

# Noise and Sound Control at Your Home

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<http://www.ewwood.com>



for those who Enjoy Peace and Quiet

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## Introduction

This booklet provides information and advice about ways to control noise and sound for people interested in and sensitive to the acoustical environment where they live. The authors have served as consultants for more than four decades during which time they have been contacted by individuals and companies throughout the United States requesting assistance to address many interesting and challenging acoustical issues. This booklet for homeowners is based on that experience. We define noise control as reducing unwanted intrusive sounds. Sound control on the other hand relates to steps that can be taken at home to enhance and improve desirable sounds such as those associated with music and entertainment systems. Names and contact information for other experienced consultants are available on the websites for the Institute of Noise Control Engineering and the National Council of Acoustical Consultants. Both organizations are described below.

When considering how to address and control unwanted noise, we find that it is often useful to subdivide the problem into the following three elements: the noise source-the path the noise travels-and the receiver. The noise source(s) might be a nearby industrial facility or transportation vehicles, household equipment, or adjacent neighbor activities. The path the noise travels from the source to the receiver is airborne and/or structure borne. For the purposes of this booklet, you and your family and other readers are considered to be the potential receivers.

Four “acoustical properties” of materials are useful to understand when reading this booklet. “Transmission loss” refers to the ability of common building materials such as gypsum board, plywood, or glass to reduce the transmission of sound along its path. Generally, solid heavy materials have greater transmission loss than do lightweight or porous materials. “Sound absorption” refers to the ability of materials to absorb rather than reflect sounds. Glass fiber insulation and ceiling tiles are examples of such materials used to absorb sound. Few materials provide both significant sound transmission loss and significant sound absorption. As an analogy for those with young children, cloth diapers serve to absorb and rubber pants serve to block liquids. “Elastic materials” are used to reduce the transmission of structure borne noise (vibration). For example, elastic neoprene pads can be installed between a washing machine and the floor to reduce vibration transmission into the floor structure. “Damping materials” are those applied to a vibrating surface to reduce radiated noise. Consider for example that a bell, a cymbal, or a kitchen sink or dishwasher will radiate less sound when coated with a viscoelastic damping material.

Noise control engineering is a fascinating discipline practiced by a small community of people, many with advanced technical degrees; some have practiced for their entire career. The National Academy of Engineering undertook a study chaired by George Maling to emphasize the importance of engineering to the quality of life in America, in particular the role of noise control technology making possible a quieter environment. The results were published in a particularly informative report, *Technology for a Quieter America*, which is available electronically without charge at:

[http://www.nap.edu/catalog.php?record\\_id=12928](http://www.nap.edu/catalog.php?record_id=12928)

This booklet also is not for sale. It is provided without charge to homeowners wanting a range of insights about ways to control noise and sound at their home – to improve their acoustical environment and quality-of-life. It does not provide technical engineering details. Several references are identified for those wanting such technical details. The authors can be contacted if consulting services are wanted. Additional useful information about engineering noise control, acoustics, and consulting services is available from professional organizations, including those listed below. Also, *Sound & Vibration* is a practical engineering magazine published by Jack Mowry that is available

monthly without charge to qualified readers in the United States. Subscription information is available at:

<http://www.sandv.com/home.htm>

**The Institute of Noise Control Engineering of the United States of America (INCE/USA)** is a non-profit professional organization with the primary purpose to promote engineering solutions to environmental, product, machinery, industrial and other noise problems. INCE/USA members are professionals in the field of noise control engineering, and many offer consulting services in noise control. INCE/USA publishes the *Noise Control Engineering Journal (NCEJ)* which contains refereed journal articles on all aspects of noise control engineering. *Noise News International* is published with International-INCE and includes news on noise control activities around the world, along with general articles on noise issues and policies. The INCE/USA also sponsors the NOISE-CON series of national conferences on noise control engineering, and the INTER-NOISE Congress when held in North America. Practical papers on solving noise control problems and on noise policies and regulations are presented at the conferences. The Institute maintains a digital library that you can access containing more than 20,000 technical papers on noise control engineering subjects assembled by our friend Courtney Burroughs. The Institute membership list identifies many knowledgeable and experienced noise control consultants. The address for the website is:

<http://www.inceusa.org>

**The National Council of Acoustical Consultants (NCAC)** is an international organization committed to supporting the acoustical profession. The Council sponsors an annual meeting of members. The Council's website includes an international directory of acoustical consultants, advice on selecting a consultant, and access to a sample copy of their newsletter. The address for their website is:

<http://www.ncac.com/>

**The Acoustical Society of America (ASA)** has members from various fields related to sound including physics, electrical, mechanical, and aeronautical engineering, oceanography, biology, physiology, psychology, architecture, speech, noise and noise control, and music. The Society sponsors two meetings each year with technical papers on those subjects. Publications of the Society include *The Journal of the Acoustical Society of America (JASA)*, *Acoustics Today* magazine, and *Echoes* newsletter. The Society also maintains an extensive digital library. The address for their website is:

<http://acousticalsociety.org>

**The International Institute of Noise Control Engineering (I-INCE)** is a worldwide consortium of organizations concerned with noise control, acoustics, and vibration. The primary focus of the Institute is on unwanted sounds and on vibrations producing such sounds when transduced. I-INCE sponsors the annual INTER-NOISE series of International Congresses on Noise Control Engineering. I-INCE also co-sponsors symposia on specialized topics within the I-INCE field of interest. The quarterly magazine *Noise/News International* is jointly published by I-INCE and the Institute of Noise Control Engineering of the USA. The I-INCE website contains contact information you can access for professional organizations in about 40 countries specializing in acoustics and engineering noise control. The address for their website is:

<http://www.i-ince.org/>

**The Audio Engineering Society** is a society of engineers concerned with audio equipment research and related acoustics, psychoacoustics, and audio systems. The society publishes the annual Journal of the Audio Engineering Society (JAES). AES Conventions are held annually in both the United States and Europe and are the largest gatherings of audio professionals in the world.

The society's website is at <http://www.aes.org/>.

Section 1 of this booklet provides advice about noise issues to consider before buying, building, or renting a new place to live. Section 2 shares advice about ways to reduce outside noises that can enter your home. Steps to reduce noise generation inside your home and the noise of children's toys are discussed in Section 3. Noise at your place of employment is addressed in Section 4. Section 5 provides insights and advice related to the room acoustics of electronic home entertainment systems. Appendices A, B, and C provide definitions of various technical terms, some thoughts about sound in lay terms, and a list of references for further information.

