Construction Noise
Measurement
Noise Barriers
Noise Compatible Planning
Noise Effect on Wildlife
Regulation and Guidance
Tire Pavement Noise
Traffic Noise Model
Training

Measurement of Highway-Related Noise

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).

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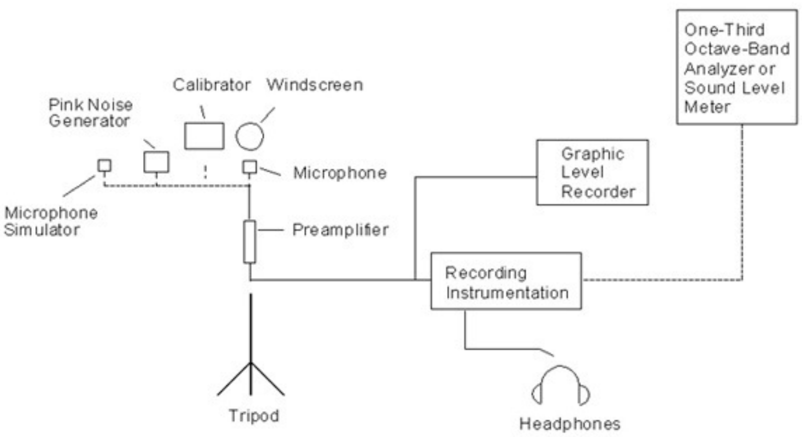

Figure 2. Generic measurement instrumentation setup.

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)

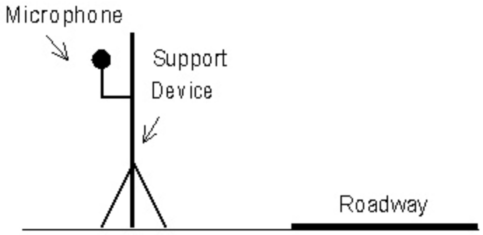

Figure 3. Recommended microphone position relative to support device.

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 3/8;-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)]

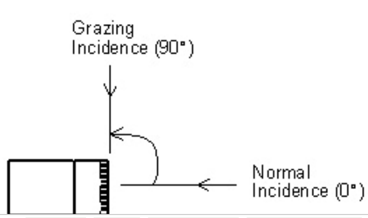

Figure 4. Microphone incidence.

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.

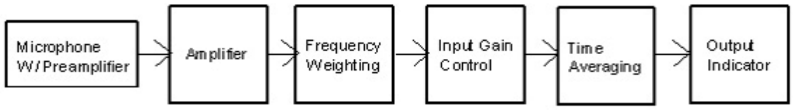

Figure 5. Components of a sound level meter.

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.

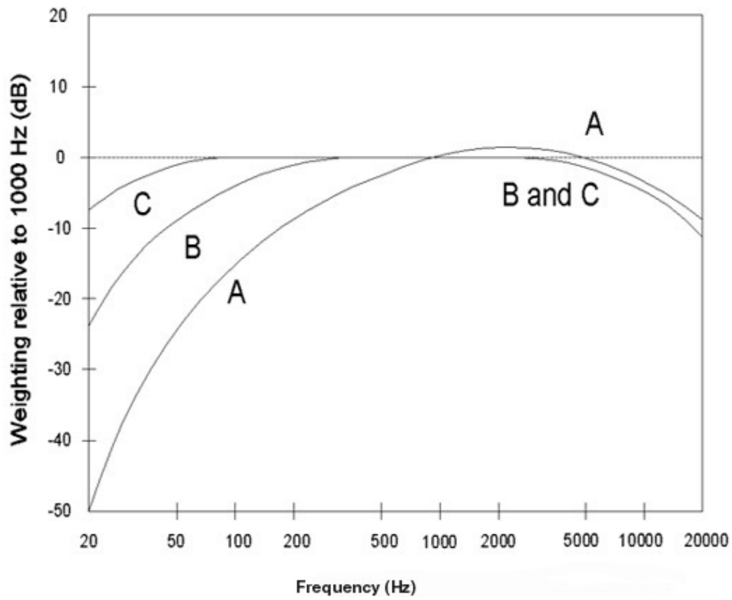

Figure 6. Frequency weighting.

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	-17.1	-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 (T) of 0.125 and 1 second, respectively (See Figure 7).

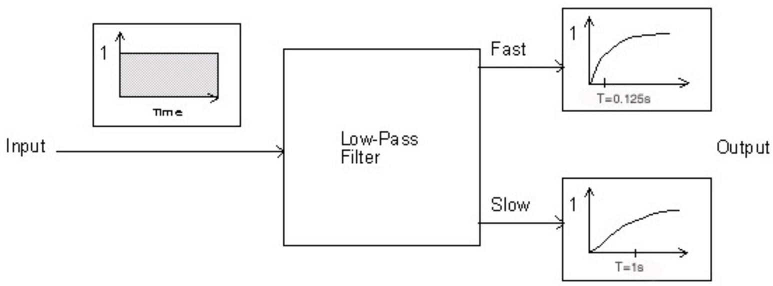

Figure 7. Exponential time-averaging.

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:
  CAL adjustment = reference level - $[(CAL_{INITIAL} + CAL_{FINAL}) / 2]$
  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 ac
  measured with that system du

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.

Table2. B & K Model 0237 windscreen typical response corrections.

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 importa

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) x 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: 1m/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 t 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.

- 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, 1

- 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.

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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.