rate of two data records each second (½-second averages).

A passive microphone simulator was used to establish the electronic noise floor of each system. In addition, the frequency response of each system was tested using pink noise generated by a Cetec Ivie Model IE-20B random noise generator.

Traffic speed was obtained with a CMI Doppler radar gun set up 6 m off the edge of the near travel lane, approximately 100 m west of the microphone centerline (See Figure D1). The Doppler radar was directed at the departing westbound traffic, thus minimizing the possibility of individual vehicles slowing down after detecting the radar signal. Readings were observed visually from the radar's digital display, and recorded continuously during each measurement period at a rate of approximately one reading every 10 seconds.

A Panasonic Model AG170 video camera was set up on a nearby overpass to record pass-by traffic at the measurement site. The camera was time-synchronized with the LD820's, so that the noise data could be correlated with the traffic data.

Table D2. Sample instrumentation log.

Item #:	Quantity:	Instrument Type:	Serial #:
1	1	General Radio 1962-9610 Microphone & Preamp	43515
2	1	General Radio 1962-9610 Microphone & Preamp	43516
3	1	General Radio 1962-9610 Microphone & Preamp	43517
4	1	General Radio 1962-9610 Microphone & Preamp	43518
5	1	Larson Davis 820 Sound Level Meter	33768
6	1	Larson Davis 820 Sound Level Meter	33769
7	1	Larson Davis 820 Sound Level Meter	33770
8	1	Larson Davis 820 Sound Level Meter	33771
9	2	Brüel & Kjær Type 4231 Calibrator	N/A
10	1	Cetec Ivie Random Noise Generator	501
11	2	Microphone Simulators	N/A
12	6	Brüel & Kjær 0237 Windscreens	N/A
13	1	Wind-Cup Anemometer	N/A
14	1	Sling Psychrometer	N/A
15	1	CMI Doppler Radar Gun	10331
16	1	Panasonic Model AF170 Video Camera	15095
17	1	Climatronics Model EWS Weather Station	66881
18	20	9-Volt Batteries	N/A
19	1	100' Tape Measure	N/A

D.4 Meteorological Data

A Climatronics Model EWS weather station continually recorded temperature, humidity, wind speed, and wind direction data on a continuous strip-chart recorder with a paper speed of four inches per hour. Wind speed and direction were measured at a height of 7.5 m above the ground (height equivalent to the highest microphone position); temperature and humidity were measured at a height of 1.5 m above the ground. In addition, cloud cover was documented periodically, as well as significant changes in weather conditions.

Using the known recorder paper speed and the time marks produced on the strip-chart, a time scale was transposed on each chart and the 5-minute measurement period for each test was identified.

The average wind speed and average wind direction *re* magnetic north (degrees) were computed for each 5-minute test run. The 5-minute averaged wind speed (WS) and direction (WD) were then used to compute the vector component of wind speed in the x-y plane from the source to receiver (VWS) for each test run.

Meteorological data are presented in Table D3. Note: Cloud cover class 2 was observed for the duration of the measurement day.

Table D3. Meteorological data (5-minute average values).

Test Run #	Start Time	Wind Speed (km/h)	Wind Dir* (°)	Temp (°F)	Rel Hum (%)	VWS (km/h)
1	9:00	10.5	65	13	46	4.3
2	9:10	11.3	80	14	45	1.9
3	9:20	6.4	130	14	44	-4.2
4	9:30	12.1	100	14	43	-2.1
5	9:40	8.8	105	14	43	-2.3
6	9:50	9.3	150	14	42	-8.0
7	10:00	12.1	115	15	41	-5.1
8	10:10	14.5	65	16	40	6.1
9	10:20	4.0	195	16	40	-3.9
10	10:30	12.9	155	16	40	-11.7
11	11:00	7.2	195	19	38	-6.9
12	11:10	0.0	-	18	36	0.0
13	11:20	7.7	15	19	34	7.4
14	11:30	10.0	35	19	33	8.2
15	11:40	8.8	325	19	32	7.2
16	11:50	13.4	10	19	32	13.2
17	12:00	7.7	350	19	32	7.6
18	12:10	5.3	45	19	32	3.7
19	12:20	-	-	-	-	-
20	12:30	7.2	330	18	32	6.3
21	13:30	10.9	345	19	32	10.6
22	13:40	6.9	20	19	32	6.4
23	13:50	8.2	50	19	32	5.3
24	14:00	-	-	-	-	-
25	14:10	-	-	-	-	-
26	14:20	-	-	-	-	-
27	14:30	8.8	30	20	30	7.7
28	14:40	6.3	30	20	30	5.5
29	14:50	10.5	40	19	29	8.0
30	15:00	0.0	-	18	29	0.0

* Wind Direction *re* Magnetic North

(-) Denotes test run was removed from the population of events to be analyzed (See Section D.7 for an explanation).