### Section 1. Before Buying a House or a Condominium or Renting an Apartment

Before buying a house or a condominium or renting an apartment or purchasing a parcel of land for a new house, we suggest that you investigate and listen to the exterior acoustical environment. Determine if there is a nearby industrial facility, landfill, highway, rail line, airport, fire station, hospital, or nightclub, as examples, creating noises you would find to be objectionable. Visit and listen not just on a Sunday morning or afternoon when an industrial facility or nightclub might not be operating – listen also during weekday daytime and evening periods. Consider also asking one or more neighbors about intruding noises they might hear. Remember that the intermittent sound of train warning signals, for example, might be particularly intrusive and apparent only at certain times if a grade crossing is nearby.



Consider using a web-based mapping routine to get a birds-eye view of the neighborhood to help determine if noisy facilities are within earshot. The city or town offices should have zoning and tax maps that you can examine to determine if nearby properties are owned by or available for use by commercial or industrial developers.

Major airports publish maps with aircraft noise level contours extending outward from the runways and encompassing areas with day-night Ldn noise levels of 60 dBA and greater. An example of the sound level contours for a major metropolitan airport is shown here. Similar figures with sound contours are sometimes available for highways and rail lines. Fortunately noise contours surrounding airports have been shrinking as quieter commercial aircraft are introduced into operation and older noisier aircraft are retired but still may be intrusive.

It can be particularly difficult for you to address or reduce intrusive noises from nearby facilities that existed before you move into the neighborhood. It is best to find and move to a neighborhood with an acoustic environment that you like.

The above suggestions address noise from exterior facilities near the location where you might consider moving. For multifamily buildings it is, of course, also important to consider the noises that will be heard from adjacent units. Examples of the wide range of unwanted noises come from people walking and children playing in the above unit, nearby kitchen and bathroom equipment, bedroom activities, televisions and music systems, elevators, stairs, and trash chutes. Unfortunately, some condominiums and apartment buildings are not designed and built with adequate consideration for effective unit-to-unit noise controls and it is not easy for you to evaluate this before moving in. Brochures with words such as quality-construction, top-of-the-line, or high-quality can sound attractive but can be misleading. We advise speaking with existing tenants about the sounds they do or don't hear from neighbors. It is also reasonable to ask if sound transmission loss measurement tests have been performed by a professional and to request a copy of the report. If such test results are not available, you could retain a professional to perform the tests for you and interpret the results.

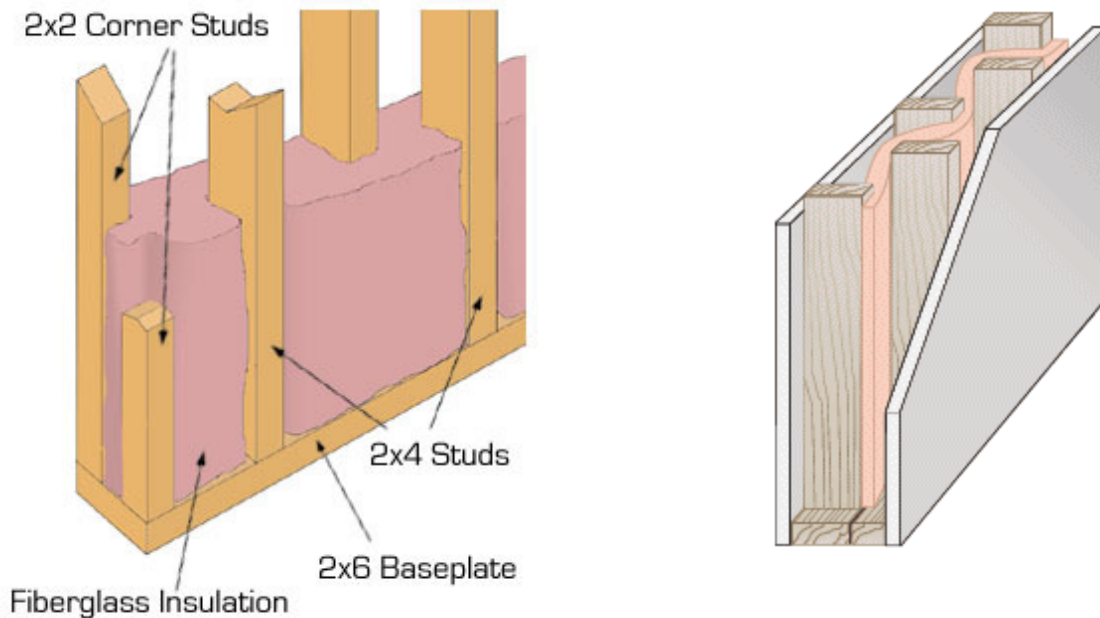
### Section 2. Reducing the Transmission of Exterior Noise into Your Home

The design and construction of most homes do not include much consideration to reducing or controlling noise. However, there are relatively simple control methods that you can consider. Some relate to reducing the transmission of exterior noise into the house. Others that relate to controlling noises generated within your home are discussed in Section 3.

The advice provided above in Section 1 should, of course, be considered when planning where to build or buy a new house. In addition, construction techniques are available that our experience demonstrates would reduce the transmission of exterior noise into your home. For example, we have helped airport authorities upgrade the sound insulation at schools and many thousands of homes located near large airports. Boston's Logan International Airport is one good example where since about 1981 more than 11,000 neighboring dwelling units have participated in an effective Residential Sound Insulation Program (RSIP). Other examples include people near highways or rail lines and people living in a city who do not want to hear the sounds of pedestrians speaking on the nearby sidewalk and the sounds of nearby street traffic.

The simplest and reasonably effective technique is to install acoustically rated windows and exterior doors that are readily available from manufacturers. This is because windows and exterior doors usually represent the weakest link in exterior construction allowing noise from the outside to enter a home. The acoustical performance of windows and doors are published with the Sound Transmission Class (STC) and/or the Outdoor Indoor Transmission Class (OITC) ratings. Both ratings provide an indication of the measured reduction of exterior noise entering the living unit. Additional reduction can be achieved with tightly fitting quality storm windows and doors installed with an airspace of at least 2 inches. In most applications the storm windows are installed outside of the primary window. For historic or other buildings where installing additional exterior windows is not practical or allowed, the additional window may be installed inside of the primary window. It is important to note that such windows and doors are, of course, only effective when they are closed. Thus, air conditioning might also be a primary requirement.

When building a new home it is relatively simple to increase the sound transmission loss of your exterior walls with the use of the staggered-stud construction technique that is illustrated below. It is shown that the exterior wall surface and the interior wall surface are not connected directly to the same studs, helping to reduce the transmission of structure borne sound. In addition, the space between the two walls includes sound absorbing glass fiber insulation.



Large noise barriers are being built by state transportation agencies along new highways (Type 1) and along existing highways (Type 2). They can be helpful in reducing traffic noise heard by nearby residential neighbors. Seldom however can an individual homeowner build a barrier that is long and tall enough to achieve much reduction of noise from a nearby highway.

Site development, demolition, and construction activities are well known sources of noise that are particularly difficult to control. Impact equipment such as hoe-rams, jack-hammers, and pile-drivers produce high intermittent noise. Engine powered mobile equipment such as dozers, loaders, excavators, and trucks are all noisy. The sound from their back-up alarms can be particularly annoying for residential neighbors. Hand tools such as hammers and powered saws are noisy.

Stationary equipment such as generators and air compressors are available with effective noise control packages. Steps are available to reduce noise impacts during excavation, demolition, and construction work. For example, work schedules can be limited to daylight hours, defective exhaust mufflers can be replaced promptly, and delivery vehicle drivers can be required to drive slowly along nearby streets. Some communities have local noise codes or ordinances to limit the impact of these sources although some lack the expertise to author effective codes or ones that can be enforced. These steps are reasonable and show respect for nearby neighbors. This type of noisy construction work is temporary but may extend for many months or even years.

A single row of bushes or trees between a house and a source of loud noise should not be expected to provide the homeowner with any noticeable reduction in the actual loudness of noise. However, a row of trees does provide a visual obstruction, and it is our experience that “out-of-sight – out-of-mind” can reduce the perceived loudness and resulting annoyance about a nearby roadway or industrial plant for some homeowners.

Some homeowners find the intermittent noise of traffic to be most annoying while outside relaxing on their patio or deck. In this case the pleasant sound of a nearby water fountain might help to mask the unwanted intermittent traffic noises and be an attractive addition to the patio.

Many but not all states and local municipalities have adopted regulations aimed at controlling environmental or community noise. It is worthwhile getting a copy and discussing them with your local regulators. Such regulations are generally a compromise between how quiet industrial facilities should be and how much noise neighbors should tolerate. Noise regulations can be viewed as providing both a license for industrial facilities to make a specified amount of noise and a limit on how much noise you might expect to receive. Experience indicates that management at most industrial facilities want to operate their plants responsibly and as good acoustic neighbors.

Operators of major airports make useful available information about their noise abatement programs. Information about the noise abatement program at Boston's Logan Airport, for example, is available at the following link:

<http://www.massport.com/environment/environmental-reporting/noise-abatement/>

Additional information about aviation and airport noise is available from the Federal Aviation Administration at links such as:

[http://www.faa.gov/about/office\\_org/headquarters\\_offices/apl/noise\\_emissions/airport\\_aircraft\\_noise\\_issues/](http://www.faa.gov/about/office_org/headquarters_offices/apl/noise_emissions/airport_aircraft_noise_issues/)

The Federal Highway Administration makes useful information available about highway noise on their website at links such as:

<http://www.fhwa.dot.gov/environment/noise/>

The Federal Railroad Administration makes useful information available about rail noise on their website at links such as:

<http://www.fra.dot.gov/search?q=noise>

### Section 3. Reducing Noises Generated and Transmitted inside Your Home

A wide range of methods are available for reducing the sounds that are generated inside a home. Some are discussed below.

Rooms with a hard floor and ceiling and hard walls without sound absorbing materials tend to cause noises to reverberate and build up to unpleasant levels. Soft sound absorbing materials such as heavy curtains, thick pile rugs, and stuffed furniture located in the room all help to reduce noises and make for a more acoustically pleasant environment. Sound absorbing ceiling materials can also be helpful but note that painting sound absorbing ceiling materials will significantly reduce or eliminate their ability to absorb and control noise.

Noise produced in room A is sometimes heard and can be distracting in adjacent room B. This is often, but not always, caused by airborne noise in room A that excites and causes the party wall between the rooms to vibrate and reradiate noise into adjacent room B. A simple test to check for this situation is to place a noise source, such as a portable radio, in room A and place your ear against the wall in room B. If you clearly hear the radio, the noise is probably being reradiated by the party (common) wall. If not, there might be another path such as a leak that you can find by listening along the top and bottom of the wall, near electrical boxes, and near air ducts. To improve the noise reduction performance of the party wall, consider increasing its mass by installing an additional layer of gypsum board covering the entire wall. Better yet, you can remove gypsum board on one side of the wall and install resilient channels between the studs and then reinstall with an additional layer of gypsum board. A small but useful additional improvement would be gained by loosely packing the stud spaces with glass fiber before reinstalling the new wall.

Open plan houses without doors between rooms can provide a wide-open appearance that some people prefer and enjoy but also allow noises to travel from room to room. It might be advisable to have a heavy solid core door to close off the room that contains a television or radio to better contain those sounds. Consideration could also be given to using staggered stud construction for those rooms to further contain the sounds and reduce transmission to other rooms in the house.

Rugs placed on upstairs floors of your home, or on the floors of units where people live directly above will help reduce transmission of the noise of people walking and children playing upstairs. Installation of a second ceiling can also be considered to reduce the noises heard and caused by people walking on floors above. The second ceiling should be constructed with a heavy material with adequate sound transmission loss to be effective and can be installed with resilient hangers to provide even more noise attenuation.

It is worth noting that the sounds of people walking, dogs walking, and dropped pots are noticeably louder in a kitchen with hard tile floors than with softer vinyl floors installed. The sound of placing a glass or plate upon a granite countertop is significantly louder than upon a laminate countertop.

To reduce room-to-room noise transmission it is advisable to avoid placing electrical outlets adjacent to each other on opposite sides of a wall because they can represent a “noise leak” between rooms.

Noise from plumbing systems can travel along water pipes and is sometimes transmitted as vibrations from the pipes via rigid connections to structural elements of the house where it is reradiated from walls into the home. Pipe hangers with resilient (soft) mounts are available to reduce this kind of structure borne noise.

Rooms with high cathedral ceilings sometimes exhibit unpleasant acoustical characteristics. Installation of sound absorbing panels can sometimes be helpful to improve the quality of the sound that is heard in the room.

### 3.1. Quiet Household Equipment

Many items of household equipment from responsible manufacturers are now available that produce relatively low sound levels. Sound level information is available in their advertising and on their websites. Stores such as Sears and Home Depot are displaying sound level information adjacent to products such as dishwashers, in-sink disposals, and leaf blowers. Sound level

information is also available in *Consumers Report* magazine for various products. The Institute of Noise Control Engineering of the USA (INCE/USA) is sponsoring a product noise label<sup>1</sup> that will provide consumers with the information they need to make informed decisions about sound before making a purchase. The authors' colleagues and others are working with many manufacturers to reduce sound generation of their equipment. Manufacturers are also responding to market pressures to design and offer quieter and better sounding products. The Quiet Mark program in the UK ([www.quietmark.com](http://www.quietmark.com)) also has useful information on this subject. When comparing published product noise levels a rule-of-thumb is that a difference of 1 or 2 dBA will probably not be noticed by most people while a difference of 4 or 5 dBA or more will be noticeable and can be significant. A reduction in noise generation of 10 dBA is usually dramatic.