D.5 Ground Surface Characterization

The roadway surface was composed of dense-graded asphaltic concrete. The roadside terrain between the road and the receivers was relatively flat and composed of packed clay with low-cut grass.

D.6 Measurement Procedures

At the beginning of the measurement day, a complete system check was performed on the entire measurement system. To establish the electronic noise floor of each system, a passive microphone simulator was substituted for each microphone. The frequency response of each system was tested by recording a 30-second sample of pink noise. In addition, 30 seconds of calibration data were recorded at the beginning and end of the measurement day.

Data were collected at a rate of two samples per second. After collecting data for ten consecutive 5-minute test runs (5-minute spacing between each run), approximately 30 seconds of calibration data were measured and stored for all microphones. Data collection then calibration were repeated until a total of thirty 5-minute test runs were measured and stored.

At the end of the measurement day, the ½-second noise data stored in each LD820 were downloaded to an AST Premium Exec Model 386SX/20 notebook computer and stored on floppy disk for later off-line processing.

D.7 Acoustical Data

Processing of the noise data files stored on floppy disk was accomplished off-line, using the LD820 support software in tandem with the Acoustics Facility-developed computer program, RFILE. The LD820 software was used to obtain a graphical history plot (noise level versus time) for the test runs identified in the field as potentially contaminated. These plots were examined and all questionable test runs were removed from the population of events to be processed.

The RFILE program, using the ½-second data stored in each file, was used to compute the equivalent A-weighted sound levels for each 5-minute test run ($L_{Aeq,5min}$). The $L_{Aeq,5min}$ values were adjusted for calibration drift. No ambient adjustments were necessary. The final $L_{Aeq,5min}$ values are presented in Table D4. Computation of experimental error is shown below.

Experimental Data Error Calculation

1.) Compute Variance* for:

C Background (Not computed if measured level > background by 10 dB):

Reference Microphone Position 0.0

High Microphone Position 0.0

C Difference (Corrected source levels at reference microphone position minus calibration corrected source levels at the high microphone position) 0.012

C Bias:

Type	Amount	Amount/2	$(Amount/2)^2$	
Calibrator	0.25	0.125	0.016	0.016
Cal. Drift	0.23	0.115	0.013	0.013

2.) Sum of Variances (Sum of above items) 0.041

3.) Standard Error (Square root of Sum of Variances) . 0.202

* Note: Variance = $(F)^2 = [n3(X_i)^2-(3X_i)^2]/[n(n-1)]$; where n is number of levels and X_i is value of i^{th} level.

Table D4. Calibration corrected $L_{Aeq,5min}$ data.

Test Run #	Start Time	REF	HIGH	MID	LOW
1	9:00	80.65	79.30	72.50	65.65
2	9:10	80.15	78.90	71.60	64.95
3	9:20	80.05	78.80	71.40	64.75
4	9:30	80.55	79.30	71.80	64.15
5	9:40	80.25	79.10	71.50	64.85
6	9:50	80.15	79.00	71.20	64.75
7	10:00	80.05	78.80	71.40	64.65
8	10:10	80.55	79.10	71.10	64.25
9	10:20	80.15	78.80	71.10	64.45
10	10:30	80.55	79.20	71.50	64.85
11	11:00	81.15	79.95	73.25	64.75
12	11:10	81.55	80.25	74.35	64.15
13	11:20	80.95	79.45	72.35	64.85
14	11:30	80.75	79.35	72.05	64.75
15	11:40	80.95	79.65	72.75	64.65
16	11:50	80.75	79.45	72.45	64.25
17	12:00	80.95	79.55	72.45	64.45
18	12:10	80.25	79.15	72.15	64.85
19	12:20	-	-	-	-
20	12:30	81.25	80.05	72.95	66.00
21	13:30	81.20	80.00	72.85	66.15
22	13:40	81.30	80.00	72.75	65.95
23	13:50	81.50	80.30	73.35	66.65
24	14:00	-	-	-	-
25	14:10	-	-	-	-
26	14:20	-	-	-	-
27	14:30	80.80	79.50	72.35	65.75
28	14:40	81.80	80.50	73.15	66.75
29	14:50	81.20	80.10	72.85	66.15
30	15:00	81.40	80.30	73.15	66.45

(-) Denotes test run was removed from the population of events to be analyzed (See Section D.7 for an explanation).

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