The use of quiet appliances has become increasingly important as homes are designed to include open plans with fewer walls and doors separating rooms. Examples include:

Toilets with quiet flush and quiet fill valves are available. Pipes to and from toilets can be isolated from floor joist and studs.

Water splash noise when filling a bathtub can be reduced with the use of a faucet that aims water flow to the side of the bathtub.

Kitchen sinks with additional sound damping material along the underside are available and effective in reducing the noise of water splash and of placing dishes and utensils in it.

Disposals located below kitchen sinks and blenders on the countertop have reputations of producing high noise levels when operating. Quieter models have been introduced to the market for those of us who appreciate their convenience, but not their noise. Blenders radiate noise themselves and also vibrate the countertop causing it to also radiate noise. Some reduction of the countertop noise can be achieved by placing a neoprene pad between the blender and the countertop.

Dishwashers are now available that are far quieter than dishwashers were years ago. They include quieter motors and pumps as well as sound damping and sound absorbing materials.

Kitchen and bath ventilation fans are relatively quiet when operating at low speed and fairly noisy at high speed when higher air flow is needed. These fans can be purchased with well-designed high-efficiency reduced-noise fans to help keep the home quiet. They are often rated in sones that relate to perceived loudness. The lower the number of sones the lower is the perceived loudness.

Window (through wall) and portable air conditions generally produce significantly more noise when operating than do central air conditioners and heat pumps with equipment located on a pad outside your home. Window air conditioners also provide a weak-link or leak constituting a path for exterior noise to enter your home that is apt to be most noticeable when the unit is not operating. A plywood box lined on the inside with glass fiber insulation can be constructed and placed over the window air conditioner seasonally when it is not in use.

When installing central air conditioners it is advisable to ensure that the inside of the ducts include properly installed and protected sound absorbing linings to reduce the transmission of unwanted noise. That can reduce noise from the unit itself and can reduce noise between rooms in your

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<sup>1</sup> Being developed by Matt Nobile, Director of the INCE/USA technical committee on product noise.

home. Insulation on the outside of ducts may be useful for thermal reasons but is insignificant in terms of reducing noise transmission through them.

Essentially all vacuum cleaners were once noisy devices. One reason was that manufacturers thought that consumers perceived that high noise meant a powerful high performance product. Quieter vacuum cleaners are now available that perform just as well.

Quieter clothes washers also are now available which is most important when the washer is located upstairs near noise sensitive bedrooms, instead of in the basement. Vibration isolation pads are available to be placed between the washer's four supporting mounts and the floor. These vibration isolation pads can be particularly important for washers located upstairs. It is important that the length of the four supporting mounts be adjusted properly to reduce vibrations. It is also reasonable that the laundry room door be heavy solid core and well gasketed all-around to keep washer and dryer noise inside the laundry room.

Some furnaces are now quieter than they were in past years. However, consideration can be given to providing a room to contain the furnace and to include some ceiling mounted sound absorbing material that is washable. The furnace room door can be well gasketed and the diameter of penetrations for pipes just large enough to avoid contact with walls and accommodate stuffing with glass fiber insulation.

Sump pumps can introduce structure borne noise into the home when adequate vibration isolation is not included between the discharge pipe and house.

Reduced noise standby electric generators will be appreciated by both the homeowner and adjacent neighbors, particularly during nighttime hours.

Equipment that continues to produce relatively high noise levels includes compression engine-powered chain saws, lawn mowers, and leaf blowers. Users are well advised to use foam or muff type hearing protectors. It is also courteous to your neighbors to avoid using noisy outdoor power equipment during early morning, evening, and nighttime periods. Better yet, consider electric motor driven yard equipment.

### Section 3.2 Children's Toys

Some toys produce noise that that can cause temporary or permanent hearing damage when held close to a child's ears. Examples can include cap guns, vehicles with horns or sirens, toy phones and walkie-talkies, certain musical instruments, toys with loud speakers, and loud talking dolls.

Some toys come with a warning from the manufacturer that it should not be held close to the ear. This warning might help to protect the manufacturer from liability but provides little protection for children that don't read and heed the warnings. Such toys might be best left in the store.

Music players with headphones or earbuds can produce dangerously loud, unhealthy noise. Fortunately, child-friendly headphones with volume protection features are now available from responsible manufacturers.

The Sight and Hearing Association publishes advice about avoiding toys that can cause hearing loss for children. Their website is available at:

<http://www.sightandhearing.org/>

## Section 4. Noise at Work

### 4.1 Offices

Open offices with individual cubicles have become increasingly common. If not designed properly these open plans lead to a lack of speech privacy and employees that are distracted by intruding noises. Fortunately, there are relatively simple means available that have proven to improve the acoustics of open plan office areas. These include absorbing, blocking, and covering unwanted sound transmission.

Sound-absorbing ceiling panels with a noise reduction coefficient (NRC) of at least 0.85 will help to reduce noise from one cubicle to adjacent cubicles. Partitions between cubicles should be fabricated to provide both sound transmission loss and sound absorption and should be high enough to block sounds between cubicles. Those less than high enough to block line of sight between occupants are ineffective in blocking speech sound. Installation of sound masking systems has been demonstrated to be effective in improving the acoustical environment in office areas. Cambridge Sound Management is one provider of in-ceiling sound masking systems. Useful information about sound masking is available at the following link:

<http://cambridgesound.com/>

### 4.2 Industrial Plants

It is the author's experience during numerous consulting assignments that management at many industrial plants understands and respects their responsibility to provide a safe and healthful work environment for employees. It is becoming increasingly common for new industrial facilities to include effective noise abatement features and for existing facilities to be upgraded to reduce employee noise exposure. A design goal for noise to be less than 85 dBA in frequently occupied areas is becoming accepted by some plant owners.

If you work in a noisy industrial plant, it is recommended that you respect the need to wear hearing protection, such as muffs and/or ear plugs that should be provided by your employer. Exposure to excessive noise, especially when experienced over long periods of time, will cause irreversible hearing damage. You might also consider offering noise reduction suggestions to your employer.

The following website recognizes organizations that document measurable achievements in hearing loss prevention and disseminates information on their real-world successes.

<http://www.safeinsound.us/>

## Section 5. Sound Control for Home Entertainment Systems

One often reads in audio and home theater magazines detailed reviews and discussions of home entertainment equipment. Some compare the relative technical and subjective merits of, for instance, loudspeaker A system costing over five thousand dollars to system B costing six thousand dollars, or large screen TV or projector A vs. that of B. Rarely does one find equally knowledgeable articles on the room acoustics or sound isolation environment which can have a more profound impact on its enjoyment than merits of the electronics equipment itself. Worse, one often encounters patently false information on room acoustic issues. We hope the discussion that follows

helps define these issues for those considering assembling a high quality music or home theater system or building the spaces where it will be installed.

From an acoustical standpoint there is a major distinction between types of entertainment systems - two channel stereo or multi-channel stereo. Both types of systems are in common use and the optimum acoustics for the two types of systems differ somewhat. Most but not all music-only systems are two channel and most home theater systems are multi-channel, at least high quality theater systems. For a high quality two channel music system one sometimes seeks to impart a sense of acoustical realism using only two loudspeakers, a daunting task indeed. On the other hand one may value certain subjective attributes of the resulting sound from two speakers that have little to do with realism in the strict sense. That is not to say two channel music systems can't be eminently enjoyable, only that the resulting sound field in some respects may have little to do with that one would actually encounter in most live music performance spaces. Good room acoustics can enhance the two-channel listening experience greatly, but one should not expect that the resulting sound presented is like that in many live music listening spaces.

Audiophiles often confuse reproduced sound they enjoy a great deal with it being "accurate", but usually it is not. In a live music space some sound arrives at a listener either directly from performers or from amplification loudspeakers, generally from the stage or other location near the performers. However, most of the sound perceived by the listener is actually sound that reflects off sidewalls and other surfaces of the performance space. This reflected sound can have a profound effect on the concertgoer's sound field perception and corresponding enjoyment of the performance. In fact acousticians often refer to the sonic "signature" of performance spaces largely on the basis of the sequence of amplitude, frequency and directions of reflected sounds arriving at a typical listening seat. If this sequence differs significantly from sounds heard in a room where the same sound is reproduced electronically it is difficult to describe the latter as accurate although it certainly may have some qualities that are actually preferred by some listeners to that in the original performance space. One might refer to the difference in these spatial qualities between performing and corresponding reproduced sound as spatial distortion. Good two channel room listening acoustics should instead enhance the overall experience and endeavor to avoid serious additional distortions of the sound, particularly changes in its acoustical frequency response, rather than striving for unattainable "realism". In addition to preserving frequency response good room acoustics can provide at least some of the listener envelopment or sense of space that characterizes good live music performance spaces.

## 5.1 Frequency Response

There are a number of alterations in the frequency response or balance that a room may impose on the sound of reproduced music. One of the most important of these is the result of resonances of materials and dimensions of the room coupled with the location of loudspeakers and listeners within the room. Structural resonances of walls, windows, and other large surface area materials can have a profound effect on the frequency balance and timing of reproduced music. A flimsy plywood wall for instance may cause unwanted absorption of bass notes, diminishing the sense of power of many kinds of music. The same wall may also tend to buzz or ring at certain frequencies, time smearing details of the music, especially that of transient sounds such as percussion and piano, but even that of non-continuous sound such as the attack sounds of strings and brass instruments.

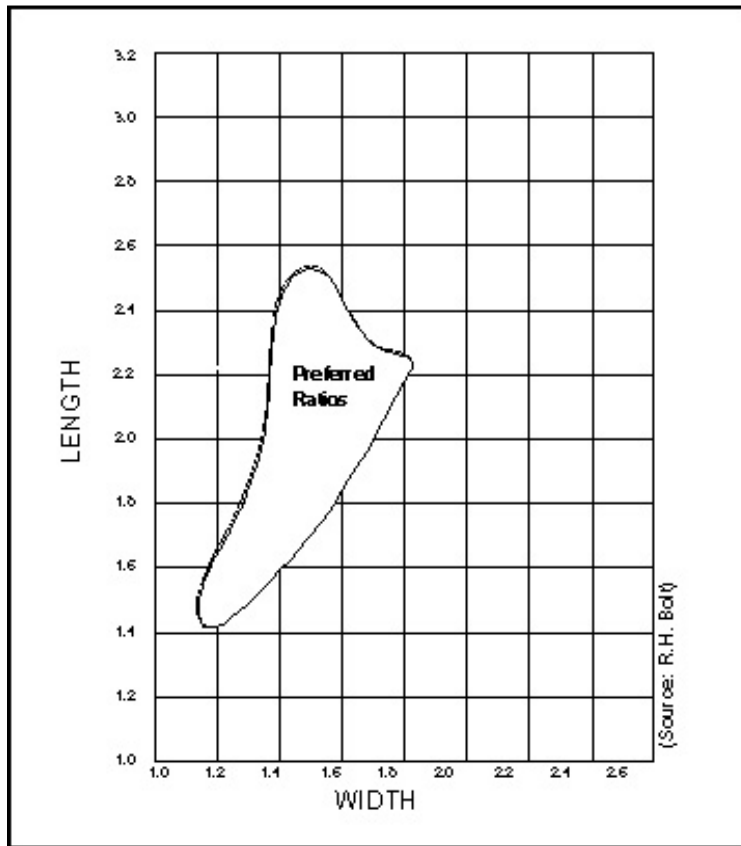
One of the authors once played a joke on a college audiophile roommate, connecting a powerful subwoofer to a sine wave test oscillator set to a very low frequency and amplitude well below the threshold of audibility but which caused a large plywood paneled wall to simultaneously resonate at a frequency well above audibility. When the roommate entered the room and encountered the

buzzing sound he asked the author what was causing it, but of course the author professed not to hear anything, instead countering that "all of you audiophiles are always hearing non-existent sounds". After pressing and releasing the wall to stop and start the buzzing, and no doubt wising to the author's known but rather warped sense of humor, the roommate "appreciated" the practical joke. One can well imagine what this same wall resonance was doing to affect reproduced organ or tympani sounds.

Generally speaking, listening room surface materials are best selected for heavy weight and stiff bracing to minimize these surface material resonance issues. One inexpensive but effective method for adding weight to gypsum board walls and other room surfaces, either in new construction or remodeling projects, is to install two rather than a single layer of the thickest feasible gypsum board, generally  $\frac{3}{4}$  inches each. If the two layers are screwed into appropriately spaced horizontal resilient channels commonly used in commercial construction rather than into the vertical studs directly, this construction will have the additional benefit of reducing transmission of sound out of and into the listening room from external spaces. One must take care that the screws do not penetrate the resilient channel and connect directly to the vertical studs behind, or the benefit of the resilient connection will be "shorted out". The same construction can be used for ceiling surfaces as well as walls, although its effectiveness is somewhat less due to the stiffness of commonly available resilient channels being optimized for the wall application. [One source for these channels](#) is US Gypsum Corp's RC-1, available at most commercial building product dealers. The link also contains much other information that may be useful in planning projects. There are other manufacturers that make competitive resilient channels although they may not perform as well according to some independent tests.

Another resonance problem that occurs in all living-room-scale spaces that can seriously affect frequency response is cavity resonances or standing wave modes of the room caused by reflections of the room's surfaces, primarily an issue for low frequencies below about 300 Hz. At higher frequencies there are also modes but many more of them that the ear is relatively insensitive to. The seriousness of these lower frequency modes largely depends on the locations of loudspeakers *and the listener* within the room so it is worth experimenting with both when possible. In the best of situations the modal structure may not have much effect at the desired listening and loudspeaker locations, but in many cases the variation is on the order of 20 - 30 dB which has a profound effect on the frequency response. These resonances may account for excessive or "boomy" bass or for serious deficits of bass frequencies at specific locations within the room. Except for conventional rectangular rooms with acoustically uniform surface materials throughout low frequency modes are not easy or inexpensive to control and even harder to predict in advance. The room dimensions and their ratios (wall-to-wall and ceiling-to-floor) determine the modal frequencies and their distribution within the room. Rooms that may be particularly problematic have dimensions that are near even multiples of each other, e.g. if the ceiling is 8 feet and the wall to wall dimensions are approximately 16 or 32 feet. There are room mode calculators available, some on the Internet, but the author is not aware of any that permit displaying a prediction of frequency response for a specific set of loudspeaker and listener locations within real rooms. [Some take a statistical approach like this one](#) based on the work of Richard H Bolt, formerly at MIT and Bolt Beranek and Newman, which indicates the modal frequencies and whether the modes associated with specific room dimension ratios are spaced optimally in frequency. The chart below indicates optimal dimensions for these rooms according to Bolt, meaning that *on average* throughout the room no one frequency will stand out from others and is therefore less likely to color the bass sound. That is a good starting point for design of rectangular rooms of uniform height but again, it doesn't indicate frequency responses for a specific set of loudspeaker and listener locations within the room and these typically will vary dramatically from point to point. So even in rooms that are

carefully designed to minimize modal response effects the frequency response usually will still not be optimum without additional considerations.



Preferred Dimension Ratios for Sound Reproduction Rooms

Fortunately, in the last two decades it has become common to use one or more (sub)woofers rather than the main loudspeakers to reproduce the lowest frequencies. There are a number of advantages to this: one of them is that one or more woofers can be placed where they provide the most uniform bass response while the main loudspeakers can be much smaller and placed for optimum imaging and subjective envelopment at the listener locations. Most modern high quality audio-visual receivers provide built-in acoustical measurement and signal processing which is helpful in integrating one or more woofers into the system. Among other benefits this processing provides time alignment of all the loudspeakers to compensate for the different path lengths from each loudspeaker to the listening positions, including those of woofers. The processing also typically provides frequency response equalization which can compensate to some degree for differences in the response of the various speakers in the system as well as that of the response effects of the room.

In addition to these modal effects, a room imposes its signature on reproduced sound due to other issues including lack of sound absorption. Half as much sound absorption will increase the amount of reflected sound in a room by 3 decibels, a very noticeable amount. Generally speaking most domestic rooms used for music reproduction have less sound absorption than desirable, especially at low frequencies. The result is that such rooms are considerably more reverberant than those in recording studios, cinema sound stages, or other professional spaces designed expressly for the highest quality of reproduced sound. The type of loudspeaker, the sound absorption, the frequency

characteristics of the sound absorption, and where all are located play important parts in the overall quality of sound. It's not an exaggeration to say that in untreated rooms we hear more of the playback room than the room where the sound was recorded! So good playback room design normally involves application of a considerable amount of sound absorbing material to the room surfaces.

One rule of thumb that acousticians sometimes use is that the total absorption in a playback room should equal an area of 100% efficient treatment at least equal to the floor area of the room, expressed in Sabins. For example, if the floor area is 500 square feet the total absorption should be at least 500 Sabins. This might be realized by treating the room with a sufficient area of heavy velour drapes or fabric wrapped glass fiber panels applied to the walls and or ceiling, or some combination. Perhaps contrary to most people's intuitive sense, most carpeting does not add much to the total absorption, although it is possible to obtain very thick unbacked carpeting which, if applied over a thick horsehair or foam underlayment, can add significant absorption.

The table of absorption coefficients below illustrates that of some common building materials. One goal that professional sound studio designers strive to achieve is a uniform reverberation time at all frequencies in order that some parts of the sound spectrum are not exaggerated or deficient. In order to achieve this goal it follows that the total amount of effective sound absorption is close to the same at each frequency.

| Product   | Octave Band Center Frequencies, Hz |      |      |      |      |      | NRC  |
|---|------------------------------------|------|------|------|------|------|------|
|   | 125                                | 250  | 500  | 1000 | 2000 | 4000 |      |
| Brick, unglazed   | 0.03                               | 0.03 | 0.03 | 0.04 | 0.05 | 0.07 | 0.05 |
| Brick, unglazed, painted  | 0.01                               | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.00 |
| Concrete block, painted   | 0.10                               | 0.05 | 0.06 | 0.07 | 0.09 | 0.08 | 0.05 |
| Carpet, 1/8" pile height  | 0.05                               | 0.05 | 0.10 | 0.20 | 0.30 | 0.40 | 0.15 |
| Carpet, 1/4" pile height  | 0.05                               | 0.10 | 0.15 | 0.30 | 0.50 | 0.55 | 0.25 |
| Carpet, 3/16" combined pile and foam                                    | 0.05                               | 0.10 | 0.10 | 0.30 | 0.40 | 0.50 | 0.25 |
| Carpet, 5/16" combined pile and foam                                    | 0.05                               | 0.15 | 0.30 | 0.40 | 0.50 | 0.60 | 0.35 |
| Fabric, light velour, 10 oz./sq. yd. hung straight in contact with wall | 0.03                               | 0.04 | 0.11 | 0.17 | 0.24 | 0.35 | 0.15 |
| Fabric, medium velour, 14 oz./sq. yd. draped to half area               | 0.07                               | 0.31 | 0.49 | 0.75 | 0.70 | 0.60 | 0.55 |
| Fabric, heavy velour, 18 oz./sq. yd. draped to half area                | 0.14                               | 0.35 | 0.55 | 0.72 | 0.70 | 0.65 | 0.60 |
| Floors, concrete or terrazzo  | 0.01                               | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.00 |
| Floors, linoleum, asphalt, rubber or cork tile on concrete              | 0.02                               | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.05 |
| Floors, wood  | 0.15                               | 0.11 | 0.10 | 0.07 | 0.06 | 0.07 | 0.10 |
| Floors, wood parquet in asphalt or concrete                             | 0.04                               | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 | 0.05 |
| Glass, 1/4", sealed, large panes  | 0.05                               | 0.03 | 0.02 | 0.02 | 0.03 | 0.02 | 0.05 |
| Glass, 24 oz. operable windows, closed                                  | 0.10                               | 0.05 | 0.04 | 0.03 | 0.03 | 0.03 | 0.05 |
| Gypsum board, 1/2", nailed to 2x4s on 16" centers, painted              | 0.10                               | 0.08 | 0.05 | 0.03 | 0.03 | 0.03 | 0.05 |
| Marble or glazed tile   | 0.01                               | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.00 |
| Plaster, gypsum or lime, rough finish or lath                           | 0.02                               | 0.03 | 0.04 | 0.05 | 0.04 | 0.03 | 0.05 |
| Plaster, gypsum or lime, smooth finish                                  | 0.02                               | 0.02 | 0.03 | 0.04 | 0.04 | 0.03 | 0.05 |
| Plywood paneling, 1/4" thick, wood frame                                | 0.58                               | 0.22 | 0.07 | 0.04 | 0.03 | 0.07 | 0.10 |
| Water surface, as in swimming pool                                      | 0.01                               | 0.01 | 0.01 | 0.01 | 0.02 | 0.03 | 0.00 |
| Wood roof decking, tongue-in-groove cedar                               | 0.24                               | 0.19 | 0.14 | 0.08 | 0.13 | 0.10 | 0.15 |

*From "Acoustical Ceilings — Use and Practice," Ceilings and Interior Systems Contractors Association (1984), p.18.*

### Sound Absorption per Square Foot in Sabins

The table lists the sound absorption per square foot of some common building materials and can be used to calculate the total absorption in a room in Sabins at each frequency by multiplying the area of the material in the room. A more detailed list covering many more materials is easily available but this table can be used to illustrate the method used. As an example assume we have a rectangular room with a smooth finish plaster ceiling with dimensions of 20' by 30' = 600 sq. ft. Our goal is then to obtain 600 Sabins of absorption elsewhere in the room as a minimum. We might also have a thick 5/16" wall to wall carpet of 600 square ft over a foam underlayment which would contribute approximately  $600 \times 0.5 = 300$  Sabins at mid frequencies, so we would need another 300 Sabins elsewhere in the room, perhaps a little over 400 sq. ft. of medium velour curtains. Of course we might have other materials in the room which would contribute, so a somewhat smaller area of curtains might be acceptable.

The 600 Sabins may be adequate for a two channel music system but a room intended for a high quality multi-channel music or movie playback system would be better served by additional absorption as typical for cinemas. Indeed, from an acoustical standpoint it is hard to overdo the amount of absorption in a practical room intended for multi-channel sound reproduction.

## Appendix A. Terminology

Provided below are informal descriptions of technical terms as they are used in this report. For detailed technical definitions, it is suggested that the reader refer to textbooks or standards dealing with acoustics and vibration.

Absorption – a material property related to its ability to change sound energy to heat and reduce reflected sound energy. The common unit of sound absorption is a Sabin, which corresponds to a square foot of perfectly absorptive material (coefficient of unity).

Acoustics – the science of sound.

Airborne noise – Noise that travels through the air from a source to a receiver.

Ambient sound level – All-encompassing sound at a location, usually a composite of sounds from many nearby and distant sources.

Attenuation – the reduction of sound energy.

A-weighted sound level (dBA) – Sound measured with a standard sound level meter that emphasizes mid-frequency sounds simulating the way people hear, and correlates well with subjective judgments of the loudness of most sounds.

Damping – the dissipation of vibratory energy in a solid surface.

Day-night sound level (Ldn) – The equivalent noise level during one or more days after a 10 dB penalty has been added to the nighttime noise levels (10 p.m. to 7 a.m.) to account for the sensitivity of people to nighttime noises. It is commonly used to quantify the environmental noise environment in residential areas.

Decibel – A measure on a logarithmic scale indicating the squared ratio of sound pressure to the reference sound pressure. See also sound pressure level.

Because sound levels are expressed in decibels they are added and averaged on a logarithmic basis in accordance with the following relationships.

$$\text{Sum} = 10 \cdot \log[10^{(0.1 \cdot L_{p_1})} + 10^{(0.1 \cdot L_{p_2})} + \dots + 10^{(0.1 \cdot L_{p_n})}]$$

for example the sum of 81 dB + 84 dB + 88 dB = 90 dB

$$\text{Average} = 10 \cdot \log\{1/n \cdot [10^{(0.1 \cdot L_{p_1})} + 10^{(0.1 \cdot L_{p_2})} + \dots + 10^{(0.1 \cdot L_{p_n})}]\}$$

for example the average of 81 dB + 83 dB + 88 dB = 85 dB

where:

$L_{p_1}, L_{p_2}, \dots, L_{p_n}$  represent a series of individual sound levels  
log is the common logarithm to the base 10

Envelopment – a listener's sense of being enveloped or surrounded by sound. It is a desirable quality of concert halls as well as sound reproduction systems.

Equivalent noise level (Leq) – A commonly used logarithmic (energy) average of measured sound levels over a stated time period. It is simply the energy average of the measured sound levels.

Frequency – the number of oscillations or cycles per second expressed in Hertz (Hz) or previously cycles per second (cps), the pitch of a sound.

Ground-borne vibration – Motion (oscillation) of the ground near a source of vibration such as passing trains.

Imaging – the ability of a listener to a sound reproduction system to localize the direction of the various recorded sound sources.

Modes – the cavity resonances of three dimensional spaces including rooms.

Noise – Commonly defined as simply unwanted sound.

Noise level (dB or dBA) – A commonly used logarithmic measure of the magnitude of noises at a location.

SLM – Sound level meter.

Reverberation time – the time for a sound in a room to decay by 60 dB, generally taken as near inaudibility for a moderate loudness sound.

Sones – A unit of subjective loudness on a linear scale, i.e. a sound of 4 Sones is subjectively twice as loud as one of two Sones. For reference, a sound of 4 Sones is very roughly 60 dB sound pressure level.

Sound pressure level (dB) - Ten times the common logarithm of the ratio of the time-mean-square pressure of a sound to the square of the reference sound pressure.

$$\text{sound pressure level} = 10 \cdot \log(p_1/p_0)^2$$

where:

$p_1$  is the sound pressure

$p_0$  is the reference pressure of 20  $\mu$  Pa (in air)

Subwoofer – A misnomer for woofer in common use. A true subwoofer is inaudible as it reproduces sound below the frequency perception of humans, generally 20 Hz. As employed in home sound systems however, a subwoofer generally reproduces sound below the frequency that permits human perception of its direction of arrival, generally about 80 -120 Hz.

Vibration velocity level (VdB) – A commonly used logarithmic measure of the magnitude of vibrations at a measurement location. Ten times the common logarithm of the ratio of the square of the amplitude of the vibration velocity to the square of the amplitude of the reference velocity of 1  $\mu$  in./sec.

Woofers – a loudspeaker for reproducing low frequencies, usually below 500 Hz. if located in the same cabinet as those radiating middle and upper frequencies, or below 125 Hz for a loudspeaker at an arbitrary location (See also subwoofer above.)

## Appendix B. Sound in Lay Terms

Sounds we hear come from small pressure oscillations, or sound waves, that travel through the air and actuate our hearing mechanism. These airborne pressure oscillations cause the eardrum and small bones of the middle ear to vibrate. These vibrations are transmitted to the fluid-filled cochlea of the inner ear's sensory organ. Sensory hair cells then transduce these vibrations into nerve impulses that are transmitted to the brain where they are perceived and interpreted.

Noise is often defined as unwanted sound and the degree of disturbance or annoyance of an intruding noise depends on various factors including the magnitude and nature of the intruding noise, the magnitude of the background or pre-development ambient sound present without the intruding noise, and the nature of the activity of people in the area where the noise is heard. For example, people relaxing at home generally prefer a quiet environment, while factory employees may be accustomed to relatively high noise levels when at work.

The magnitude, or loudness, of sound waves (pressure oscillations) is described quantitatively by the terms sound pressure level, sound level, or simply noise level. The magnitude of a sound is measured in decibels, abbreviated dB. Decibels are used to quantify sound pressure levels just as degrees are used to quantify temperature and inches are used to quantify distance. The faintest sound level that can be heard by a young healthy ear is about 0 dB, a moderate sound level is about 50 dB, and a loud sound level is about 100 dB.

Sound level meters are usually equipped with electronic filters or weighting circuits, as specified in ANSI S1.4 - 1983, for the purpose of simulating the frequency response characteristics of the human ear. The A-weighting filter included with essentially all sound level meters is most commonly employed for this purpose because the measured sound level data correlate well with subjective response to sounds. Sound levels measured using the A-weighting network are designated by dBA.

Sound energy spreads as it travels away from its source causing the sound level to diminish. Other factors that reduce sound levels include absorption in the atmosphere, diffraction and refraction in the atmosphere, terrain, and forests.

The frequency of a sound is perceived as its tonal quality or pitch. The unit for frequency is hertz, abbreviated Hz (formerly cycles per second or cps). Thus, if a sound wave oscillates 500 times per second, its frequency is 500 Hz. The fundamental frequency of Middle C on a piano keyboard, for example, is 262 Hz. However, most sounds include a composite of many frequencies and are characterized as broadband or random. The normal frequency range of human hearing extends from a low frequency of about 20 to 50 Hz (a rumbling sound) up to a high frequency of about 10,000 to 15,000 Hz (a hissing sound) or even higher for some people. People have different hearing sensitivity to different frequencies and generally hear best in the mid-frequency region that is common to human speech, about 500 to 4000 Hz.

The background or ambient acoustical environment in most communities varies from place to place and varies with time at any given location due to the composite of many nearby and distant sound sources. The ambient environment includes high sound level single-events such as the passby of an airplane or nearby car, the barking of a dog, thunder, or a siren. The ambient acoustical environment also includes relatively steady residual or background sounds caused by sources such as distant traffic and ventilation equipment. The quantity of the single-event sounds and the

amplitude of the background sounds are usually least during the late night hours from about midnight to 5:00 am. Indeed, the pre-development ambient sound level at a location is typically related to the amount of human activity in its vicinity. The amplitude statistics of this rather complex acoustical environment include the presence of a relatively-steady lower-level background and diurnal and seasonal variations.

At any location, a complete physical description of the ambient acoustical environment might include its sound level at various frequencies, as a function of time. As a first step towards simplifying this multi-dimensional description, it has become common practice to eliminate the frequency variable by measuring the A-weighted sound level (dBA), as observed on a standard sound level meter. The A-weighting filter emphasizes the mid-frequency components of sounds to approximate the frequency response of the human ear. A-weighted sound levels correlate well with our perception of the loudness of most sounds.

It is our experience that sensitivity to noises and annoyance varies greatly among people. Some people are tolerant and accepting of most noises while some people find even relatively low-level sounds to be unacceptable, especially if the noise includes discrete frequency tones or unusually high-frequency or low-frequency components. If you suddenly find that even modest sound levels become intolerable we suggest that a visit to an experienced audiologist is in order to determine the cause that might relate to an injury or illness within your ear. On the other extreme, if you are finding it difficult to understand speech a visit to an experienced audiologist is in order to determine the cause.

An increase or decrease of the ambient sound level by 1 or 2 dB is generally not noticeable. Whereas a change of the ambient sound level by 5 or 6 dB is generally noticeable and an increase or decrease of the ambient sound level by 10 dB is generally considered to represent a doubling or halving of the perceived sound and is perceived as a dramatic difference.

To report time-varying outside ambient community sound levels it is common practice, using the A-weighted scale, to measure the equivalent Leq sound level. The equivalent sound level is the level of a continuous sound that has the same total (equivalent) energy as the time-varying sound of interest, taken over a specified time period. Thus, the equivalent sound level is a single-valued level that expresses the time-averaged total energy of the entire ambient sound energy. It includes both the high sound level single-event ambient sounds and the relatively steady background sounds.

It is also common practice to measure and report statistical sound levels in a community. For example, the L90 sound level which is the level exceeded during 90% of the measurement time. It represents the equivalent average of background sound, in the absence of loud intermittent sounds. The Lmax sound level is the highest sound level observed during the measurement interval.

## Appendix C. Additional Reading Materials

Listed below are a few references for readers interested in learning technical engineering and scientific details about acoustics, noise control, and high-quality sound systems.

*Acoustics: Sound Fields and Transducers*,  
Leo L. Beranek and Tim Mellow, 2012

*Noise and Vibration Control Engineering: Principles and Applications*,  
István L. Vér and Leo L. Beranek, 2005

*Technology for a Quieter America*, National Academy of Engineering, 2010,  
[http://www.nap.edu/catalog.php?record\\_id=12928](http://www.nap.edu/catalog.php?record_id=12928)

*Noisy Motorcycles – An Environmental Quality-of-Life Issue*, published by The Institute of Noise Control Engineering, 2013, <http://www.inceusa.org/>

*Cost Benefit Analysis – Noise Barriers and Quieter Pavements*, published by The Institute of Noise Control Engineering, 2014, <http://www.inceusa.org/>

*Protecting National Park Soundscapes*, published by the National Academy of Engineering, 2013,  
[http://www.nap.edu/catalog.php?record\\_id=18336](http://www.nap.edu/catalog.php?record_id=18336)

*Sound reproduction: Loudspeakers and rooms*, Floyd E. Toole, Elsevier Focal Press, 2008, ISBN 978-0-240-52009-4

*Note on the normal frequency statistics in rectangular rooms*, Richard. H. Bolt, J.Acoust.Soc.Am. 18(1) 130-133. (1946)

*Master Handbook of Acoustics*, F. Alton Everest, McGraw Hill Professional Publishing, ISBN-13: 9780071603324